



**System Elements Required to Guarantee
the Reliability, Availability and Integrity
of Decision Making Information in a Complex
Airborne Autonomous System**

by

Karthik Ramalingam

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Abstract

Current air traffic management systems are centred on piloted aircraft, in which all the main decisions are made by humans. In the world of autonomous vehicles, there will be a driving need for decisions to be made by the system rather than by humans due to the benefits of more automation such as reducing the likelihood of human error, handling more air traffic in national airspace safely, providing prior warnings of potential conflicts etc. The system will have to decide on courses of action that will have highly safety critical consequences. One way to ensure these decisions are robust is to guarantee that the information being used for the decision is valid and of very high integrity. To meet regulatory requirements there will still need to be some form of human involvement, or back up, and the interface between computer and human will be very important. This doctorate will examine the issues associated with guaranteeing that information on which decisions will be made is valid and of very high integrity. The issues that will be addressed in the research are understand and examine the current architecture of the Air Traffic Management System (ATM) and its evolution to enable integration of UAS into the national airspace system in a phased-approach. Investigate UAS Sense and Avoid, a key UAS integration challenge, in order to determine the best place for decision-making processing (i.e. on board or remotely) from a technical and economical perspective. And finally, to develop a Ground-Based Sense and Avoid simulation architecture in order to investigate the impact of different configurations of GBSAA information display system on the decision-making capability of human operator

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Table of Contents

Chapter 1: Introduction	13
1.1 Rationale: The Need for Autonomy.....	13
1.2 Autonomous Systems.....	14
1.3 Motivation for the study of Unmanned Aircraft System (UAS).....	21
1.3.1 The Wider motivation	23
1.4 Thesis Structure.....	26
1.4.1 Part I – Introduction and Background	26
1.4.2 Part II – UAS Integration in ATM: A System of Systems Architecture Analysis	26
1.4.3 Part III – UAS Sense and Avoid	27
1.4.4 Part IV – Conclusions	29
1.5 Aim and Objectives	30
1.6 Why Unmanned Aircraft?.....	32
1.6.1 Unmanned Aircraft Systems (UAS) Overview.....	33
1.6.2 Historical Perspective of Unmanned Aircraft	36
1.6.3 UAS Types and Classifications.....	38
1.6.4 UAS Applications	44
1.6.5 UAS Market Overview	46
1.6.6 Current Regulatory and Operational mechanism of UAS	52
1.7 Historical context of introduction of new technology into Aviation	60
1.8 Positioning the Study	62
1.8.1 Factors influencing the research approach.....	62
1.8.2 Scope	63
1.9 Summary	65
Chapter 2: System-of-Systems Overview	67
2.1 Introduction to System-of-Systems	67
2.2 System-of-Systems (SoS) Analysis	76

2.2.1 Architecture Design Process	77
2.2.2 Architecture Design Principles	80
2.2.3 SoS Architecture Design.....	81
2.2.4 Architecture Frameworks.....	84
2.2.5 Modelling Language.....	86
2.3 Methodology to Architect and Analyse SoS	87
2.4 Air Traffic Management (ATM) as SoS	89
2.5 Scope	91
2.6 Summary	92
Chapter 3: SoS Analysis of ATM and integration of UAS in ATM Using Architecture Patterns.....	93
3.1 Introduction	93
3.2 Architecture Patterns	93
3.3 Architecture Patterns Mining	95
3.4 Verification and Validation of Architecture Patterns.....	98
3.5 Air Traffic Management (ATM) Architecture Patterns	99
3.5.1 Air Traffic Control Organisational Structure	99
3.5.2 Airspace Classification Structure.....	104
3.5.3 Air Traffic Surveillance	107
3.5.4 Air Traffic Communication	117
3.5.5 Air Traffic Navigation.....	120
3.5.6 Air Traffic Weather.....	126
3.5.7 Future Air Traffic Management Structure	131
3.6 Summary	133
Chapter 4: Integration of UAS in National Airspace System – A Complex SoS problem	134
4.1 Introduction	134
4.2 Wicked Problem.....	135
4.3 UAS operations in ATM: A Wicked Problem Analogy	141
4.4 Discussion on ways to address airspace integration.....	153
4.5 Summary	157

Chapter 5: UAS Sense and Avoid Overview	160
5.1 Current Progress	162
5.1.1 Airborne Sense and Avoid (ABSAA)	163
5.1.2 Ground Based Sense and Avoid (GBSAA)	166
Chapter 6: Ground Based Sense and Avoid (GBSAA) System Concept Overview	170
6.1 Introduction	170
6.2 GBSAA System Concept	172
6.2.1 System Requirements	172
6.2.2 Stakeholders	173
6.2.3 System Definition	174
6.2.4 GBSAA Functional Overview	182
6.2.5 GBSAA System Elements	184
6.3 GBSAA Systems Operation.....	186
6.3.1 GBSAA Concept of Operation.....	186
6.3.2 Operational Level Description	188
6.3.3 GBSAA system Analysis.....	192
6.4 GBSAA: Proving the Safety Case	203
6.4.1 See and Avoid.....	205
6.4.2 Visual Acquisition Model.....	205
6.4.3 Visual Acquisition Performance	207
6.4.4 Sense and Avoid Encounter Timeline.....	209
6.5 Summary	210
Chapter 7: Ground Based Sense and Avoid Experiment Design	211
7.1 Introduction	211
7.2 Background.....	211
7.2.1 GBSAA Overview.....	213
7.2.2 GBSAA Display Concept.....	217
7.2.3 Existing Air Traffic Display Systems for use as GBSAA display	219
7.2.4 Separation Assurance	222
7.3 Experiment Method	223
7.3.1 Display Concepts	224

7.3.2 Design and Selection of Scenarios.....	224
7.3.3 Participants.....	225
7.3.4 Experiment Set-up.....	225
7.4 Experiment Design.....	232
7.5 Experiment Procedure.....	233
7.5.1 Training.....	233
7.5.2 Experiment Scenarios.....	234
Chapter 8: Ground Based Sense and Avoid Experiment Results and Discussion..	238
8.1 Introduction.....	238
8.2 Results.....	238
8.2.1 Technical Performance Measures.....	239
8.2.2 Workload Measurement Results.....	243
8.2.3 Scenario Specific Results.....	245
8.2.4 Final Questionnaire Results.....	248
8.3 Discussion.....	253
Chapter 9: Conclusions.....	257
9.1 Thesis Contributions.....	259
9.2 Further Research.....	260
References.....	262
Appendices.....	268

List of Figures

Figure 1.1 Autonomy classification model [13].....	18
Figure 1.2 History of accident rates in civil aviation [27]	25
Figure 1.3 Thesis Structure	29
Figure 1.4 A typical Unmanned Aircraft System.....	35
Figure 1.5 Worldwide UAS Market Forecast [48]	48
Figure 1.6 UAS R&D expenditure by country (%) 2011 – 2020 forecast [48]	49
Figure 1.7 UAS category wide distribution market forecast [50]	50
Figure 1.8 Global UAV Production Forecast by UAV Type	51
Figure 2.1 A basic SoS model [55].....	71
Figure 2.2 Interactions between SoS and constituent systems in a Directed SoS....	72
Figure 2.3 Interactions between SoS and constituent systems in a Virtual SoS	73
Figure 2.4 Interactions between SoS and constituent systems in a Collaborative SoS	74
Figure 2.5 Interactions between SoS and constituent systems in an Acknowledged SoS	76
Figure 2.6 SoS context [55].....	82
Figure 3.1 Overview of UPDM views used in DANSE methodology	95
Figure 3.2 Pattern mining process [104]	98
Figure 3.3 Air Traffic Control Organisational Structure (US)	100
Figure 3.4 Air Traffic Control Organisational Structure (Europe)	103
Figure 3.5 Airspace Classification Structure	105
Figure 3.6 Air Traffic Surveillance	109
Figure 3.7 Air Traffic Management Non-Cooperative Surveillance	110
Figure 3.8 Air Traffic Management Cooperative Independent Surveillance	112
Figure 3.9 Air Traffic Management Cooperative Dependent Surveillance	113
Figure 3.10 Air Traffic Management Cooperative Independent Surveillance (Multi- lateration System)	117
Figure 3.11 Duplex Radio Communication.....	119
Figure 3.12 Air navigation Aids	121

Figure 3.13 Satellite Based Augmentation System (SBAS) [67]	125
Figure 3.14 Air Traffic Weather Service	127
Figure 3.15 Future Air Traffic Weather Service	130
Figure 3.16 Future Air Traffic Management Structure [88].....	132
Figure 4.1 An overview of systems approach used to identify and analyse the key challenges of UAS Integration in ATM	142
Figure 5.1 Airspace Conflict Management	161
Figure 5.2 Ground Based Sense and Avoid (GBSA) dedicated sensor	168
Figure 6.1 Potential Stakeholders and their Grouping	173
Figure 6.2 Stakeholder Influence Map	174
Figure 6.3 Ground based UAV Collision Avoidance System.....	175
Figure 6.4 Ground based UAV CAS use case diagram	176
Figure 6.5 System level interactions of Ground based CAS	177
Figure 6.6 Overall system Overview	179
Figure 6.7 GBSAA functional block diagram	183
Figure 6.8 Concept of using GBSAA for operations of UAS in non-segregated airspace.....	187
Figure 6.9 GBSAA service level view	188
Figure 6.10 GBSAA System Performance Model	202
Figure 6.11 Observed acquisition probability and modelled visual acquisition probability for both unalerted and alerted search [16].....	207
Figure 6.12 Relative airspeed frequency distribution of several types of aircraft in uncontrolled airspace [19]	209
Figure 6.13 Time to react to collision threats [18]	210
Figure 7.1 GBSAA Simulation Architecture	227
Figure 7.2 GBSAA System Experiment Set-Up	227
Figure 7.3 Prototype GBSAA display	229
Figure 8.1 Boxplot of total decision processing time for the display configuration used	240
Figure 8.2 Clustered bar chart of number of correct manoeuvres performed against the display configuration used.....	242
Figure 8.3 Clustered bar chart of frequency of correct manoeuvres performed against the scenario level.....	243
Figure 8.4 Boxplot of NASA-TLX workload rating	244

Figure 8.5 Box plot of Spotting scores	245
Figure 8.6 Bar chart of average time taken to decide manoeuvre	246
Figure 8.7 Box plot of total time taken to decide manoeuvre (Scenario 3).....	247
Figure 8.8 Box plot of total time taken to decide manoeuvre (Scenario 6).....	247
Figure 8.9 Bar chart of Average time taken to decide manoeuvre for correct manoeuvre selected	248
Figure 8.10 Participant Display preference	249
Figure 8.11 Value of 'highlight of UAV track' information	250
Figure 8.12 Value of 'prediction vectors' information	251
Figure 8.13 Value of 'Highlight of intruder track' information.....	251
Figure 8.14 Value of 'Surrounding aircrafts colour format' information	252
Figure 8.15 Value of 'Track list window' information	252

List of Tables

Table 1: Levels of Automation [11]	17
Table 2: The PACT (Pilot Authorisation and Control of Tasks) Framework [11]	19
Table 3: NHTSA Classification of Vehicle Automation [11]	20
Table 4: UAS classification group in UK airspace (CAP722)	42
Table 5: EASA UAS Classification	43
Table 6: UAS Groups recommended by small UAS ARC	44
Table 7: Architecture Pattern Template	97
Table 8: Quality of Service Aspects [15]	190
Table 9: Quality of Service Aspects [15]	191
Table 10: Quality of Service Aspects [14], [15]	192
Table 11: Comparison of radar sensors	197
Table 12: Alternative Sensor Technologies	199
Table 13: Aircraft Flight Information (On the two-dimensional system grid 1 unit = 1 Nautical Mile for both X and Y axis)	235
Table 14: Overall repeated measures ANOVA result	241

List of Abbreviations

UAV(s)	Unmanned Aerial Vehicle(s)
UA	Unmanned Aircraft
NAS	National Airspace System
UAS(s)	Unmanned Aircraft System(s)
ISR	Intelligence, Surveillance & Reconnaissance
NextGen	Next Generation Air Transportation System
SESAR	Single European Sky ATM Research
EOD	Explosive Ordnance Disposal
PACT	Pilot Authorisation and Control of Tasks
LOA	Levels of Automation
UK MOD	United Kingdom Ministry of Defence
NHTSA	National Highway Traffic Safety Administration
FMVSSs	Federal Motor Vehicle Safety Standards
ACC	Adaptive Cruise Control
SoS	System-of-Systems
ATM	Air Traffic Management
COTS	Commercial off the Shelf
ATC	Air Traffic Control
ABSAA	Airborne Sense and Avoid System
GBSAA	Ground-Based Sense and Avoid System
ISR	Intelligence, surveillance and reconnaissance

Part I: Introduction and Background

Chapter 1: Introduction

1.1 Rationale: The Need for Autonomy

According to the English dictionary the word 'Autonomy' is defined as 'the right to self-governance'. This word is used in various contexts in several varied spheres of studies ranging from sociology, politics, philosophy, medicine and many more. When used in the context of autonomous vehicles or systems, it means the car, air vehicle or any other vehicle or system that has the ability to self-govern i.e. the freedom to act independently. That is an autonomous system is one that can operate and manage (includes the ability to plan actions, reassess goals and make decisions) independently without any human intervention under any external environmental conditions. However, an autonomous system can have varying degrees of autonomy incorporated depending on the level of human intervention involved.

Autonomy (i.e. self-governance), when used in the context of autonomous systems or vehicles, can significantly improve the efficiency and safety of a system [1]. This in turn can provide potential benefits both in cost and risk reduction [1]. Despite this the day-to-day/routine use of autonomous vehicles/systems in a wide range of commercial applications has not yet been possible [2]. This is especially true in the case of autonomous systems operations in safety critical environments i.e. air transportation, road transit system. The main reasons for the restricted usage of autonomous systems in commercial applications include technical, economic, social and political factors [3]. Among them key challenges include ensuring integrity and resilience in autonomous systems (i.e. ability to predict behaviour of systems that can adapt to changing conditions), certification and regulation of these systems, and public perception of risk about safety and privacy issues [4], [5]. However, there are great rewards for advancement of autonomous systems technology in terms of improving system safety and efficiency as well as the potential for providing entirely new capabilities in environments where direct human control is not physically possible.

The main benefits of autonomous systems are that they can be operated and managed (includes the ability to plan actions, reassess goals and make decisions)

independently without any human intervention under any external environmental conditions. This enables them to perform missions that are characterised as dull, dirty or dangerous for manned systems [6]:

- Dull missions involve performing mundane/routine tasks for long-duration. The nature of these tasks makes them ill-suited for manned systems, however they are ideally suited for unmanned systems. A good example is surveillance missions which involve observation for prolonged period of time ranging from few hours to several days. An unmanned system can perform such a surveillance task constantly for the entire duration unlike a manned system where the human can perform a surveillance task only for several hours due to tiredness. There is also the possibility of human error occurring due to boredom from repetitive tasks.
- Dirty missions are those that can potentially expose personnel to hazardous conditions. For example, missions such as surveillance in nuclear plant accident site, biological or chemical leak detection. Unmanned systems can perform these dirty missions with less risk exposure to the operators [6].
- Dangerous missions are those which involve high risk for damage or loss of system in turn endangering operator's life or people. A prime example is forest fire monitoring/firefighting missions [7]. Unmanned systems can significantly reduce the risk to personnel by increasingly having capability to fulfil inherently dangerous missions.

1.2 Autonomous Systems

Autonomous systems are systems that can decide for themselves what to do and when to do it [8]. They have the ability to adapt their behaviour in response to unforeseen events in their operational environment. The capability and domains of application of such systems has expanded significantly in the recent years, with increasing incorporation of autonomy in industrial, household and military systems [8]. There are several examples of such systems used to perform range of tasks, all varying in the degree of autonomy incorporated, from almost complete human control to fully autonomous capability with minimal human interaction. The usage of

autonomous systems for commercial and military applications has increased in recent years with application areas ranging from industrial robotics to autonomous vehicles [8]. The use of robotics and autonomous systems has evolved from their initial use in industrial automation to their usage now across the domains of air, ground, sea and space [8]. Autonomous systems have been successfully implemented in commercial applications such as mining, agriculture, warehousing and medical logistics. These systems employ similar technology but have basic sensing and automated decision-making to accomplish tasks i.e. they are more complex and larger than earlier adoption of such automated systems in industrial automation and household robotic solutions. Other area where autonomous systems have seen large proliferation is in government/military applications in the last decade [4]. Unmanned aircraft, ground, and maritime systems have been used by defence forces to perform functions such as Intelligence, surveillance and reconnaissance (ISR), weapons delivery platform and other dangerous jobs such as explosive ordinance disposal (EOD) [6]. The government applications of autonomous systems are not only limited to military applications but also in multiples areas such as search and rescue, law enforcement, scientific research and disaster management [9].

Autonomous systems can operate independently without any degree of human intervention under all external environments. Most of the autonomous systems in operation today have mission execution capability, which is they are typically fully pre-programmed to perform tasks repeatedly and independently of any external influence or control [6]. However, in the future autonomous systems are envisaged to have mission performance capability without any human control, that is they have the ability to adapt/deviate from pre-programmed tasks when the mission outcomes change which may happen even during a mission [6]. A fully autonomous system is capable of self-deciding by choosing a behaviour it follows to operate itself to fulfil a human-directed goal. Thereby various levels of autonomy exist in any system that determines the level of human interaction and frequency of their interaction with the autonomous system [10]. It is necessary to ensure the degree of autonomy incorporated in any system needs to be appropriate to the task.

In order to enable interaction between the human and the system a framework

is required that defines the level of human control or intervention under a variety of different situations for autonomous systems operation. There have been several efforts in the past towards classification of levels of autonomy. The various frameworks for classification of autonomy are described briefly here, few of which are application domain specific [11].

The earliest model for defining levels of autonomy between the human and computer was put forward by Sheridan & Verplanck [11], which was later revised by Parasuraman *et al.* [12]. The first proposed framework consists of 10 possible levels of decision-making tasks between the human and computer, ranging from human making all the decisions (Level 1) to the computer making all decisions without any form of human control/intervention (Level 10), as shown in Table 1. The revised model also has 10 possible levels of automation however the framework considers the application of automation to a four-stage model of information processing function (information collection, analysis, decision selection, and action implementation) [12]. These levels of control provide a spectrum that can be correlated with proportional increase/lessening of the degree of human intervention/interaction with the system [10]. Thereby gives a way of understanding the type of interaction required between the human and system from a system design point of view.

Levels of Automation (LOA)	Description
10	Fully Autonomous: The autonomous system decides everything; act autonomously, coordinating with other autonomous systems, ignoring the human.
9	The automation system informs the human supervisor only if the system decides to.
8	The automation system informs the human, only if asked.
7	The automation system executes actions autonomously and then necessarily informs the human supervisor.
6	The automation system allows the human supervisor a restricted time to veto before automatic execution.
5	The automation system executes that suggestion if the human supervisor approves.
4	The automation system suggests one decision action alternative.
3	The automation system narrows the decision choice selection down to a few.
2	The automation system offers a complete set of decision/action alternatives.
1	The computer offers no assistance; human must take all decisions and actions.

Table 1: Levels of Automation [11]

In the Aerospace domain, variable levels of autonomy are achieved by adopting the PACT (Pilot Authorisation and Control of Tasks) framework, as shown in Table 2. This model was originally developed for UKMOD for use within the fast jet environment in order to alleviate the workload from the pilot and delegate some elements of decision support to computer automation [10]. The PACT levels of automation proposed by Bonner *et al.* [11], [12] outlines three automation or autonomy modes

namely, fully automatic, assisted or pilot commanded, which can be changed dynamically by the system or by the pilot. This provides a framework through which variable levels of autonomy can be assigned to different tasks, ranging from routine task to safety critical events, from a system design point of view [11].

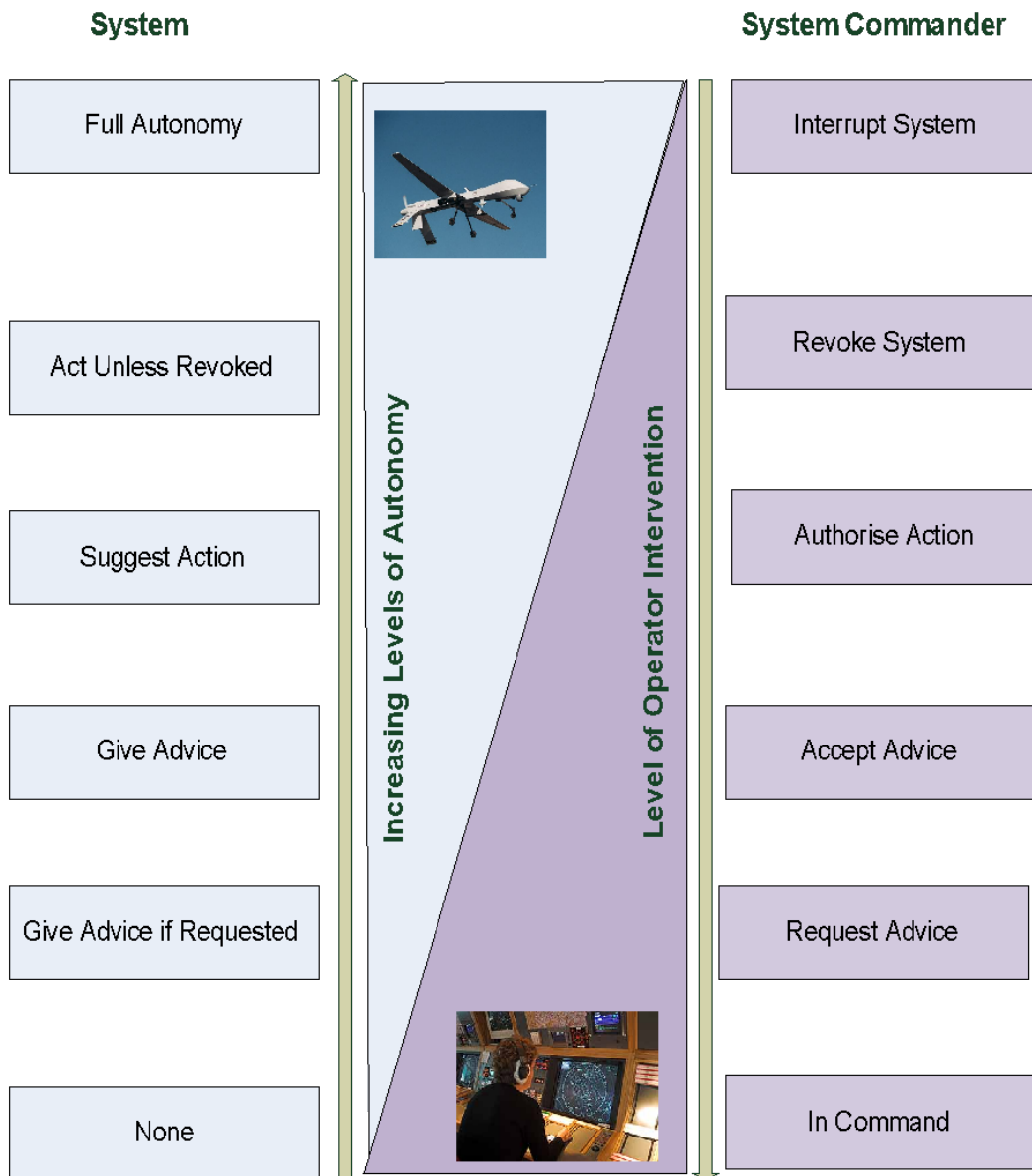


Figure 1.1 Autonomy classification model [13]

Mode	Level	Operational Relationship	Computer Autonomy	Pilot Authority
Automatic	5	Automatic	Full	Interrupt
Assisted	4	Direct support	Advised action unless revoked	Revoking action
	3	In support	Advice, and if authorised, action	Acceptance of advice and authorising action
	2	Advisory	Advice	Acceptance of advice
	1	At call	Advice only if required	Full
Commanded	0	Under command	None	Full

Table 2: The PACT (Pilot Authorisation and Control of Tasks) Framework [11]

Within the Automotive sector there has also been an increasing trend towards more automation of safety-critical control function (e.g. steering, braking or throttle) of vehicle, which has led to push towards crafting set of guidelines for regulating operations of autonomous or self-driving cars. One such effort to set guidelines has been by the NHTSA (National Highway Traffic Safety Administration) in USA [14]. NHTSA is responsible for developing, setting, and enforcing Federal motor vehicle safety standards (FMVSSs) and regulation for motor vehicles and motor vehicle equipment [14]. During the process of setting guidelines for self-driving cars the NHTSA has also created a framework for classification of autonomous vehicles. The model segments vehicles automation into five levels, ranging from vehicles that do not have any of their control systems automated (Level 0) through to fully automated vehicles (Level 4), as shown in Table 3. Currently the commercial use of vehicles operating at Level 3 and Level 4 are not sanctioned by the transport authorities [14]. However, the well-known Google driverless car is a Level 3 (Limited self-driving automation) vehicle under the NHTSA definition, which has already clocked over 1.7 million miles test driven on the streets of Mountain View, California with city speed of the cars limited to 25 mph [16].

Level	Function	Description
0	No automation	Driver in control
1	Function-specific automation	One or more specific primary control system utilises automation
2	Combined function automation	At least two primary control systems are automated in order to assist the driver
3	Limited self-driving automation	Driver is able to cede all safety-critical functions to the vehicle in some instances
4	Full self-driving automation	Vehicle able to perform all safety-critical driving and monitor external conditions

Table 3: NHTSA Classification of Vehicle Automation [11]

In recent years there has been increasing trend towards automation in transportation systems (rail, road, air etc.) which are becoming more complex and interconnected [4]. As technology advances, systems are moving towards autonomy where more and more decisions will be made by the system rather than by humans. The system is intelligent in perceiving, deciding, learning etc. without any direct human control/involvement, in any environment it's operating in. This trend towards autonomous systems technology can be seen in aviation, where unmanned aerial vehicles have found its way from original military applications into variety of commercial and civil applications. Unmanned Aerial Vehicles (UAVs) have been used for scientific research, disaster prevention (forest fire monitoring, earthquake damage assessments etc.), homeland security (border protection, coastal surveillance, monitoring public events etc.), protecting critical infrastructure (monitoring of oil and gas pipelines, monitoring the power grid etc.) as well as environmental protection (monitoring illegal fishing, pollution emissions etc.) [9]. Most of these civil applications have carried out primarily by state or government agencies [9]. The commercial use

of unmanned aerial vehicles has not yet started fully [2].

Similar to air transportation sector, application of autonomous systems to automotive domain is also being explored by various automotive manufacturers. Already the vehicles produced in recent years have varying levels of “driver-assist” technologies being incorporated such as Adaptive Cruise Control (ACC), Forward collision warning with brake support, Active parking assist, Rear view camera, Lane keeping system etc. [17], [18]. Many of the major manufacturers (Ford Motor Company 2013; Nissan Motor Company 2013; Toyota Motor Company 2013) have announced research and development initiatives to explore even more sophisticated autonomous capability in vehicles moving toward driverless cars [4]. Google self-driving car program has successfully tested prototype driverless cars logging over 1.7 million miles in the test zones in Mountain View California since 2010 with total of 11 accidents. According to Google, the accidents have been minor in nature with light damage and in none of them the Google’s robot cars are to at fault.

The consequences of system failures in the transportation domain are potentially dire; hence ensuring that autonomy incorporated into these systems can be trusted and remain resilient is essential [4]. The regulatory and certification standards for operation of autonomous systems to ensure they operate robustly in safety-critical situations have not kept pace with the technology advancements [4]. This research is only focussed on the air transportation sector, and the issues related to the integration of Unmanned Aircraft (UA) in the National Airspace System (NAS).

1.3 Motivation for the study of Unmanned Aircraft System (UAS)

Unmanned Aircraft Systems (UAS) are envisaged to provide many commercial and technical benefits due to their unique operational capabilities as compared to their manned counterparts. Due to the benefits they provide, UAS have been widely used in the military domain in the past decade primarily in performing Intelligence, Surveillance & Reconnaissance (ISR) missions and more recently over the last few years have been used in a few state civilian applications (i.e. homeland security, disaster prevention, scientific research etc.) [19]. The potential benefits of UAS include

[19]:

- High endurance capability i.e. can stay for a long time ranging from several hours to many days.
- Ability to perform tasks that are risky or dangerous to human pilots in conventional manned aircraft.
- An overall reduction in the cost of performing a mission.
- Capability to reduce response time to attend to some missions.
- Possible spin-off from new technologies developed for UAS into commercial manned aircraft.
- In future may lead to new civil applications which have not been conceived yet.
- Potential improvement in efficiency and reliability of future Air Traffic Management system as more and more decisions would be made by the system rather than the humans.

Despite the great deal of benefits and the belief that more and more autonomous systems will be part of the future Air Traffic Management system (ATM), such systems have yet to be commonplace in commercial civil applications. Their operations have been restricted to certain segregated areas of the national airspace and for some civilian applications by state authorities. After the considerable amount of funding and effort spent in the domain of UAS airspace access it has brought very little progress. The systems developers and regulators together have not been able to address the technical and operational requirements for the introduction of such systems in order not to cause a detrimental effect on the efficiency and safety of the current airspace environment. Whilst many of the technologies needed to realise these systems exist, the process of integration of manned and unmanned aircraft in civil airspace is not routine.

The UAS airspace integration problem seems to be a complex one, with challenges that are well beyond the technical and regulatory hurdles. The economic, social and political issues also govern the integration and acceptance of autonomous systems. These systems have to ensure they are robust and establish a perception of trust to enable their operation routinely. The multiple stakeholders involved that

impose different constraints and requirements some of which are contradictory and changing, makes this problem more complex. Thus, there is a compelling case for looking at the barriers and challenges with different perspectives bringing a paradigm shift in thinking. One of the ways to formulate an understanding of the challenges from different perspectives is through looking at the problem holistically by following an underlying system thinking approach.

1.3.1 The Wider motivation

In the past 40 years the volume of air travel worldwide has expanded tremendously (almost tenfold increase when measured through revenue passenger kilometres). This is broadly in line with the rise in world trade during the same period, and the process has facilitated globalization [20]. Today's globalized world would not be possible without the air transport sector. To meet this growing demand for air transport, airlines are incorporating new routes and providing more connectivity to passengers. This in turn has led to more and more aircrafts taking to the skies every year. As a result, air traffic volume is growing at an average rate of 5% every year, which is equivalent to doubling of air traffic in 15 years [21], [22]. This rapid growth has led to a big challenge in terms of ensuring safe and efficient performance of air transport sector to required levels. The anticipated growth in air traffic volume will far outstrip the capacity of the existing air transport system infrastructure [23]. The ageing technology and existing paradigms of existing Air Traffic Management have repeatedly been scaled up in the past to accommodate air traffic growth; however, they are rapidly approaching or exceeding their natural air traffic capacity limits [23]. The challenge of this air traffic growth will not only be about handling traffic in air but also on ground, as already there is saturation at our major hub airports [24]. Hence in the future the growing traffic has to be handled safely and efficiently in the air and on the ground. Along with capacity constraints, another big challenge that today's aviation faces is the impact on the environment. There is growing demand to address aviation's environmental footprint in terms of greenhouse gas emissions, noise and air quality [21], [25].

To cope with these multiple challenges, large-scale modernisation efforts are underway which are aimed at replacing old infrastructure and also providing new

operational capabilities by incorporating new technologies and operational procedures. The proposed changes and modernization to the airspace system in US and Europe are being carried out through the Next Generation Air Transportation System (NexGen) and Single European Sky ATM Research (SESAR) programs respectively [25], [26]. The modernisation initiatives are large-scale system levels integration effort where several components are combined together on a large scale with the significant procedural changes that will deliver new operational capabilities. These strategic aviation technology programs will bring air traffic management fully into the 21st century. It is envisaged these initiatives will help ease congestion in an era where air traffic volume is expected to double and also lead to cleaner skies through lower CO₂ emissions as well as drastically reduce the amount of fuel used by aircraft [25].

One of the new operational capabilities proposed for the future ATM system is the introduction of trajectory-based operations that will incorporate time as the fourth dimension in the management of air traffic [25]. Also, other new technologies such as Automatic Dependant Broadcast Surveillance (ADSB) and data communication b/w pilots and Air Traffic Controllers are also proposed which will enhance the performance and efficiency of air traffic control [25]. With the use of these new technologies and operational capabilities, it is envisaged that in the future the workload of the humans (pilots and Air Traffic Controllers) will be reduced and several functions will be performed by the system, which are today being performed by humans [22]. Hence the air traffic capacity and its efficiency can be improved drastically by taking an integrated approach through all phases of aircraft flight [25], [26].

Other reason for the future Air Traffic Management Systems to be based on decisions made by the system rather than humans is that the contribution of human error in the mishap rate of aircrafts is high. According to a 2002 congressional Service report, more than 70 percent (DoD, 2003) of all class A aircraft mishaps have been caused due to human error. When the figures are looked at for manned aircraft, it rises to approximately 85 percent [27].

Generally, there has been a trend of increasing safety in the air transportation system. The total accident rates per hour of operation for general aviation have

reduced by a factor of 10 since 1940, and in the same period the total accident rates per hour of operation for commercial aviation have reduced by a factor of 1000 (DoD, 2003) [27].

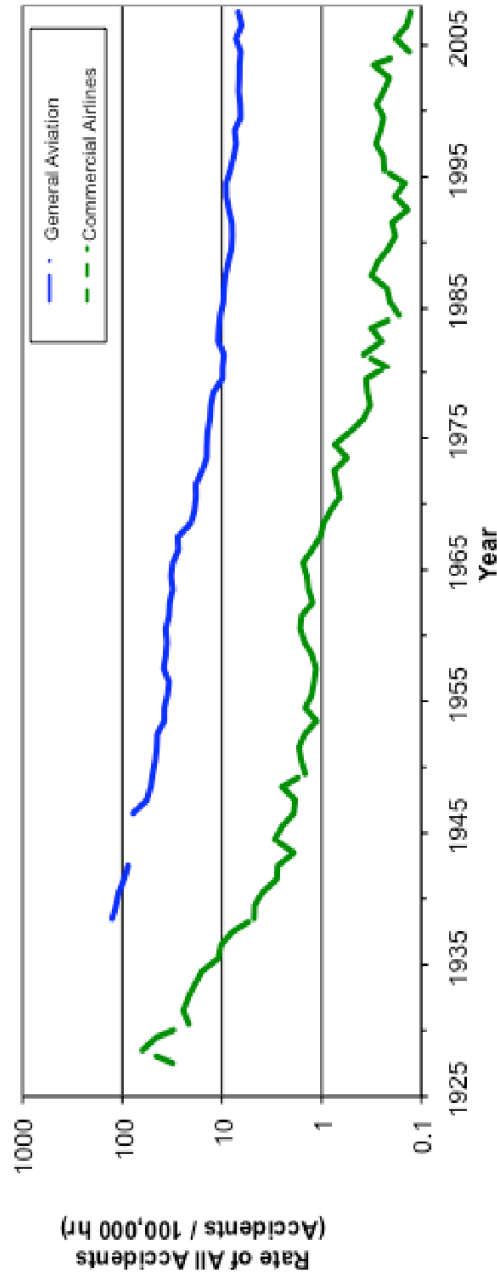


Figure 1.2 History of accident rates in civil aviation [27]

Hence for increasing capacity and also to improve the reliability of manned

aircraft, more and more decisions in the future will have to be made by the system [25]. The involvement of humans will be reduced to more of a monitoring role and taking decisions only during an emergency or any such situations. Thus, this will mean the design of interaction of the human with the system will have to be updated to new ways in which the decisions would be made. The shared decision-making environment would also lead to several new questions in terms of operator alertness level and his/her situation awareness as the operator will no longer be actively involved in the decision making at every level.

1.4 Thesis Structure

This thesis consists of four parts: Introduction and Background, System of Systems (SoS) architecture analysis, System Concept implementation and Evaluation, and Conclusions. Each of these sections is briefly described below.

1.4.1 Part I – Introduction and Background

Chapter 1 provides an introduction to research context, key Aims and Objectives and an extensive literature review. It gives an introduction into Unmanned Aircraft Systems (UAS) and its various elements. The literature study also highlights the previous academic literature in several areas especially focussing on UAS classifications, civil UAS market potential, current regulatory environment for UAS operations and key challenges involved with their integration in national airspace. The industrial context of the research is also outlined by briefly describing the industry wide project under which this research was a part of. The knowledge gained from the literature review is used to position the study and further substantiate the research objectives keeping in mind the industrial context of the research undertaken. Further background information and previous academic literature is provided in the thesis at the beginning of Part II and part III, and also where necessary.

1.4.2 Part II – UAS Integration in ATM: A System of Systems Architecture Analysis

The underlying framework for a holistic approach towards addressing the research

problem is presented in Part II of the thesis. Chapter 3 introduces the Design for Adaptability and Evolution in System of Systems Engineering (DANSE) project under which this part of the research was carried out. It also provides an overview of the methodology used in order to perform a high level SoS architecture analysis of the Air Traffic Management (ATM) System and the integration of UAS into the ATM system. Finally, the chapter describes the SoS architectural patterns which are fundamental blocks in the creation/representation of any architecture. Chapters 4, 5 & 6 explain the different architectures of ATM ranging from the current to its evolution into a next generation ATM and also the possible architecture solutions of integrating UAS in such an evolving ATM architecture. Chapter 4 provides information on how and which of the architecture patterns were mined in order to represent the current ATM system. It also describes the operations of UAS in the current ATM architecture and analyses the operational deficiencies for UAS operations in the ATM system, based on the high level SoS architecture patterns developed. Chapter 5 gives information on the architecture patterns that were mined to represent the ATM architecture in the medium term (next 3 - 5 years) and also of the possible architecture solutions for UAS operations in the ATM system. Chapter 6 briefly mentions some of the architecture patterns that were mined to represent the next generation ATM architecture. It also briefly discusses the possible architecture solutions foreseen for routine UAS operations in the next generation ATM system (10 years' time frame).

1.4.3 Part III – UAS Sense and Avoid

Parts III of this thesis gives background information on the sense and avoid system for Unmanned Aircraft (UA), a concept solution for near-to-medium integration of UAS, a proof of concept system development and finally the evaluation of concept on UAS synthetic environment. Chapter 7 provides the necessary information to understand the concept of sense and avoid and overarching requirements of a UAS sense and avoid system. A literature study on the various approaches to the design of sense and avoid system and architectural frameworks that could be implemented to avoid other airspace users in the air traffic environment is also given. The review highlights areas where considerable academic literature in this area and the gaps that exist with

regards to the UAS sense and avoid research. Finally, the reason for focussing the next phase of research study on Ground based approach to the sense and avoid problem is detailed. Chapter 8 gives a detailed overview of the Ground Based Sense and Avoid System (GBSAA) concept and the systemic analysis of its functions as well as the system functional and operational requirements to enable them to be able to operate in the current airspace environment. It also gives information on the key design requirements of a UAS separation assurance display and the academic literature that exists on previous work on the topic of separation assurance displays for UAS. The following chapters (9 & 10) explain the proof of concept development and the system evaluation. Chapter 9 explains the proof of concept display system for providing the function of UAS separation display that has been developed from a COTS Air Traffic Control (ATC) System. It also describes the experimental set-up for the evaluation of the concept display by integrating it with a UAS synthetic environment. The design of the experiment and also the parameters that will be evaluated in the research experiment are also detailed. Chapter 10 provides the results from the evaluation of various aspects of the separation assurance display are presented. The results demonstrate the ability of the proof of concept to be able to present aircraft traffic information in a manner that aid the UAS pilot to avoid other aircraft in its vicinity. A full-scale demonstration system for UAS sense and avoid can be further developed with this approach to have pre-operational demonstration system to validate the concept fully.

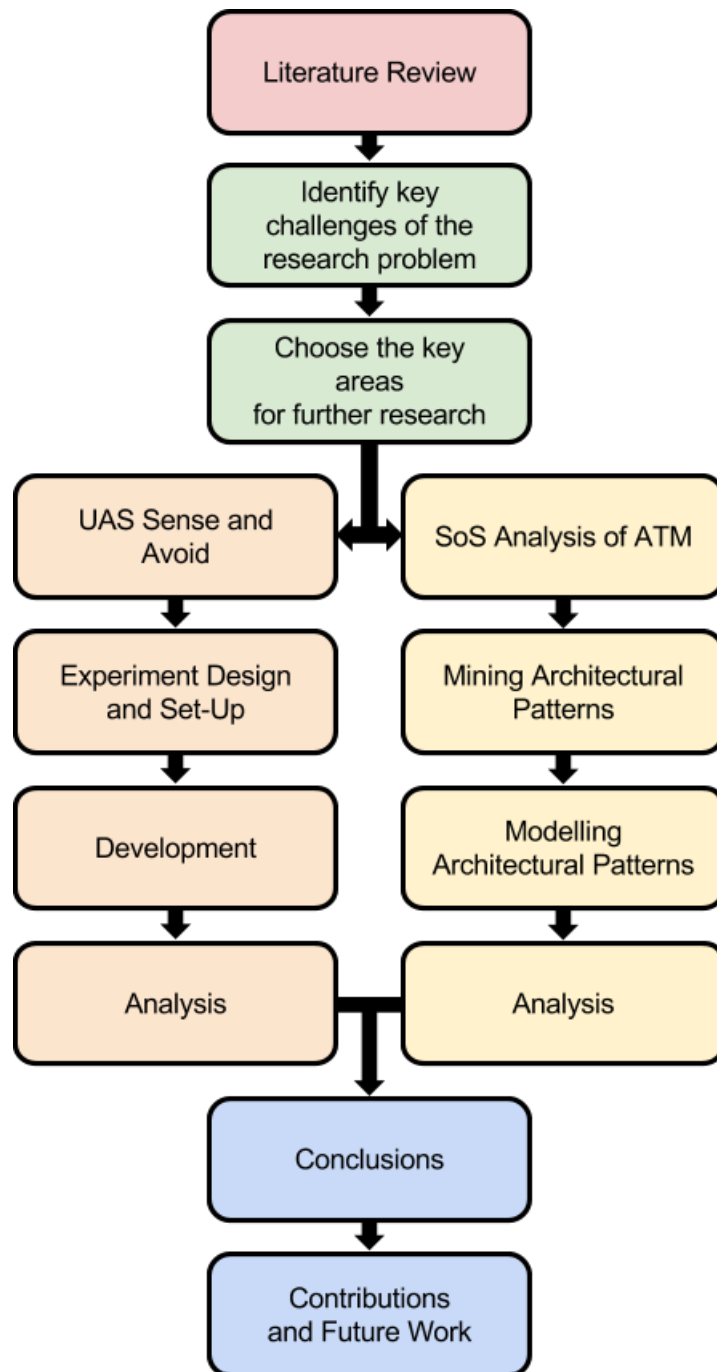


Figure 1.3 Thesis Structure

1.4.4 Part IV – Conclusions

The final part of this thesis consists of conclusions. This section presents the conclusions on the SoS analysis of the integration of UAS in ATM using the DANSE methodology. It also presents future work in terms of the SoS modelling and simulation

to compare SoS architectural solutions. The conclusions section also includes the strengths of the approach towards proof of concept development and its evaluation for UAS Sense and Avoid; as well as the contributions made by this research. The various weaknesses with the method are discussed and also drawbacks of the experimental set-up are provided. The potential improvements to the proof of concept display system and further development of the demonstration system towards a full scale UAS sense and avoid system for further validation are also provided. Lastly, the subject areas for further research are mentioned.

1.5 Aim and Objectives

The Aim of this research is to examine the issues associated with guaranteeing that information on which decisions will be made is valid and of very high integrity in an Air Traffic Environment where Unmanned Aircraft System (UAS) will be an integral part. The research will be undertaken using a systems engineering approach as an underlying framework. Given the industrial context of the research, gaining an understanding of problem and designing candidate solutions will be based not only on technical performance but also on their commercial viability.

The issues that will be addressed in the research to ensure that decisions made by the UAS are robust and will consist of looking at the following aspects:

- To understand and examine the current architecture of the Air Traffic Management System (ATM) and its evolution to enable integration of UAS into the national airspace system in a phased-approach.
- To investigate UAS Sense and Avoid, a key UAS integration challenge, in order to determine the best place for decision-making processing (i.e. on board or remotely) from a technical and economical perspective.
- To develop a Ground-Based Sense and Avoid simulation architecture in order to investigate the impact of different configurations of GBSAA information display system on the decision-making capability of human operator.

In order to achieve these objectives, this research uses a systems engineering approach to understand, evaluate, propose and develop proof of concept solution so

as to enhance the validity and integrity of the information for decision making process. A systems approach enables one to understand the problem much better by looking at it more holistically through the use of various systems engineering tools/techniques and methods.

The research considers the context of the problem from various stakeholders' perspectives and the major issues associated with the integration of UAS in the national airspace in order to realise the potential benefits of such systems as listed in the previous section 1.3.

The research also follows a holistic approach to tackle the problem of UAS integration. The underlying framework for this holistic approach was a high-level System-of-Systems (SoS) Architecture analysis of the integration of UAS into the Air Traffic Management System. The inherent complexity of a SoS makes it very difficult to model and analyse it through conventional means. In order to perform detailed analysis of SoS one of first challenges faced is how to represent the SoS especially when full details of the constituent systems may not be readily available. Among the many encompassing methodology, models, tools and flows that enable future engineering of SoS, one such method is to use architecture patterns that can sufficiently deal with many analyses needs of SoS. This research involves use of architecture patterns to analyse the SoS, which in this case is the Air Traffic Management System, in order to compare different architectural solutions for integration of UAS into the air traffic management system. Further based on the analysis of existing ATM architecture using architecture patterns, a basis for analysis of future ATM architectures where UAS will be allowed to operate routinely emerged. This involved a high level SoS architecture analysis of UAS integration into the ATM system in its current architecture to its progressive evolution into the next generation ATM architecture.

Among the key challenges regarding the problem of UAS integration, the UAS Sense and Avoid emerged as a prominent factor. Hence all the research aims were then investigated through the key integration of UAS sense and Avoid. This was decided through detailed analysis of the current academic literature and current industrial/regulatory perspective on the issue of UAS integration in national airspace.

In order to achieve the aims for the specific case of UAS Sense and Avoid, the following aspects were involved:

- Gain an understanding of the problem of UAS Sense and Avoid system and the generic system requirements for such systems in view of current regulatory environment.
- A systemic study of the Sense and Avoid system, to identify all the data sources involved internal and external for separation of UAS from other aircrafts.
- Evaluate several system architectures for UAS sense and avoid with regards to decision making processing i.e. whether it is to be performed on-board or remotely.
- The probable solution for UAS Sense an Avoid system based in ground or air to be decided based on investigating the technical as well the commercial viability of the concept solution.
- To develop a systemic overview and operational procedures for the probable solution that is chosen for detailed study.
- To develop a proof of concept system based on Commercial off the Shelf (COTS) hardware and software.
- Evaluate the developed proof of concept through various simulations in a synthetic environment.

1.6 Why Unmanned Aircraft?

The main drivers for the increased expansion of UA in the military sphere and the potential commercial uses are:

- UA have increased capabilities to perform “dull, dirty or dangerous” tasks in place of manned aircrafts which are limited due to the human capability to perform these tasks for long periods of time without increased fatigue and also high risk to human life [19]. ‘Dull’ tasks are those which may require the aircraft to stay airborne for several hours/days at high altitudes [7]. ‘Dirty or dangerous’ tasks are those which involve operations with high risk for damage or loss of aircraft that may endanger human operator’s life [7].

- The operations of UA are also economically beneficial for performing surveillance, communication and other commercial operations compared to their manned counterparts. The cost of development, maintenance and training of personnel are much less compared to the overall costs of equivalent manned aircrafts [7].

The unique operational capabilities of UA such as flying at high altitudes for long duration, better manoeuvrability and ability to fly very close to structures on the ground, as well as several new technologies emerging from its use in military applications provides the opportunity for new applications in the future that have not been conceived of yet [28].

1.6.1 Unmanned Aircraft Systems (UAS) Overview

An Unmanned Aerial Vehicle (UAV) also commonly known as a drone aircraft refers to an aircraft/flying machine without an on-board human pilot or passengers [29]. The term UAV has been commonly used in the past several years to describe unmanned aerial systems. Although the term ‘unmanned’ implies control totally absent from a human who guides and actively navigates the aircraft, in most instances there is some degree of direct human control involved by a pilot who is off-board located on the ground. Thus, the flight control functions for unmanned aircraft can be based on-board or off-board the air vehicle [29]. This is the reason the terms Remotely Operated Aircraft (ROA) or Remotely Piloted Vehicle (RPV) are also used commonly to refer to such air vehicles [30]. There have been various definitions proposed for this term and a few of them are given below as a comparison.

The CAA definition of Unmanned Aircraft or UA is as follows [31]:

“An aircraft which is designed to operate with no human pilot on board and which does not carry personnel. Moreover, a UAV:

- *is capable of sustained flight by aerodynamic means,*
- *is remotely piloted or automatically flies a pre-programmed flight profile,*
- *is reusable,*
- *is not classified as a guided weapon or similar one-shot device designed for the delivery of munitions.”*

*A reusable aircraft designed to operate without an on-board pilot. It does not carry passengers and can be either remotely piloted or pre-programmed to fly autonomously. [32]
[STANAG 4671]*

A device used or intended to be used for flight in the air that has no on-board pilot. This includes all classes of airplanes, helicopters, airships, and translational lift aircraft that have no on-board pilot. Unmanned Aircraft are understood to include only those aircraft controllable in three axes and therefore exclude traditional balloons. [33]

[FAA definition]

The development of any new technology brings with it new terms and definitions. In the past few years, various international organizations such as ICAO, EUROCONTROL and several national aviation authorities have moved to the position where the term UAV has been phased out and replaced by the phrase Unmanned Aircraft System (UAS) instead [29]. The change in acronym is caused by following aspects [29]:

- The term 'unmanned' refers to the absence of an on-board pilot.
- The term 'aircraft' signifies that it is an aircraft and as such properties like airworthiness have to be demonstrated.
- The term 'system' is introduced to emphasise that it's not just the aircraft but a system consisting of various ground systems, communication links and other human assets needed to operate the aircraft itself.

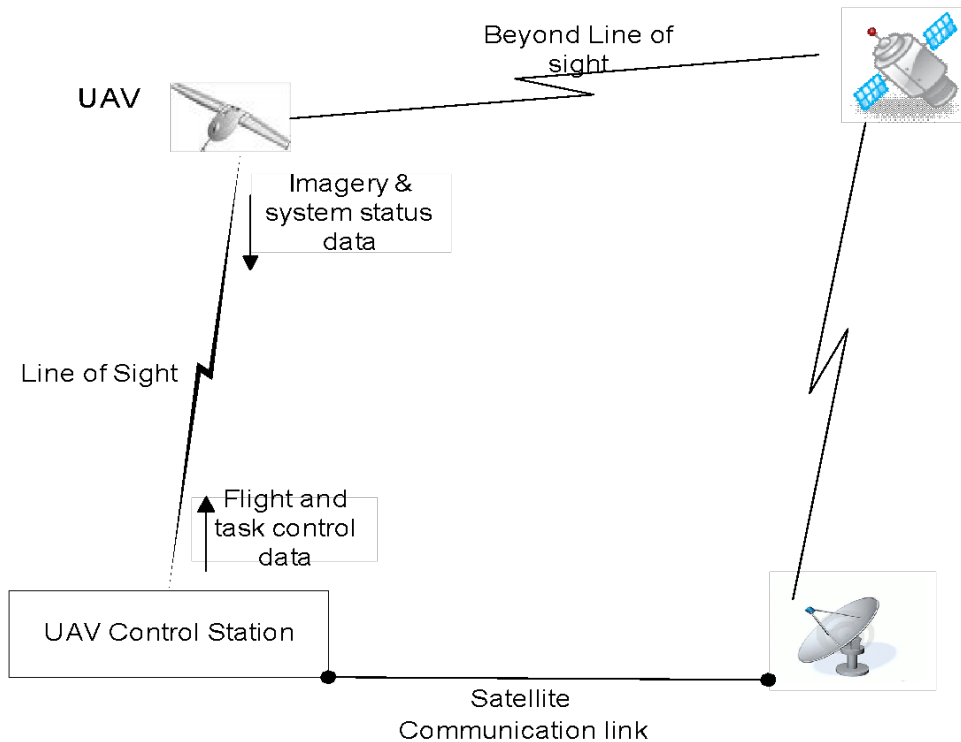


Figure 1.4 A typical Unmanned Aircraft System

A generic UAS can be categorised into systems consisting of three major parts as shown in figure 2.1:

- *Air system* – The air system consists of the Unmanned Aircraft (UA) platform that carries the payload and the payload itself, which consists of various sensors for collecting remote sensor data and other communication equipment's [34]. For the purpose of this research, a UA is a reusable, powered aircraft capable of controlled, sustained and level flight. It also referred to as Unmanned Aerial Vehicle (UAV) or Remotely Piloted Aircraft (RPA) [34].
- *Ground system* – The ground system consists of the UAV control station (UCS) and the Air Traffic control (ATC). The ATC is responsible for maintaining safe, orderly and efficient flow of air traffic. Whereas the UCS is responsible for the following tasks [7]:
 - Mission planning and setting objectives
 - Flight control during taxi, take-off, approach and landing as well as

- guidance during flight
- Control of sensors for gathering data and processing it, for further display and usage
- Communication with UAV and the ATC
- Communication System – It consists of control and data links between the ground segment and the air system which can range from direct line-of-sight and also non-direct line-of-sight via satellite communication system [7].

The analogy UAS is used for single or multiple systems and means the same in the plural form as well.

1.6.2 Historical Perspective of Unmanned Aircraft

The modern notion of UA appeared during the First World War in 1917 [35]. However, the first breakthrough or earliest reported successful work on autonomous flight occurred about 2500 years ago during the era of Pythagoras (first student of Thales' for few years and Pythagorean mathematicians), and is attributed to Archytas from the city of Tarentum in South Italy [36]. He was known as Archytas the Tarantine, also referred to as the Leonardo Da Vinci of the Ancient World. He created the first UAV in 425 B.C by building a mechanical bird, a pigeon that could fly by moving its wings getting energy from a mechanism under its stomach [36]. It is alleged that it flew 200 metres before falling to the ground. The pigeon could not be flown again, unless the energy mechanism was reset [37].

During the same era, around 400 B.C the Chinese were the first to document vertical flight aircraft. In China, the first version of the aircraft was a Chinese top that consisted of feathers at the end of the stick [29]. The stick was spun between the hands to generate enough lift before it was released into free flight.

Nearly seventeen centuries later a 'flying bird' was documented, similar to the initial idea of Archytas, credited to some unknown engineer of the Renaissance [29]. It is unclear whether this new design was based on the Archytas idea; however, the concept was very similar.

Leonardo Da Vinci, in 1483, designed an aircraft capable of hovering, called

aerial screw or air gyroscope [29]. It had a 5-meter diameter and the idea was to turn the shaft and apply enough force so that the machine would spin and fly [29]. It is considered by some experts that this machine is the origin for today's helicopters.

In 1860s, Ponton d' Amecourt flew small helicopter models powered by steam. It was the first time the term helicopter was coined. Additional helicopter models were introduced between 1860 and 1907. One of the standout models was introduced by Thomas Alva Edison who in the 1880's experimented with different rotor configurations, eventually using electric motor for power. The experiment revealed that a large diameter of the rotor was needed with a low blade area for best hovering capabilities. In 1907 Paul Cornu developed a two-rotor vertically flying machine that presumably carried the first human off the ground. The two rotors rotated in the opposite directions and the machine flew for about 20 seconds and merely being lifted off the ground.

The modern origin of UAV was first developed in 1916 by the Americans Lawrence and Elmer Sperry [35]. They manufactured it by combining wood and fabric airframes with either gyroscope or propeller revolution counters to stabilize the aircraft body to carry payload of almost 200 pounds of explosives at distances exceeding 30 miles [38]. They called their device 'aerial torpedoes' and were experimented by the American Navy and Army during World War I (WWI) but never fielded them in battlefield [38]. The periods following the war their development was limited and UAVs were successfully used target drones in Naval exercises. The military soon realized the potential benefits of unmanned aircrafts and increased efforts towards development of UAVs and their use. Such systems were used in World War II as unmanned ordinance delivery platforms and radio-controlled flying bombs also called 'smart bombs' [38]. UAVs were also used during the war to operate as target 'drones' to assist the training of anti-aircraft gun operators.

After the limited success of UAVs as weapon delivery systems, UAVs began to be used for reconnaissance missions during the Cold War by USA [38]. The first unmanned aircraft which resembles the today's definition of UAS which was Ryan Model 147 series aircraft were using during this period [36]. They were also used during the Vietnam War and the further development of UAVs continued through the

1960s and 1970s [29]. After the Vietnam War UAVs were developed that were smaller and cheaper. They also carried video cameras and transmitted images to the operator on the ground [29]. The UAVs were then put to practical use by USA during the Gulf war and by the time Baltic conflict began; UAVs were being used regularly to collect Intelligence, Surveillance and Reconnaissance (ISR) information which were incorporated frequently by the military personnel in their analysis [38]. After this the usage of UAVs for military applications increased quickly and was extensively used in the wars in Afghanistan and Iraq. The use of UAVs during these wars was not only limited to reconnaissance but also expanded to carrying missiles for striking at targets with more precision. The most famous of the UAV used by the military for this purpose is the Predator [29]. They have also been used in various countries by USA and its allies for the war against terrorism since the beginning of the 21st Century.

Most of the early applications of UAVs were in military sphere however the civilian use of UAVs began gradually [29]. NASA has been at the forefront of research for UAVs use in civilian applications. The initial development of UAVs in civil use started in the early 1990's and focussed on using UAVs for scientific and environmental research missions [39]. One such project is the Environmental Research Aircraft and Sensor Technology (ERAST) which was a joint NASA-industry initiative to development and demonstration of aeronautical technologies that could validate the capability of UAVs to fly at high altitudes and for long durations to carry out earth sciences and environmental missions [39]. The research efforts also included the development, miniaturization and integration of special-purpose sensors and imaging equipment for UAVs [39]. The UAVs developed in this project include Pathfinder, Predator B, Perseus B, Altus II, Proteus etc. [29]. Gradually the use of UAVs in civil use has expanded over the last decade into homeland security and monitoring/protecting of critical infrastructure such as oil pipelines, transmission lines etc. [9].

1.6.3 UAS Types and Classifications

The large proliferation of UAS, due to their increasing demand in the military domain over the recent decades has resulted in different configurations ranging from different

sizes, shapes, endurance levels and capabilities. During the last decade, the significant efforts in the development of UAS have focussed towards increasing the flight endurance and the payload carrying capacity in order for UAS to perform some missions in place of manned aircrafts in the military domain.

The tremendous growth in the number of UAS over the last decade has led to the development of several new design concepts and configurations. Hence there are several approaches to the classification of UAS. However, there is no consensus on a single UAS classification protocol from a civil use perspective that has been agreed by the aviation community yet.

One of the criteria used to classify UAS is size and endurance, which are often used by the military. Weibel and Hansman of the Massachusetts Institute of Technology (MIT) describe a UAS classification approach which is similar to the one presented in US DoD report on Unmanned Systems Roadmap 2005 – 2030, is as follows [40], [19]:

- High altitude long endurance (HALE) UA, as for example the Northrop Grumman Global Hawk (65000 ft. altitude, 35 hours flight time, 1900 lb payload).
- Medium altitude long endurance (MALE) UA, as for example the General Atomics' Predator (25,000 ft. altitude, 35 hr endurance, 120 kt max. Speed, 450 lb payload).
- Tactical UA, as for example Hunter (15,000 – 18,000 ft., 11 – 18 hr flight endurance, 106 kt max. speed, 200 lb payload); also, Shadow 200 and Pioneer (15,000 ft. altitude, 5-11 hours flight time, 105-110 kt max. speed, 25 kg payload).
- Small and mini-portable Mini UA such as the Pointer, Raven and Dragon Eye (1000ft, 1-2 hr flight time, 1-2 lb payload); or Scan Eagle, Silver Fox, Aerosonde (16000 – 20,000 ft., 10-30 hr, 5 -12 lb payload).
- Micro Aerial Vehicles (MAV) is class of UA that have a size restriction and may be autonomous. These have dimensions as small as 15 cm and recently the development of MAVs inspired by biological systems (flying birds or insects) has enabled to achieve unprecedented flight capabilities. Some examples

include gMAV (10,500 ft. altitude, 40 min flight time, 2 lb payload) manufactured by Honeywell, AeroVironments' Hornet and Wasp (1, 200 ft. altitude, 60 min flight time, 0.1 lb payload). Also include new design concepts produced by several universities such as Entomopter (Georgia Tech Institute of Technology) with a wingspan of 15 -18 cm and a payload in the range of 10 grams, Delfly Micro (TU Delft University) built a small ornithopter which measures 10 cm and weighs 3 grams, along with other designs such as Micro Bat (California Institute of Technology), MFI (Berkeley University), MuFly, etc.

Another way in which UA could be categorised is according to their characteristics such as aerodynamic configuration, size etc. [29]. UA platforms typically fall into one of the following four categories [29]:

- Fixed-wing UA's are a category of unmanned aircrafts having wings that require a dedicated runway for take-off and landing or catapult landing mechanism. These aircrafts usually have high cruising speeds and long flight endurance as well as in most instances at high cruising altitudes.
- Rotary-wing UAs also referred to as vertical take-off and landing (VTOL) UAs, are driven by rotary internal combustion engines as the name suggests. This provides them the advantages of hovering capability and high manoeuvrability. A VTOL UA may consist of different configurations, with main and tilt rotors (a conventional helicopter), coaxial rotors, tandem rotors, multi-rotors, etc.
- Flapping-wing UAs are such unmanned aircrafts which have been developed by inspiration from biological systems such as birds and flying insects. They have flexible and/or morphing wings which enable them to achieve unprecedented flight capabilities.
- Blimps consists of both balloons and airships, which are large in size and are lighter than air. They have the capability to fly at low speeds/tethered at a location and also have a long endurance typically ranging from several days to months. This capability enables them to be used primarily for surveillance roles in both military and civilian domains.
 - Hybrid or convertible configurations, also referred to as tilt rotor category,

which combine the vertical take-off capability of VTOL UA's and with a speed and range of a conventional fixed-wing UA's.

The Civil Aviation Authority (CAA) which is responsible for regulating UAS operations in the United Kingdom (UK) provides guidance under Civil Aviation Publication (CAP) 722: *Unmanned Aircraft System Operations in UK Airspace* (CAP-722) for a path to UAS certification [31]. CAP 722 outlines the current framework used by the CAA (see Table 5), which is similar to the framework used by other National Aviation Authorities (NAAs) that classifies aircraft based on simple type (e.g. balloon, fixed or rotary wing) and mass [31]. Although this classification method reflects the historic development in manned aviation but do not necessarily fully appropriate for UAS that have unique operational characteristics [31]. Hence until an alternative classification protocol is established which takes into consideration the concept of operations of UAS, the current classification framework is used in the interim. International Civil Aviation Organisation (ICAO) and Joint Authorities for Rulemaking on Unmanned Systems (JARUS) are currently undertaking work to formulate internationally recognised classifications for UAS. These classifications will likely use mass as a discriminator but will also other factors including operating environment and system complexity [31].

The European Aviation Safety Agency (EASA) provides a common regulatory framework for the member states in the European Union. EASA's responsibilities include type certification of aircraft and components. EASA also provides guidance on general principles for type certification of UAS in EASA Policy Statement (EASA-EY013-01-2009), *Airworthiness Certification for Unmanned Aircraft Systems (UAS)*. EASA UAS policy is only applies to civil use UAS and UAS more than 150 Kg [41]. Other categories of UAS less than 150 Kg are regulated based on the NAAs in the member states. The EASA describes an approach for UAS classification for the purpose of civil certification based on kinetic energy principles and equivalence with conventionally piloted aircraft [41]. Table 6 summarizes the classification approach which applies based on per design feature basis. For features those would affect the ability to maintain altitude, "unpremeditated descent" standard is use. For features

whose failures would affect the ability to maintain control, the “loss of control” standard is used [41]. EASA’s classification approach towards type certification for civil UAS for ensuring airworthiness is primarily targeted at protecting people and property on the ground. The classification framework also has preference to maintain the existing manned aircraft categories/classes for CS-23, CS-23 etc. (equivalent to 14 CFR Part 23, Part 25, etc.) [41].

Weight Classification group	Civil category	Weight (Kg)	Broad military equivalent	Civil regulation
1	Small aircraft	0-20	Micro (<5Kg)	National
			Mini (<30Kg)	
2	Light UAV	>20 - <150	Tactical	
3	UAV	150 or more	MALE	EASA (State Aircraft are national)
			HALE	

Table 4: UAS classification group in UK airspace (CAP722)

In the US, the Federal Aviation Administration (FAA) established a small UAS Aviation Rulemaking Committee (ARC) to provide recommendation on standards for integration of small UAS in the NAS [41]. Based on the recommendations the FAA released its notice of proposed rulemaking (NPRM) for the regulation of small UAS (sUAS) in February 2015 [42]. The sUAS ARC report recommends sUAS as UA weighing less than 25 Kg and classifies sUAS into five different groups based on their take-off weight as well as speed [42]. The operational limitations and required capabilities for five different groups of sUAS are as shown in Table 6 [41].

Failure Consequence	If the Kinetic Energy, KE (GJ), of the aircraft is...	Fixed Wing Airplanes would apply the airworthiness requirements from	Rotorcraft would apply the airworthiness requirements from
	$0 \leq KE \leq 0.0015$	Microlight (similar to ultralight)	
	$0 \leq KE \leq 0.003$	CS-Very Light Airplanes (similar to light sport aircraft)	
	$0.0015 \leq KE \leq 0.02$	CS-23 single engine	CS-27
	$0.01 \leq KE \leq 0.1$	CS-23 dual engine	CS-29
	$KE \geq 0.06$	CS-25	
	$0 \leq KE \leq 0.01$	Microlight (similar to ultralight)	
	$0 \leq KE \leq 0.025$	CS-Very Light Airplanes (similar to light sport aircraft)	
	$0.01 \leq KE \leq 0.2$	CS-23 single engine	CS-27
	$0.1 \leq KE \leq 2$	CS-23 dual engine	CS-29
	$KE \geq 0.3$	CS-25	

Table 5: EASA UAS Classification

Group	Group Characteristics: Gross Take-off Weight (GTOW), w (lbs.) Speed, s (Kts)	Operational Limitations	Recommended System Standards
I	$w \leq 4.4$ $s \leq 30$ Frangible	Generally, include: ▪ Limitations on how high they can fly, within certain distances from airports; e.g., Operate ≤ 400	7 of the 17 recommended standards apply to Group 1
II	$w \leq 4.4$ $s \leq 60$		17 of 17 recommended standards apply to Groups
III	$w \leq 19.8$ $s \leq 87$		

IV	$w \leq 55$ $s \leq 87$	AGL in Class C, D, E, and G airspace <ul style="list-style-type: none"> ▪ Requirements on the pilot in control and visual line of sight ▪ Proximity to airports Requirements become more stringent as weight increases.	II-V. These include <ul style="list-style-type: none"> ▪ standards for: <ul style="list-style-type: none"> Structural integrity ▪ Fire protection ▪ Control Station synchronization ▪ Powerplant fail safe ▪ Weight and balance ▪ Fuel/power markings ▪ Materials
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Table 6: UAS Groups recommended by small UAS ARC

1.6.4 UAS Applications

Over the last decade the UAS have been primarily used for military applications and this trend has continued until now. Most of the investments in the development of UAS are also predominantly in the military sphere. In the past, the UA's were used primarily in performing Intelligence, Surveillance and Reconnaissance (ISR) missions, however more recently UAs have been used increasingly in military strike capability role as seen in the recent conflicts in Iraq, Afghanistan, Libya and elsewhere.

According to the UAS market forecasts by Teal Group, the current worldwide expenditure on UAS is around \$6.4 billion and set to nearly double over the next decade to \$11.5 billion annually, totalling almost \$91 billion in the next ten years [43]. A significant portion (approximately 89%) of the overall UAS spending is in the military domain [44]. The primary reason for use of UAs in the military domain has been to

replace manned missions, especially in 'dull, dirty and dangerous' tasks. Although most military missions can be dulling or dangerous, humans continue perform them whether as a matter of technology or as a substitute for technology inadequacies [19]. However, in the future, this trend is set to change as the next generation of UAS will be executing much more complex missions such as target detection, recognition and destruction, air combat, electronic attack, anti-submarine warfare, mine warfare and other offensive capabilities.

The growing use of UAS in the last several years in military applications, has increasingly lead to the demand for potential applications of UAS in civil/commercial scenarios. Although the current share of global UAS spending for civil purposes is very small at nearly 11% cumulative for last decade, according to several market forecasts, the civil UAS market is set to expand tremendously in the future, with Teal Group market forecasts predicting a shift for civil UAS spending from 11% to 14% of the overall worldwide UAS spending at the end of next ten years [44]. The civil UAS sector has not yet started significantly due to the inability of the UAS to access national airspace for routine flight.

Presently, there are a few organizations that have used UAS to perform a few civil applications. Some of the civil applications where the UAS have been used in the past are performing topographical land surveys, aerial photography capability for monitoring construction and highway projects, agriculture land survey and monitor as well as forestry monitoring uses. However, all the civil applications are limited in scale due to the operational restrictions on the use of UAS in the national airspace.

There are several research efforts ongoing by various organizations in order to realize the potential use of UAS in a range of scientific and civil operational mission scenarios. A few organizations which are focusing on the civil applications are Radio Technical Commission for Aeronautics (RTCA) and NASA in US and in Europe an example is the UAVNET. Based on several research studies and workshops performed by such organizations, broad areas of potential UAS civilian mission concepts and their requirements have emerged. From these research analyses, the potential civil applications of UAS can be categorized into five groups [9], [45].

- Monitoring Applications: These include forest fire detection, crop and harvest

monitoring, coastal monitoring, homeland security (law enforcement, international border patrol, traffic monitoring, infrastructure monitoring (pipelines, power lines, oil/gas lines etc.) and terrain mapping (high accuracy terrain mapping, forest mapping, oil/gas lines, etc.).

- Communications/ Navigation applications: A few examples of communication applications are telecommunication relay services, broadband communications and satellite based navigation aids.
- Environmental (or earth science) applications: These include atmospheric research, geological surveys (i.e. mapping of mineral resources, oil exploration, etc.), oceanographic observations, weather forecasting, hurricane evolution research, volcano study and eruption alerting, etc.
- Emergency applications: A few examples of these are search and rescue, firefighting, catastrophe situation assessment, humanitarian aid delivery and disaster operations management, etc.
- Commercial applications: These include transport of cargo and postal service, agricultural purpose such as precision crop spraying and farm land mapping, aerial photography, etc.

1.6.5 UAS Market Overview

The large proliferation of UAS in the military domain in the last decade has led to several countries defence forces and private defence companies, involved with developing and producing a large variety of UA designs. Many large defence contractors are developing and producing UA designs (like Lockheed Martin, Northrop Grumman, Boeing, EADS and Raytheon, etc.) [29]. This is evident from the rapid growth in the number of UA designs registered with UVS international, a non-profit society that promotes unmanned systems. According to UVS international, the number of registered UA designs more than doubled between 2005 and 2011. During the same time period the number of developers and producers has also more than doubled. At the same time, smaller companies have also emerged providing innovative technologies for largely developing sub-systems as sub-contractors for major defence contractors or developing and producing small/mini UAS [29]. With the advent of new

technologies and growth of many companies it is envisaged that in the world aerospace industry, UAS sector would be the most dynamic growth sector [44].

The UAS market has seen unprecedented growth since 2001 [19]. There are numerous market forecasts that project global UAS markets will experience strong growth during the next 10 years [46]. According to Teal Group, the worldwide UAS spending on research and development as well as procurement is expected to double from the current annual spending of \$6.4 billion in 2014 to \$11.4 billion in 2024 (see figure 2.2) [44]. Cumulatively, the market for UAS during the forecast period is expected to value just over \$91 billion (see figure 1.5) [44]. Throughout the forecast period, Teal Group expects the US to account for 65% of worldwide spending in Research, Development, Training and Evaluation (RDT&E) while US will hold 55% of the procurement spending worldwide [44], [46]. It also expects the military applications to dominate the market and the UAS spending to follow the recent demand for high-tech arms procurement worldwide (for internal and national security; territorial and defence modernization initiatives), with Asia-Pacific representing the second largest market (about 18% of total worldwide spending) followed closely by Europe at approximately 15% [46]. Out of the worldwide UAV market 89% is expected to be military and 11% civil cumulative for the decade, with the numbers shifting to 86% military and 14% civil by the end of the ten-year forecast in 2024 (see figure 1.5) [44].

The United States remains a key driving force behind the world UAS market. And the sales of UAS equipment have been driven primarily by military needs. In the US, annual budget for FY2013 requested \$3.8 billion for UAS acquisition, down from \$4.6 billion in FY2012 [46]. In April 2012, the US DOD reported that it had more than 7,100 UAS in its inventory [47]. The DOD has emphasized that in a highly constrained fiscal environment “Unmanned Systems (must) be affordable at the outset and not experience significant cost growth in their development and production evolution” [47]. Although there are fiscal constraints, the DOD procurement costs for the period 2011 – 2020 are reported to be nearly \$37 billion [46].

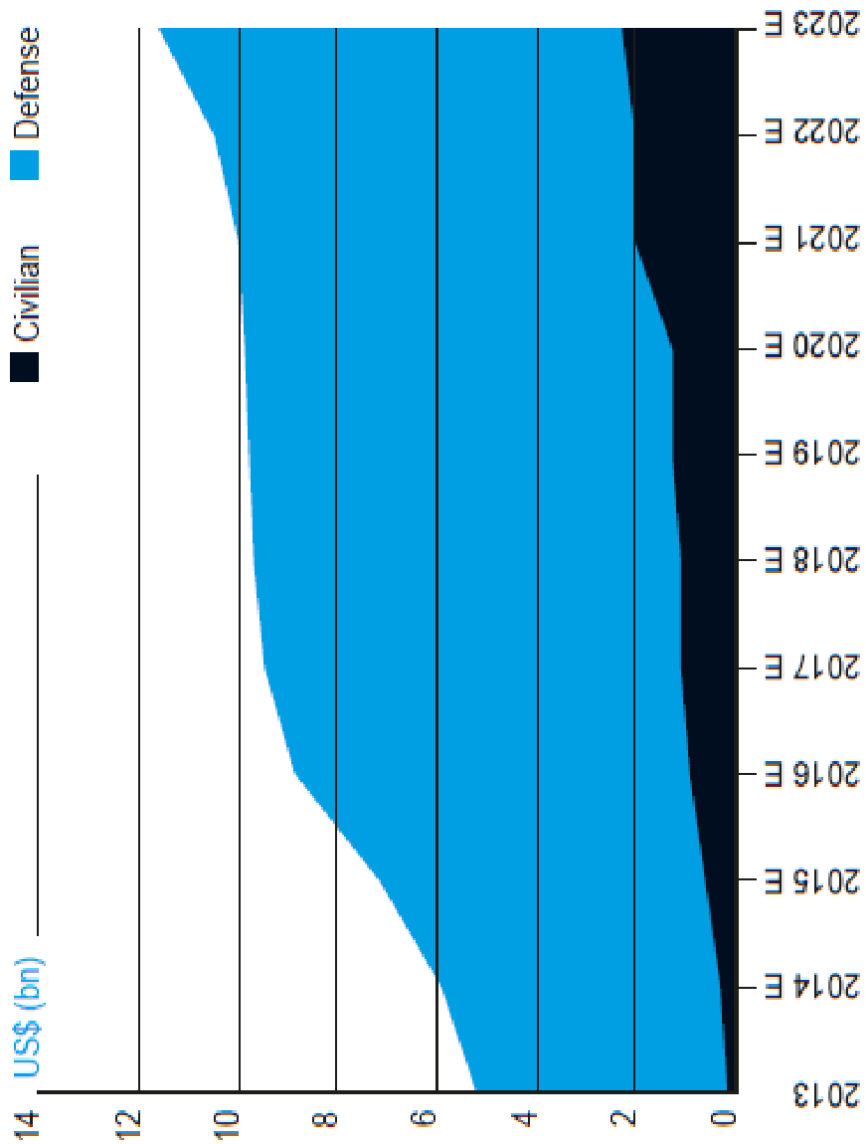


Figure 1.5 Worldwide UAS Market Forecast [48]

The US aerospace and manufacturing firms have a significant lead in military UAS and this is expected to continue. In 2007, US firms accounted for about 63-64% of the market share; Israeli companies were also a strong competitor while European companies held less than 7% of the overall market [49]. In 2005, some 32 nations were developing or manufacturing more than 250 models of UA, and about 41 countries were operating some 80 types of UA, primarily for reconnaissance in military applications [19]. Forecast International projects that US based companies account for 41 percent of the market's production value (nearly \$16.5 billion) and could gain

more in the future. Similarly, the Teal Group also forecasts US dominance is set to continue in the future. The projections carried out by Teal Group place USA far ahead of other countries in the world when it comes to production of UAVs as shown in Figure 1.6 [48]. US manufacturers with the largest market share of global UAS market could include General Atomics (20.4%), Northrop Grumman (18.9%), Boeing (1.5%) and AAI (1.2%) [46]. On the contrary European companies are projected to produce only 3.9% of the global production value over the next decade, slightly more than 3.7% share that Israeli companies are expected to hold [46].

When it comes to R&D expenditure on UAS, the scenario is no different with US accounting for majority (56%) of worldwide R&D spending. The relative distribution of total R&D expenditure on UAS in the period 2011-2020 is as shown in figure 2.3. The figure also shows that Europe lags far behind when compared to US, China and Israel.

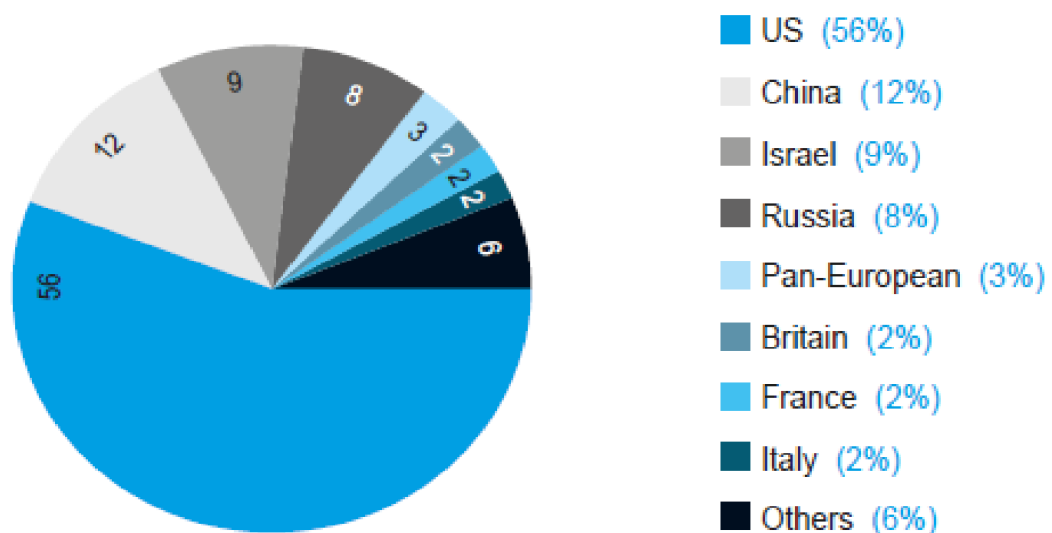


Figure 1.6 UAS R&D expenditure by country (%) 2011 – 2020 forecast [48]

There have also been a few market studies on the production forecast for the category wise distribution of UAS. A Teal group study in 2011, estimated the market for the year would be led by MALE (Medium Altitude Long Endurance) at 28% of market share, followed closely by HALE (High Altitude Long endurance) UAS with 27% of share and Tactical UAVs would account for 26% of the total UAS market (see figure 2.4) [50]. Further a Teal Group study in 2014, on world UA production forecast by UA

type estimated that small-sized UAVs, and in particular the mini-UAV category, is expected to dominate the market in the next ten years (see figure 2.5) [48].

A category wise study of global UAS market by ICD forecasts that in the next 10 years, the MALE UAs are most likely to account for a higher spending of the world UAS market [50]. The demand for MALE UAs is expected to be higher due their better Intelligence, Surveillance and Reconnaissance (ISR) capabilities. As has been the case until now, MALE, HALE and TUAs will hold a substantial market share and are expected to be the three most popular UA categories during the forecast period [50]. A few examples of current MALE UAS include the US Reaper, Israeli Heron TP, Heron I and Hermes 900. Other new entrants into the market are the Turkish Anka and India's Rustom [29].

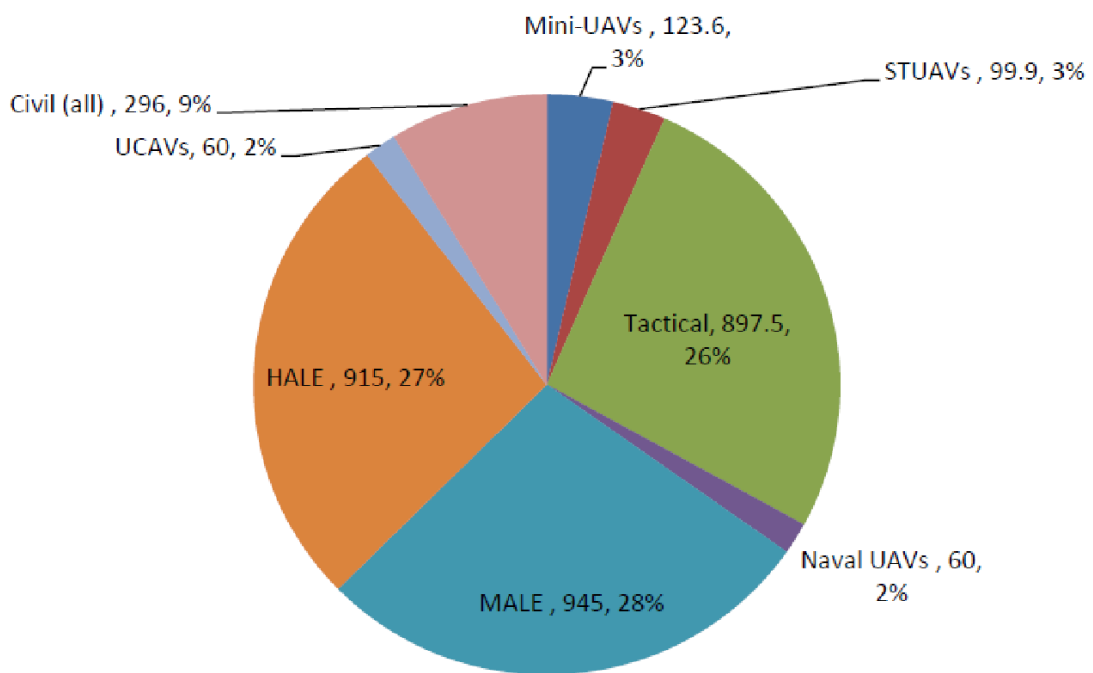


Figure 1.7 UAS category wide distribution market forecast [50]

While the global demand for UAS is increasing, the military expenditure of most national governments especially in the developed economies has reduced due to the global economic slowdown in 2008/2009. Hence many countries are establishing joint projects in order to share Research and Development (R&D) costs [50]. An example

of which is the joint UAS development initiative between UK and France to develop next generation of military UAs. This environment has also led to the increase in partnership between defence companies across different countries, to further strengthen the strategic alliances between countries and have technology transfer agreements with global UAS manufacturers, in order to provide greater investments and commitment to the growth of the domestic UAS markets in their host countries [50].

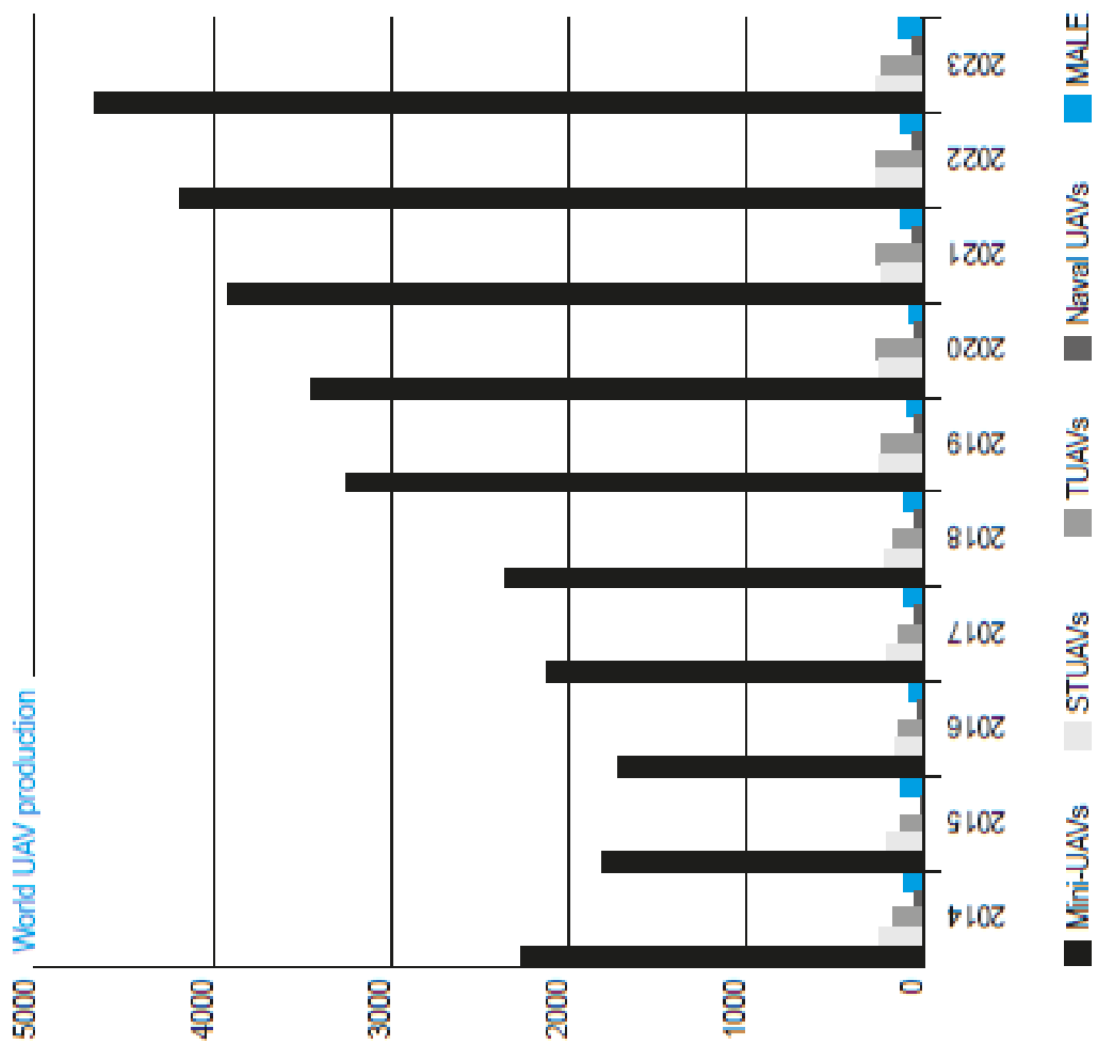


Figure 1.8 Global UAV Production Forecast by UAV Type

The global UAS industry is a dynamic and a highly fragmented market due to a large number of established defence manufacturers and a significant number of small

and medium- scale companies in leading production markets, namely US, Europe and to an extent Israel [50]. As the military expenditure in the coming years is set to reduce in these leading markets, there is pressure that could drive consolidation in these markets, as more and larger defence manufacturers are acquiring small UAS manufacturers, who have niche capabilities [50]. This has also led to the increase in the partnership between the defence companies, who are partnering with defence companies from outside their host countries to form strategic alliance and technology transfer deals, so as to align with their host countries investments and commitments for the growth and development of the domestic UAS markets. For example, in 2011, Selex Galileo (a part of Italy-based Finmeccanica group) acquired the Unmanned Technology Research Institute (UTRI), an Italian developer of MUAs for defence and homeland security [50].

Although majority of UAS spending in the next decade is projected to be in the defence segment, however the share of the UAS spending aimed at the civilian market is progressing steadily and is set to be one of the fastest growing segments in the next decade due to easier access to national airspace for UAVs [44]. According to Teal Group civilian applications of aerial drones is projected to be nearly 12% of global UAS spending (estimated at \$98 billion) through to 2023 [44]. The commercial use of UAS in the national airspace is restricted and thus the civil UAS market has not yet made much progress. However, as the access to national airspace for UAS becomes easier the future the civilian UAS market is set to grow the coming years, initially with the non-military government use of UAS for coastal surveillance, border patrolling and other homeland security applications. Teal Group expects the largest single portion of UAS spending over the next decade to be shaped by non-military government use of UAVs [48]. As the safety and regulatory challenges are addressed, a commercial non-government UAS market is expected to emerge much slowly.

1.6.6 Current Regulatory and Operational mechanism of UAS

The operation of UAS in the national airspace can provide several benefits (as outlined earlier in section 2.2), however those have not been realised due to the restrictions on the use of UA in certain segregated areas of the national airspace. Currently UAS are

authorised to fly only in segregated airspace. That is the UA operations are carried out only in restricted zones, where the manned and unmanned flight operations are physically separated in order to avoid an encounter between manned aircraft and UAS. Whilst the segregation of UAS from other airspace users (i.e. manned aircrafts) provides a safe environment presently for UAS operations, however the process of establishing such airspace reduces the flexibility of operation sought by the UAS user community [31]. These strict operational limitations adversely impact both the commercial profitability of civil missions and also the military missions (i.e. training, surveillance) during peace time.

Several countries around the world foresee international civil UAS operations in the near future. In view of this a first exploratory meeting of ICAO member states was organised in Montreal, Canada in May 2006; in which all the attending members agreed that ICAO was not the appropriate body to lead the regulatory effort and that although it could guide and coordinate to some extent the regulatory efforts, the latter should be based on the work of RTCA, EUROCAE and other standardisations bodies. Following on from the initial exploratory meeting the ICAO had established a UAS study group in its second ICAO exploratory meeting on UAS in January 2007, with a goal to supporting the regulation and guidance development within ICAO. The UAS Study Group enables ICAO to serve as focal point for the development of common terminology, definitions and non-technical aspects associated with the operation of UAS.

The acceptable means of compliance issued by various regulatory authorities relies on the standards published by the different standardization bodies. These standardisation bodies usually constitute working groups in which different stakeholders involved with the product or activity to be standardised are represented. Many working groups exists, however the most representative ones in terms of UAS regulations are:

- EUROCAE Working Group 73 (WG-73) – This working group is addressing the standards required for civilian UAS to fly in non-segregated airspace. This group is further sub-divided into four groups that are responsible for publishing standards for operations and sense and avoid (SG-1), airworthiness aspects

(SG-2), command and control, communication, spectrum and security (SG-3) and visual line of sight operations for UAS below 150 Kg (SG-4).

- RTCA special Committee 203 (SC-203) - This working group is responsible for developing standards for UAS to enable safe, efficient and compatible operations with other air vehicles in the operating environment. The committee aims to produce a finalised document on Minimum Aviation System Performance Standard (MASPS) for Sense and Avoid (SAA) for UAS based on the premise that UAS operations will not have a negative impact on the existing airspace users.
- ASTM International Committee F38 – This committee is responsible for developing standards including the design, manufacture and operation of UAS, as well as the training and qualification of aircraft crew. This committee is also divided into different sub-committees which are Airworthiness Standards (F38.01), Operations Standards (F38.02) and Pilot & Maintenance Qualifications (F38.03).

According to the various aviation authorities, the integration of UAS in the national airspace must be such that it does not have any detrimental impact on the safety and efficiency of airspace operations in the current ATM environment. The UAS operating in the national airspace must at least meet the safety and operational standards of manned aircrafts. Thus, UAS operations must be as safe as manned aircraft insofar as they must not present or create a greater hazard to persons, property, vehicles or vessels, whilst in the air or ground, than that attributed to the operations of manned aircraft of equivalent class or category (CAP 722). The principle of a minimum level of safety objectives in terms of regulations, engineering and training standards, general flight rules of air and operational practices equivalent to conventionally piloted aircrafts has proven difficult to achieve for UAS manufacturers and operators. Thereby the UAS are operating under significant restrictions by inhibiting their flight within un-segregated airspace and over populated areas. Presently, the aviation authorities use two different mechanisms to allow UAS access in the national airspace and they are:

- Special permission to fly: A special permit to fly for individual UAS is currently the primary means by which civil operators of unmanned aircraft are accessing the national airspace. A specific airworthiness certificate in the experimental category of civil aircraft that is subject to operational restrictions has to be obtained for civil UAS operators. The UAS flight operations under this approval mechanism cannot be performed for commercial purposes. Majority of UAS operating in the national airspace could be under this approval mechanism, since there are not many certification specifications that exist at the moment. The conditions under which the UAS is eligible for a permit to fly may differ slightly from country to country.
- Certificate of Authorisation (COA): A certificate of authorisation is provided on a case-to-case basis to particular UAS primarily for public aircraft operations in the civil airspace. The Certificate of Waiver or Authorization (COA) permits public agencies and organisations to operate a particular aircraft, for a particular purpose, in a particular area. The COA allows an operator to use a defined block of airspace and includes special safety provisions unique to the proposed operation. The COA is aimed to ensure a level of safety equivalent to that of manned aircraft. The conditions and limitations imposed on UAS operations by the aviation authorities are to ensure they do not adversely impact the safety of other aviation operations. Some examples of the current users include the military, law enforcement, other governmental agencies and public universities. The COA application includes aspects on airworthiness, flight operations and personnel qualifications. COAs are usually issued for a specific period – ranging from one or two years in most cases.

The access to UAS in the national airspace currently is based on many operational restrictions to their flight. The permission to fly UAS in national airspace is issued to individual UAS subject to several operational limitations imposed on UAS flight. A COA or permit to fly is provided by aviation authorities based on following general and operating principles:

- COA allows UAS to be operated in a restricted area of the

airspace/segregated airspace through the use of temporary Danger Areas (DAs) and also includes certain provisions unique to the proposed operation. For example, a COA may impose UAS flight only under VFR and/or in daylight hours, normally issued for a certain time period.

- For flights outside of segregated airspace, most COAs issued require continuous communication with the ATS provider and also include carrying of special equipment (e.g. SSR transponder) mandated for manned aircraft in certain classifications of airspace.
- When operating outside of segregated airspace, UAS must have an approved method of aerial collision avoidance (to avoid collision with other airspace users). Without an acceptable detect and avoid system, the operation of UAS outside segregated airspace is constrained by restrictions detailed below that are normally applied. The following restrictions are those applied in the UK airspace:
 - Within visual line-of sight of the remote pilot/Remotely Piloted Aircraft (RPA) observer of the particular UA, or a maximum range of 500 metres, whichever is less.
 - Cannot be flown in controlled airspace without prior permission of appropriate ATS provider.
 - Within a height not exceeding 400 feet above the earth's surface.
 - Cannot be flown in/near any aerodrome traffic area without prior permission from aerodrome in charge or appropriate ATC unit.
 - Within 50 metres of any person, vehicle, vehicle or structure not under the control of remote pilot; while during take-off or landing, the aircraft must not be flown within 30 metres of any person, unless that person is under the control of the remote pilot.
- Safety requirements need to be considered such as including mechanisms or procedures in place for emergency situations such as land in the event of disruption to or failure of its control systems, loss of control or radio link.

In US, the FAA presently issues COA to a public operator for a specific UA

activity. A comprehensive operational and technical review is carried out by the FAA before issuing COA. If necessary operational limitations or conditions are imposed as part of the approval process to ensure UA can operate safely with other airspace users. The operational restrictions usually are in the form of a prohibition of operations over populated areas and a requirement that the UAS can be constantly observed. FAA issued an updated guidance document titled “Interim Operational Approval Guidance 08-01” that contains operational guidelines for both public and civil UAS operations. The typical COA application approval process is completed within 60 business days of receipt by the FAA and is valid for up to two years in many cases.

According to the aviation policy FAA only accepts COA applications for public UAS operations. Civil UAS can get a special certificate under the experimental category with the limitations imposed for that category in FAR part 21 and additional provisions set by the FAA, specifying operational restrictions. The procedures and requirements for issuing such a certificate have been provided by the FAA in “Order 8130.34 Airworthiness Certification of UASs”. The other mechanism through which civil UAS operations in the US can take place is by determination by secretary of transportation that airworthiness certification is not required and an exemption from the FAA’s regulations is approved. The FAA modernisation and Reform Act 2012 (FMRA) created the specific authority for the secretary of transportation to determine whether an airworthiness certificate would be required for certain civil, including commercial, UAS operations. Civil UAS operator can petition for exemption pursuant to section 333, after the receipt of which the FAA begins its approval process. Firstly, FAA determines whether the request for exemption meets the section 333 elements and provides a recommendation to secretary of transportation on whether he/she should make a determination that an airworthiness certificate is not required. Secondly, FAA determines the proposed operations would not adversely affect safety and whether the operations would be in public interest. If these conditions are satisfied, the FAA issues an exemption valid for two years to the petitioner with conditions and limitations on proposed operations to ensure safety. Since 2012 FAA has been using this process to authorise civil UAS operations in national airspace. This has provided significant relief for UAS operators because FAA has issued very little airworthiness

certificated for UAS in the past. As of June 2015, FAA has issued nearly 700 exemptions to allow civil UAS operations using this process.

Model aircraft may be flown in the national airspace without a need for FAA authorisation. The FMRA prohibits the promulgation of any rule or regulation regarding model aircraft by the FAA. The FMRA also specifically defines a model aircraft and only those which satisfy these criteria can be considered as model aircraft. The act defines the term “model aircraft” as an unmanned aircraft that is (1) capable of sustained flight in the atmosphere, (2) flown within visual line of sight of the person operating the aircraft, and (3) flown for hobby or recreational purposes. Also, the aircraft must meet the following additional statutory criteria:

- The aircraft is operated in accordance with a community-based set of safety guidelines and within the programming of a nationwide community-based organization;
- The aircraft weighs no more than 55 pounds unless otherwise certified through a design,
- The aircraft is operated in a manner that does not interfere with and gives way to any manned aircraft; and
- When flown within 5 miles of an airport, the aircraft operator provides the airport operator and the airport air traffic control tower (when an air traffic facility is located at the airport) with prior notice of the operation.

In Europe, the national regulators retain the authority to certify UAS that weigh below 150 kg [31]. The CAA (Civil Aviation Authority) in UK is the first organisation in Europe so far which has come up with a guidance document for the civil UAS operations in national airspace. The CAP 722 document issued by the CAA highlights the safety requirements to be met by UAS, in terms of airworthiness and operational standards, before they can be allowed to fly in the UK airspace [31]. It also provides assistance to those who are involved with the development of UAS towards the route of certification, in order to ensure that all UAS operators meet the required standards and regulations. It sets out the primary factors for consideration in the development of UAS so that they will have a better chance of getting certification to fly UAS in UK

airspace.

The current view of CAA as outlined in CAP 722 is that the UAS must meet at least the same level of safety and operational standards as manned aircrafts for them to be able to fly in national airspace [31]. The integration of UAS should not require any changes to the rules of the air or any such special provision is likely to be made. It also suggests that UAS must be as safe as manned aircraft of equivalent class or category in so far as not to present or create a greater hazard to persons, property, vehicles or vessels while in the air or on the ground [31].

According to the latest version of CAP 722, in UK the non-military state unmanned aircraft must have a certificate of airworthiness or a permit to fly issued by the Civil Aviation Authority (CAA) under the Air Navigation Order (ANO) unless it is a small unmanned aircraft (UA weighing not more than 20 Kg) or it is an UA of mass 20 -150 Kg with an exemption from the ANO issued by the CAA [31]. Small UA can be flown without any prior approvals however under a certain set of conditions. The set of conditions include flying at a maximum altitude of 400 ft. above the surface, not permitted to fly within an aerodrome traffic zone or in controlled airspace unless prior permission is obtained from the CAA and also a prohibition on flight for purposes of aerial work without the permission of the CAA [31].

Australia also has similar programs run by CASA (Civil Aviation Safety Authority) to regulate UAS operations in their airspace [51]. Australia was the first country in the world to regulate remotely piloted aircraft, with the first operational regulation for unmanned aircraft in 2002. The regulation referred to as Civil Aviation Safety Regulation (CASR) Part 101 is being reviewed and CASA aims to modernise it into CASR Part 102 which is expected to be completed by 2016. The CASA waives the certification requirements for micro light UAS (weight below 0.1 kg) and require rest of the light UAS to operate away from populated areas at a maximum altitude of 400 ft. [52]. The ARCAA (Australian Research Centre for Aerospace Automation) was founded in order to facilitate UAS research and certification by providing simulation, development and testing facilities with regards to all aspects of UAS operations [52].

In Japan, the use of UAS for civil applications started almost 25 years ago [9]. Japan first developed and introduced unmanned helicopters that were used as

efficient way of supplementing the manned helicopters to spray pesticides on rice fields. Later, as unmanned helicopters namely Yamaha Rmax models became more useful and changes in social environment surrounding agriculture changed, unmanned helicopters use surged for agricultural purposes mainly for spraying pesticides. The fleet of Yamaha Rmax model has been steadily rising with 2000 in service by 2002 [10] and the use of unmanned platform for agriculture is immense, which are now expanding into other applications. These include aerial seeding for forestation and tree planting, eradicate insects that cause harm to pine trees, and observation of geological features during natural disasters such as landslides, earthquakes etc. [9]. Japanese civil aviation authorities have issued UAS certification procedures, which allow vehicle weighing up to 50 kg to fly over unpopulated areas [9]. The current operational rules are such that the unmanned aircraft are such that they can be flown at or below 250 m above ground except near airports. However, a recent incident where a drone (about 50 cm wide) which was equipped with a camera and a plastic container with liquid believed to have a tiny amount of radioactive material was found on the roof of Prime Minister's office. This sparked security concerns and a need to strengthen the security of important facilities, rules of UAS operations and legal regulations surrounding their use. The new regulations that have been introduced for the operation of UAS, prohibit civilians from flying them above or around a 300-metre radius around the important government buildings (such as Prime Minister's Office, Imperial Palace etc.), nuclear power plants and other sensitive areas.

1.7 Historical context of introduction of new technology into Aviation

Unlike many other sectors, aviation is a highly safety conscious domain. The main reason for it is the perception of risk to the benefits by society is different. Because the relationship between benefit and the primary individual at risk (people on ground and inside the aircraft) is not as apparent or difficult to show when compared to other domains [53]. Hence the acceptability of risks against its benefits by society is different. This means that introduction of new technology into aviation is a slow and difficult process. It must be ensured that it does not have any detrimental impact on

their operations in the current Air Traffic Environment.

The past history of aviation substantiates the point that the introduction of new technology and corresponding regulations has been slow and long process. It is also being seen that many of the new regulations adopted in the past has been more of a reactionary process where major incident or accidents have forced or prompted the regulations to be brought in until after their occurrence.

A brief look at the history of the aviation with a few instances where the major regulations have followed a reactionary approach is described. The Grand Canyon crash in 1956 triggered the introduction of new terminal area aircraft speed limit and mandatory use of TACAN (Tactical Air Communication and Navigation) distance-measuring equipment in the airports [53]. There were also recommendations to introduce the computer-generated displays for the Air Traffic Controllers to be able to visualize the traffic information better. However, this recommendation was not adopted until after a crash in 1965, which could have been a worst crash in aviation history, then prompted the aviation authorities to act in order to introduce computers generated displays as supporting aids for controllers. This was the beginning for the introduction of Terminal Radar Approach Control (TRACON), where individual centres could keep watch on all traffic within major metropolitan areas [53].

The history of introduction of regulation of airborne collision avoidance system shows that the initial interest in the development of a collision avoidance system dates back to the mid 1950's when an accident occurred between two US carriers over the Grand Canyon [53]. There were several approaches to collision avoidance that were explored before the FAA (Federal Aviation Administration) narrowed to the use of Beacon Collision Avoidance System (BCAS). Only after a second mid-air-collision near San Diego in 1978 and then a third such mid-air collision in 1986 near Cerritos which prompted a legislation to be passed which mandated the FAA to implement an airborne collision avoidance by the end of 1992 [53]. The BCAS effort was expanded and its name was changes to Traffic Alert and Collision Avoidance System (TCAS) [53].

The perception of risk to the benefits by the public as well as the impact of an accident that can have on the public sentiments must also be taken into account when

new technologies are brought into the aviation domain [54]. Thus, safety is of highest priority because of which meticulous risk assessment and rigorous testing are required before they can be certified to enter the air traffic environment.

However, unlike the past, the introduction of unmanned aircraft brings in entirely new concept and set of technologies associated with it. Fundamentally the presence of pilot remotely on the ground rather than the aircraft system in a UAS, presents a paradigm change from the basic concept of the airspace users that access the national airspace presently. Thus, the need to introduce new technologies and regulations for UAS operations has been slow and is also envisaged to be a gradual process in the near future [2].

1.8 Positioning the Study

This section combines the knowledge gained in the background and literature review chapters to position the study and further substantiate the research objectives. In order to narrow down the research area there were various factors considered in the process of selecting the specific areas of the research and the methodology which are also discussed here.

1.8.1 Factors influencing the research approach

There are a number of important aspects that emerged from the background study and literature review which significantly influenced the research approach. These factors are broadly related with the aims of the research, gaps in academic research and the industry research needs.

- The stipulated research has a broad focus and in view of the research degree in the Systems Engineering, the approach to the research was based on a systems perspective. The literature review looks at a system level analysis of the major issues involved with the integration of UAS in the national airspace.
- Thales, as an industrial partner in the UK industry-led consortium programme was responsible for Autonomy and Decision-making work package. Hence the research focussed on the specific issue of UAS Sense

and Avoid after the system level study of all the major issues related to UAS integration in non-segregated airspace in the literature review.

- Most of the academic literature and industry related research on UAS Sense and Avoid were based on UAS using airborne sensors to avoid collisions with other aircrafts except a few research programmes in US(US Army) and Australia (Smart Skies Project) which focussed on the ground based sensors for UAS Sense and Avoid. The lack of research on ground based sense and Avoid in Europe was also a factor in pursuing further research in GBSAA system.
- Important to look at architectures and understand the current ATM structure and its evolution in order to have a phased approach to UAS integration in non-segregated airspace.
- In order to fulfil the degree regulations, it is necessary the research should make both academic and industrial contribution.
- The industry needs stipulated that this research should not only consider the system's technical success but also lead to a system implementation that is commercially viable.

1.8.2 Scope

The various factors outlined in the previous section influenced the scope of the research. The scope of the research is as follows:

- The problem of UAS Sense and Avoid has several approaches to solve which have varying technology readiness, commercial viability, development risks and timescales for operational implementation. Hence this research focuses on a Sense and Avoid approach to integrate small UAs (i.e. less than 30 kg) as a near-to-medium term integration alternative and the development of a proof of concept for the same, based on the academic gaps in understanding and the needs of the sponsoring company (Thales).
- The research considers only the evaluation of proof of concept in a simulation environment and not the wider validation of the concept

thorough field trails.

- System architectures looks at the architectures only but it was part of DANSE project which looked at end-to-end system engineering toolset for developing complex systems.

Further to the scope of the research outlined above, there are several constraints and limitations that influenced the research approach adopted:

- The proof of concept system development was conceived as pre-operational demonstration system for evaluating different interrelated aspects of the sense and avoids system.
- The Sense and Avoid Display concept was developed using a Commercial Off-the Shelf (COTS) Air Traffic Control display. As this was COTS Air Traffic Management System software, the changes that could be made to the aircraft track information display format and air track data processing were limited.
- The UAS simulation environment that is part of the overall UAS sense and avoid concept demonstration system was not conceived as part of a complete pre-operational system for evaluation and proving the concept solution. This was a basic prototype display test environment and a full scale UAS Ground Control Station (GCS) simulation environment which would be needed for full scale operational demonstration of the sense and avoid system concept.
- The limitation of using a basic UAS GCS simulation environment is a product of the resources made available to this research and also logistical difficulties leading to inability in accessing Thales system laboratory facilities consisting of a full scale UAS GCS demonstrator (developed as part of Autonomous Systems Technology Related Airborne Evaluation & Assessment (ASTRAEA) programme).

1.9 Summary

The literature review has provided background information on UAS and also outlined academic literature on the various aspects related to UAS such as UAS classifications, their market potential and currently regulatory environment for UAS. Currently UAS are restricted to certain segregated areas of the NAS and the integration into the current Air Traffic Management System has not yet occurred. A high-level system study of the key issues involved with the inability of UAS to access the non-segregated airspace was described. The academic literature review combined with the industrial requirements of the research enabled in narrowing down the research problem to focus further research on two specific areas which were: A System-of-Systems (SoS) architecture analysis of the problem of UAS integration into NAS and UAS Sense and Avoid.

Part II: UAS Integration in ATM: A System-of-Systems Architecture Analysis

Chapter 2: System-of-Systems Overview

2.1 Introduction to System-of-Systems

Recently there has been a rapid growth in the inter-connected nature of systems, whose constituents are themselves complex. The ubiquitous nature of software intensive systems has meant that software is embedded into systems ranging from household appliances, automobiles, to large complex systems such as air transportation; which has in turn accelerated the growth of inter-connectedness of these systems. In its elemental form the term SoS is defined as a collection of entities that are in themselves systems; which are distributed, evolve over time and have different kinds of hardware and software working together to achieve a common goal [55]. Each element of the SoS is designed to achieve well-substantiated goals even if they are detached from the SoS [55]. Some of the examples of SoS are transportation systems, disaster management system, water management systems, healthcare systems, space systems and many others. The SoS concept presents a high-level viewpoint of the whole and describes the interactions between each of the independent systems [55]. This view of systems as SoS enables to obtain higher capabilities and performance than would possible with a traditional system view [55].

The origin of the SoS concepts dates back to the period of 1960's – 1970's, which provided early insights into the concept of SoS as we know now [56]. Berry [1964] and Ackoff [1971] provided the earliest references in literature to terms such as “systems within systems” or “system of systems”. Although the term SoS was not used extensively during the early years, SoS were being designed and developed. The SoS concept was used primarily by the US defence community to design and develop SoS. Some of the SoS that were conceptualised and developed during this period were Anti-Submarine Warfare System used during cold war, Integrated Undersea Surveillance System, Sound Surveillance System, Global Positioning System (GPS) and Military Command and Control Centres [56]. Also during the 1970's the concept for the modern-day battlefield emerged, where the battlefield consists of autonomous vehicles interacting with each other and the human managing them from

geographically distant location from the battlefield. All the intelligent vehicles would be managed in a way that enables them to work together to achieve a common goal.

There are numerous definitions of SoS based on the literature survey, however the term System-of-Systems does not have a clear and accepted definition as noted by Maier [58]. Here are only five of many potential definitions of SoS:

Definition 1: Defence Acquisition Guide [57], [58]

A SoS is defined as a set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities [DoD, 2004].

Definition 2: Sage and Cuppan [57], [58]

System of Systems exists when there is a presence of a majority of the following five characteristics: operational and managerial independence, geographic distribution, emergent behaviour, and evolutionary development.

Definition 3: Jamshidi [57], [58]; Carlock and Fenton [57], [58]

System-of-Systems are large-scale concurrent and distributed systems that are comprised of complex systems.

Definition 4: Manthorpe [57], [58]

In relation to joint war-fighting, system of systems is concerned with interoperability and synergism of Command, Control, Computers, Communications, and Information (C4I) and Intelligence, Surveillance and Reconnaissance (ISR) Systems.

Definition 5: Pei [57], [58]

Systems of Systems integration is a method to pursue development, integration, interoperability, and optimization of systems to enhance performance in future battlefield scenarios.

Definition 6: Carlock and Fenton [57], [58]

Enterprise Systems of Systems Engineering is focussed on coupling traditional systems engineering activities with enterprise activities of strategic planning and investment analysis.

Most of the definitions mentioned above provide a definition of SoS that is applicable to the field of military and engineering. Among the several definitions described, Sage and Cuppan [57], [58] provide a more concise definition that is applicable to varied fields. However, none of the definition address all the characteristics of SoS and there is a need for the development of a clear and generalised definition of SoS [57], [58].

There is an emerging class of systems whose constituents are large-scale systems in their own right, however not all of them are System-of-Systems. The taxonomic grouping of Systems-of-Systems implies that they are distinct classes within systems. The term “Systems-of-Systems” does not have a widely accepted definition but there is a useful taxonomic distinction between various complex, large-scale systems that are referred to as System-of Systems. Maier states that SoS should be distinguished from large, but monolithic systems, by the independence of their components, their evolutionary nature, emergent behaviours and a geographic extent that limits the interaction of their components to information exchange [58]. Maier argues that the taxonomic distinction of SoS is based on their unique characteristics of operational and managerial independence of the system components and not the commonly cited characteristics of SoS such as complexity of systems and geographic distribution [58]. Based on Maier [58] and previous works of Shenhar and Eisner [58], the significant characteristics of SoS are as follows:

- ❑ Operational Independence of the elements: The constituent systems can usefully operate independently when disassembled from the SoS.
- ❑ Managerial Independence of elements: The constituent systems are acquired and integrated separately but maintain operational independence to fulfil their own purposes.
- ❑ Evolutionary Development: The constituent systems evolve over time, as the functions of the component systems are changed, added or removed.

- Emergent Behaviour: The SoS exhibits functions and capabilities that are beyond those of the constituent systems which are referred to as Emergent behaviour.

Emergence is defined as:

“Emergent system behaviour can be viewed as a consequence of the interactions and relationships between system elements rather than the behaviour of individual elements. It emerges from a combination of the behaviour and properties of the system elements and the systems structure or allowable interactions between the elements, and may be triggered or influenced by a stimulus from the systems environment.” [59]

Emergence is a main objective of SoS as capabilities and functions are generated by interaction of the constituent systems, however unanticipated/unintended emergent behaviour is a risk to SoS that can have a detrimental impact on the SoS.

- Geographic Distribution: The constituent systems are separated from each other over large geographic areas.
- Collaborative: SoS is collaboratively integrated systems in which the constituent systems collaborate with each other to achieve a common goal. The constituent systems may also compete with each other during normal operation.

A basic SoS model can be outlined based on the definitions and characteristics of SoS mentioned in the above paragraphs. The figure 2.1 shows the basic SoS model, which depicts the SoS is comprised of system elements that are themselves systems [55]. The system elements have their own purpose of existing, address own needs, solve their own problems. They also have their own emergent properties resulting from interaction of sub-systems within the system elements. However, the system elements are part of the larger SoS that enables achieve higher capabilities and performance. The SoS has its own needs, solve its own problems and has emergent properties, resulting from the interaction of systems within the SoS. The objectives and purpose of existence of the system elements within the SoS may not always be aligned with

the objectives and purpose of SoS. Hence the need to maintain autonomy while at the same time operating within the SoS context greatly increases the complexity of an SoS.

Many of the examples of SoS in operation today have some components of the SoS that already exists, also commonly referred to as legacy systems. The legacy systems have been interconnected with other new component systems much later into their system lifecycle to spontaneously evolve into a SoS over time, in order to achieve a set of high-level objectives and capabilities. As a result, many of SoS have developed and evolved without concern for SoS design considerations. Many SoS that exist may not be recognized and treated as SoS (NATO SoS Characterisation and Types). However, based on a recognised taxonomy of SoS, SoS can take different forms. SoS can be categorised into four types based on the levels of authority and responsibility exercised between the SoS and its constituent systems.

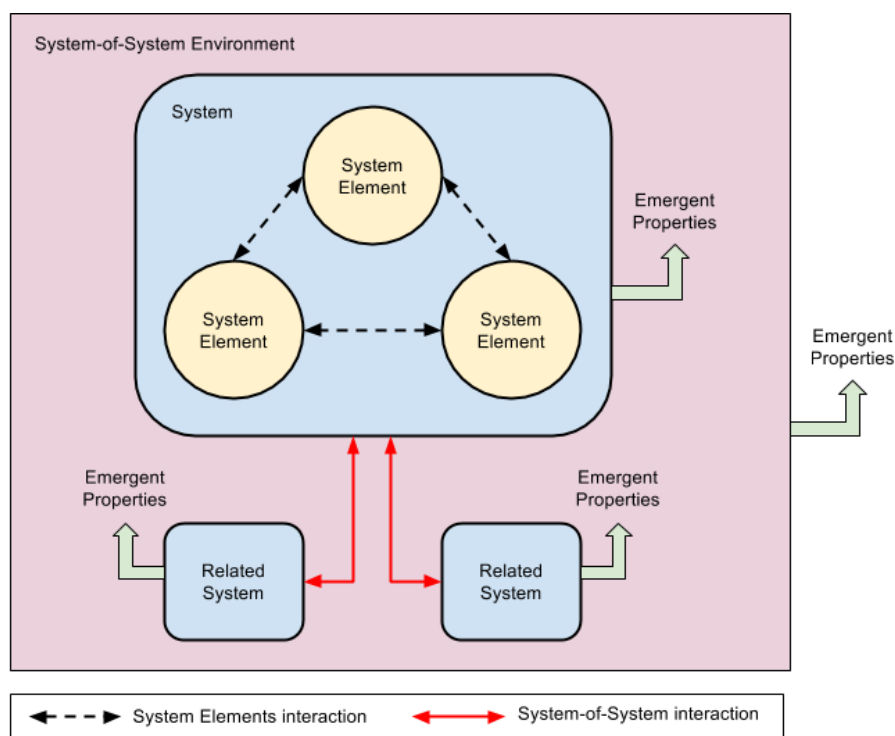


Figure 2.1 A basic SoS model [55]

Each of the types is as shown in figure and are discussed below [58], [55]:

- Directed: Directed SoS are integrated SoS that are developed and managed to fulfil specific purposes. Directed SoS are centrally managed and evolved. While the component systems in a directed SoS maintain the ability to operate independently, however the normal mode of operations of the component systems are centrally managed to align with central purpose of the SoS. The relationships between the SoS and the constituent systems in directed SoS are depicted in figure 2.2. The figure shows that operator/owner O2 owns systems S2 and S3, whereas O3 owns system S4. Operators/Owners O2 and O3 are highly controlled by a central managing operator O1. In this type of SoS O1 directs O2 and O3 in terms of design specification and operation of the systems owned by O2 and O3, hence referred to as directed SoS.

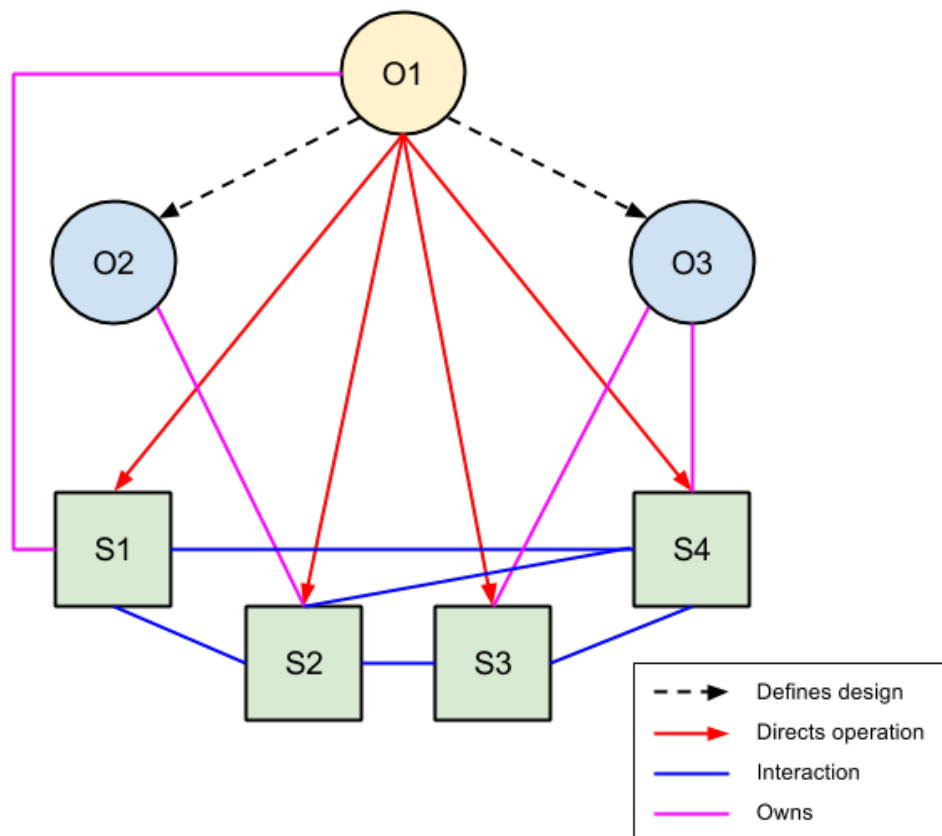


Figure 2.2 Interactions between SoS and constituent systems in a Directed SoS

- Virtual SoS: Virtual SoS is a type of SoS that lacks a central management authority and have no commonly agreed purpose for the SoS. The constituent systems in a virtual SoS may not be necessarily known and also the emergent behaviours exhibited from Virtual SoS rely upon relatively invisible mechanisms to maintain the SoS. The best example of a Virtual SoS is the Internet, where all the component systems (products/services) are integrated in an ad-hoc manner. Figure 2.3 shows the relationships between the systems and the SoS in a Virtual SoS. As the figure shows in a virtual type of SoS there is no central management entity, no overall goal or contract between operators. The operators O1, O2 and O3 access other system through their own systems which interoperate by recognised standards or protocols.

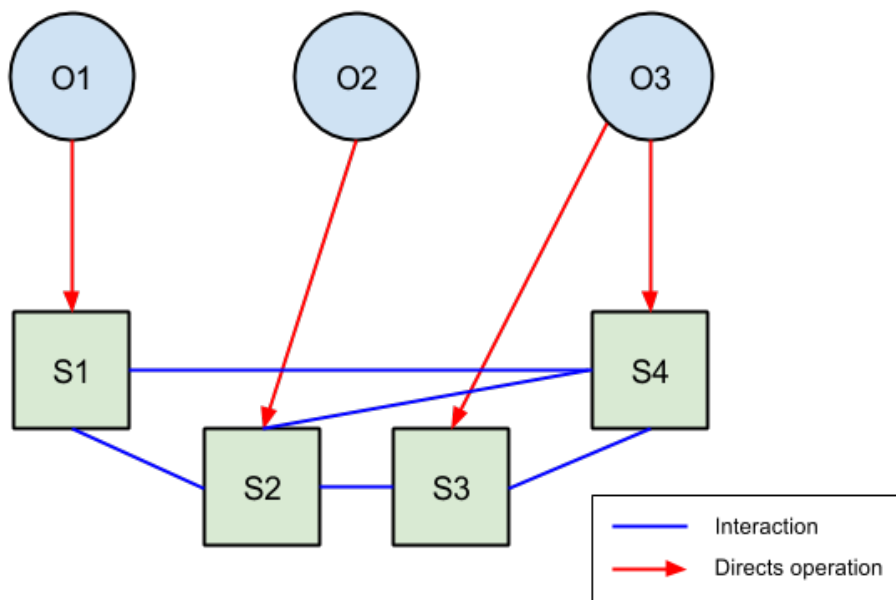


Figure 2.3 Interactions between SoS and constituent systems in a Virtual SoS

- Collaborative SoS: In Collaborative SoS, the constituent systems interact voluntarily to fulfil agreed central purposes of the SoS. Collaborative SoS do not have a central authority, rather the systems collectively decide based on agreements among the systems alone on how to interoperate between themselves, by developing, enforcing and maintaining standards. An example of

Collaborative SoS might be the regional area crisis response system where each agency that is involved in the first responder situation is responsible for its own systems and have an agreed protocol for interacting between the agencies to respond to the situation. The relationships between the constituent systems and the Collaborative SoS are as shown in Figure 2.4. The figure shows systems owners O1, O2 and O3 operate their own systems and collaborate with others realize a shared benefit. The collaboration between system owners in a collaborative SoS is based on a mutual agreement with no overall management entity controlling it.

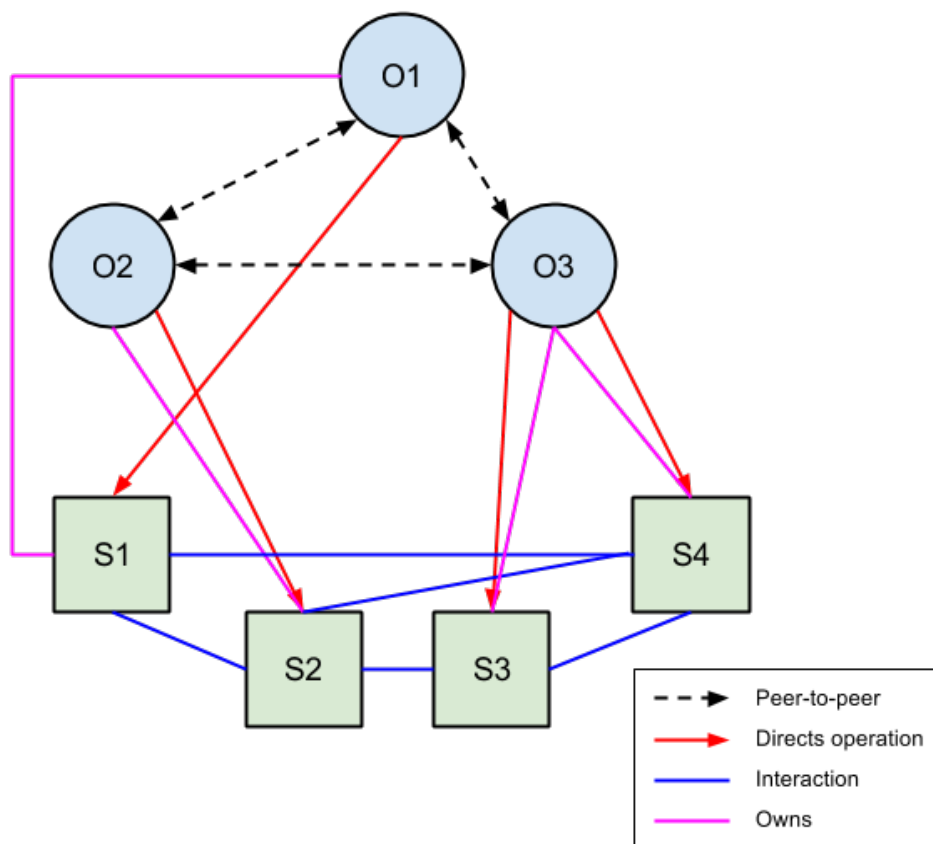


Figure 2.4 Interactions between SoS and constituent systems in a Collaborative SoS

- **Acknowledged SoS:** Acknowledged SoS is a type of SoS with recognised objectives, a designated manager and resources for the SoS. The constituent systems in the Acknowledged SoS maintain their independent ownership,

purposes, management and resources. These types of SoS essentially fall between directed and collaborative SoS. Figure 2.5 shows the relationship between the SoS and the constituent systems in the Acknowledged SoS. The figure shows that in an Acknowledged SoS, the system owner O1 has a contractual relationship with O2 (owns S2) and O3(owns S3 and S4), and has less control over the systems owned by them. The central managing entity O1 in this type of SoS must rely more on influence on direct choice of systems and operation. The most common examples of Acknowledged SoS can be found in the military. For instance, the military command and control SoS can transition from collaborative SoS to an acknowledged SoS to address a new capability that arises. In order to fulfil the new top-level mission objectives, the SoS would tend to be formed with ensemble of existing systems with the purpose of improving the way the systems work together to achieve new agreed capability. The designated SoS manager typically balances the top-level mission objectives with the objectives of the constituent systems that participate in the SoS not by controlling/directing the constituent system but by influencing the constituent systems to meet the purposes of the SoS.

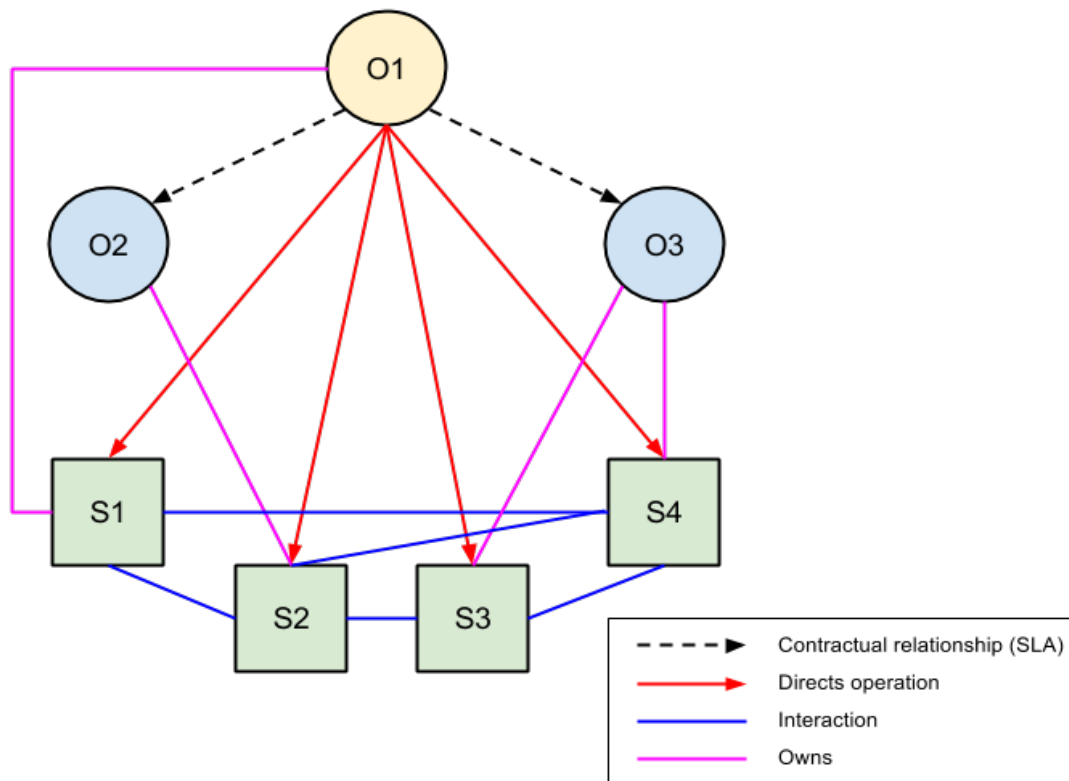


Figure 2.5 Interactions between SoS and constituent systems in an Acknowledged SoS

2.2 System-of-Systems (SoS) Analysis

The several definitions and characteristics of SoS described in Section 2.2 help to illustrate the complexity of these systems, which affect the way systems engineering can be applied to SoS. Hence the Systems engineers when developing SoS must approach the design process with that complexity in mind. One of the important jobs of the systems engineers apart from defining the problem is to partition the problem into smaller, more manageable ones and make critical decisions about the solution [55]. One of the most critical decisions to be made by systems engineers is the system architecture [55]. While designing any system, the first stage in the design process is the development of the system architecture. System architecture can be defined as - the fundamental organisation of a system embodied in its components, their relationship to each other and to the environment, and the principles guiding its design

and evolution [ANSI/IEEE-1472, 2000]. In this context, it is the primary role of the systems architect to decide on the system structure during initial stage of design process, although at this early stage of the system development all the characteristics and consequences of the architecture may not be known. However, at this early stage of the design process, it is possible for the system architect to produce a system architecture that maximizes the capability of the system to meet user needs, while minimizing the unintended consequences.

2.2.1 Architecture Design Process

The basic process of architecture design and its principles are the same whether architecting a simple system or a large complex system that consists of a number of independent systems interacting with each other. The process of architecture design has been well documented; it starts with recognition of a need, definition of the problem and proposing a solution strategy [55]. It continues with the synthesis phase where various solution designs are developed and then all these alternatives are evaluated to eventually arrive at a solution. The process ends with the solution description which involves an architectural model of the system to be designed. On the face of it the process of architecting a system looks pretty straightforward as it seems the design process flows logically from the customer needs and requirements. However, the process is complicated due to the fact that there can be needs that are contradictory and also multiple stakeholders can have competing requirements. Thus, the Systems architect has to balance these competing priorities which require design compromises to be made. There is no simple method or way to be followed to make the necessary design compromises. There is, however a well-defined process for architecting systems and a comprehensive set of design principles that must be considered when architecting any system.

The various stages involved in the architecture design process are as shown in figure and are briefly described here [55]:

Analysis

The first stage of the architecture design process is the analysis of the needs. It is

important that the needs are well understood in order to produce an effective design. The needs can be communicated concisely and thoroughly through user requirements, statement of needs and/or operational concept descriptions. But it hardly occurs that all the needs of the user are well understood by the system architect. Among the stated needs, there is the possibility that some user requirements may be extremely contradictory and also commonly some of the needs may also be based on perception rather than real needs. The role of the systems architect in the analysis phase involves fully understanding all the needs including non-stated needs, remove the extremely contradictory and non-feasible requirements and also separate the real needs from the perceived ones stated by the user. Also, another important role of the systems architect in the analysis phase is not to overlook understanding solution constraints, which can have significant effect on the design. In certain cases, the design can be driven by constraints as much as the needs. This is particularly true for SoS, which consists of systems that have their own needs and solve their specific problems. The solutions to the SoS needs are based generally on existing systems and their infrastructure. This certainly provides rich readily available resources from which to explore new solutions, however this may also constraint the solution space to produce an effective design.

Synthesis

The next phase in the architecture design phase is the solution synthesis. This is the phase where all the needs and constraints are merged together to into solution designs. The design synthesis phase is where the creative and innovative characteristics of the system architect are brought to the fore. It is a process of truly human endeavour. The role of system architect during the synthesis phase is to make critical decisions on how to balance between the characteristics that are important and those which can be compromised to produce effective solution designs. While designing a system in the real world, the problem is usually large where multiple designers with wide range of skills needed to solve the problem tend to work together from geographically distributed locations. However, in the case of designing a SoS, the decision decisions made by the system architect has to contend with many other

factors such as operations and infrastructure of existing systems, environment context (i.e. politics, economics) and other risks along with the usual challenges of space and time. The synthesis phase ends with system architect coming up with a set of solution alternatives so that they can be evaluated by comparing the solutions with each other. In order to evaluate these solutions, it requires that the solutions have to be modelled in a way that will support evaluation. The output of the synthesis phase is a set of alternative solutions that are modelled to a sufficient level to enable the evaluation stage to proceed.

Evaluation

The final stage in the design process is the evaluation phase. The primary aim of this phase is to evaluate the alternative solutions that resulted from the design synthesis stage. The evaluation of multiple alternative solutions is a crucial part of the architecture design process. However, the design evaluation process is not only concerned with evaluation of alternatives; there are other criteria's to be considered as well. The most significant factors among them are cost and capability which drive the selection and further refinement of design solution. Evaluation stage in the architecture design process does not only include the evaluation of the alternative solutions with respect to a set of design criteria and down selection to a single "best" alternative, but this is the stage where the design optimisation/refinement occurs. Design optimisation can be driven by the requirement to meet the cost and performance targets outlined by the customer need. Similarly, critical design refinement that may require a major architecture design rework can be caused due to implementation and technical feasibility issues. The output of the architecture design process is the description of solution. The solution must be described based on three critical aspects. The first aspect is the architecture model – basic structure of solution - which clearly communicates the solution to those who implement the solution and to the users. The second aspect is to outline the lower-level system requirements (at the sub-system level) including interface requirements which may affect the design and implementation of the system elements within the architecture.

The final aspect is the implementation concept, which describes the strategy

for implementation of the solution concept. The architecture design process is an iterative process and it is difficult to determine when the design has been completed. This is because design refinement and implementation issues occur throughout the system lifecycle. However, the system designers have to decide on a baseline high-level architecture design so that the design of the lower-level entities of the architecture can proceed. Hence the goal of the architecture design process is to perform enough analysis, design synthesis and evaluation so as enable the system designers to decide on baseline architecture to allow the next stages of design refinement and implementation to proceed, with minimal risk for need of a significant architecture rework.

2.2.2 Architecture Design Principles

While following the architecture design process for architecting a system there are a set of guiding principles that exist and need to be taken into account. The four guiding architecture design principles have been outlined by Mo jamshidi, are based on the comprehensive set of principles laid out by Mayhall that can be applied to all types of engineering design [55]. The four architecture design principles are [55]:

- Needs often compete - The nature of needs is that they have a tendency to compete. A complete set of needs often impose a competing set of criteria on design solutions. The systems designer has to reconcile with these competing needs and balance between competing needs to produce an effective design solution. The trade-off involves prioritising one need to be satisfied to an acceptable level by sacrificing the optimal satisfaction level of a competing need. For example, in a car need for improving safety and minimising cost can compete with each other. Similarly, the need for fuel efficiency and power can also be a difficult balance to achieve effectively while designing a car.
- Needs change over time – The system development lifecycle is time consuming. Most systems take time to design, implement, test and deploy. It is perfectly possible that some of the needs defined at the design phase may have changed during the operational lifecycle of the system. This may be due to several factors such as expectation of users may have changed over time or technology has

advanced within that time etc. As the size and complexity of system grows so does the time to design and build these systems. The most important needs are those that are present during the prime of the system lifecycle. Hence it is important aspect to keep in mind for system designers when architecting systems.

- Availability of resources constraints solution space – The availability of resources is necessary for the design, development, implementation, operation and maintenance of all systems. The most critical resource that has a significant impact on the design solution is money. As the size and complexity of the system increases so does the increase the capital required to design, build and operate these systems. However, money is not the only resource that can considerably constrain the solution space for system designers. Other resources that are important for an effective design are availability of knowledge and skill as well as the necessary technology infrastructure, which are especially relevant for architecting SoS.
- Design compromise is necessary – The result of following the above three principles, leads inherently to the final principle of the necessity for design compromise. As has been described in the above three principles, design process is driven by needs – which have a tendency to compete and change over time – and is constrained by resources. Thus, compromise is necessary to generate an effective solution that balances the competing user needs and deal with the resource constraints such as cost, availability of human capital and technology. In the end, as all designs are a result of compromise, there is really no perfect design, just those that are less flawed than others.

2.2.3 SoS Architecture Design

The architecture design process and architecture design principles apply to systems architecting at all levels. However, SoS architecting presents its own set of challenges and requires some special considerations has to be kept in mind while architecting SoS solutions. Systems-of-Systems (SoS) architecture is primary concerned with architecture of systems whose constituent elements are themselves systems. The system elements of SoS may already exist having their own behaviour and operational

autonomy within the SoS. The SoS architect is unable to influence the operation or behaviour of constituent systems of SoS as they are outside the scope of architect's control. Therefore, while architecting SoS the SoS architect must consider the characteristics of the component systems that comprise the SoS, the design of those systems is not be their main focus. The SoS architect must also consider the larger enterprise context of the SoS. The figure 2.6 shows the SoS context, which illustrates that normally systems that make up an enterprise interact with each other to enhance the capabilities of the enterprise. However, the core functions of systems comprised in the enterprise are not dependent on other systems which they interact with. A SoS can consist of collection of systems from one enterprise or in some instances it may consist of systems from multiple enterprises. Thus, it is necessary for the SoS architect to also consider multiple enterprises. The SoS architect need not consider the design of the enterprise as the enterprise architecture is the primary concern of the enterprise architect. Enterprise architecture is principally concerned with organizational resources (information, capital, and people and physical infrastructure) and process within an enterprise.

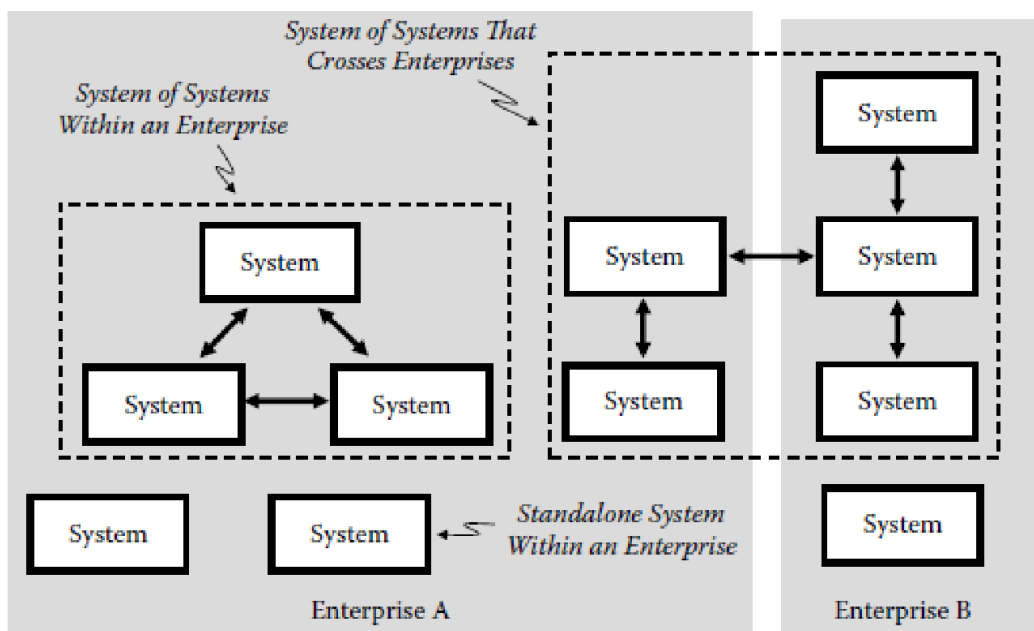


Figure 2.6 SoS context [55]

The design process of SoS is not so different from that of design process of any other systems. However, the challenge of design in a SoS is to leverage the functional and performance capabilities of the constituent systems to achieve the desired SoS capability as well as ensure the characteristics of SoS across all its constituent systems meet the broad SoS user needs. The performance of a SoS is not only dependent on the performance capability of the constituent systems but on their combined end-to-end behaviour. To ensure effective performance of SoS, the constituent system elements must work together to achieve necessary end-to-end performance. The definition of boundaries in a SoS is not a static problem as in the case of engineering of a single system, but it is more ambiguous. It is necessary first to identify the capability needs of SoS and to then use these capability requirements to choose the systems that are expected to fulfil the SoS capability objectives. It is important to focus on these set of identified systems which will affect the SoS objectives and understand their interdependencies. As these constituent systems themselves have varied purposes, needs and structures, it is particularly important to analyse their capabilities and interrelationships and how will affect the SoS capability objectives. Although this process of identifying constituent systems is analogous to establishing boundaries for the SoS, but other individual systems in the enterprise can also affect the SoS. Thus, SoS boundaries can be ambiguous. (SE guide for SoS military OSD)

The design of a SoS follows similar process as that of any individual system. The SoS systems engineer is responsible for initially translating the SoS capability objectives into high-level technical objectives of SoS, identify the constituent systems that affect the SoS objectives and define the current performance of the SoS. Consequently, the architecture structure of the SoS is developed, either a new SoS architecture is designed or it is evolved from an existing architecture of SoS. SoS architecture design is an iterative process similar to an individual system design process, where incremental decisions are made to satisfy the architectural and functional requirements. Architectural requirements are usually extracted and specified using quality sensitive scenarios. Scenarios have widely been used by the software community for a long time as a technique during requirements elicitation,

evaluation of design alternatives and performance modelling. Scenarios can be used effectively for specifying architecture requirements as they differ widely in their scope and breadth; and also, they are generally specific thereby enabling the user to understand their desired effect. The architectural requirements provide the criteria to be considered by SoS systems engineer while making architecture design choices. The SoS systems engineer identifies the design options and based on trade-offs to maintain the balance between system's needs and constraints, decides from available design options that satisfies most of the desired non-functional requirements.

The architecture of the SoS provides a technical framework for assessing the changes needed in systems for evolution of SoS. Whether the SoS systems engineer is beginning with a new architecture or an existing architecture, he/she needs to consider the current state of objectives and future plans of the constituent systems in the SoS as important factors in developing an architecture for the SoS. The architecture of a SoS addresses the following aspects [SoS guide] [60]:

- Concept of operations for the SoS
- Encompasses the functions, relationships and dependencies of constituent systems, both internal and external
- Includes end-to-end functional and data flow as well as communications

The focus of the SoS architecture is on the relationships and interdependences of the constituent systems and not the specific aspects of the constituent systems. The SoS architecture is constrained by the capability objectives of the individual systems and extent to which they affect the SoS behaviour to meet the user needs.

2.2.4 Architecture Frameworks

Numerous architecture frameworks exist for architecting systems. They have been developed and matured over the last several decades, to meet specific needs. An architecture framework is an encapsulation of a minimum set of practices and requirements for artefacts that describe a system's architecture [Mite.org]. Some of the architecture framework standards address different elements of the architecture process; however, there may be natural synergies among the frameworks. Also, some

of the standards are more suited to SoS architecture development than the others. The various architecture frameworks that are used widely are as listed below [55]:

- The Zachman Framework – It was invented by John Zachman in 1980 for IBM [61]. This was the first architecture framework introduced that was applicable to SoS architecture. It is still in use today and has been the foundation from which most other architecture frameworks have been derived [55].
- The Department of Defence Architecture Framework (DODAF) - The DODAF framework is primarily used by the US DoD for the development of architectures to facilitate the ability of DoD managers to make key decisions effectively [62]. It is maintained by the Office of the Secretary of Defence (OSD). Its structure has three core views namely Operational view, System view and Technical standards view; and several view products within each view [63]. The structure is well suited for describing architectures large scale systems and SoS with complex integration and interoperability issues [63]. DODAF is an established industry-standard architecture framework for defence and aerospace applications. Although it was designed for use in defence applications, it can also be used for commercial applications.
- The Ministry of Defence Architecture Framework (MODAF) – The UK MOD MODAF based on DOAF. As it was derived from DODAF, MODAF structure has similar core views as DODAF along with two additional core views which are Strategic view and Acquisition view [55]. MODAF is also a very good framework for representing SoS architectures.
- The Federal Enterprise Architecture Framework (FEA) – This architecture framework is used to represent enterprise architectures to support planning and decision-making information in all US federal government agencies except defence [64]. The structure of this framework is such that it provides an abstracted view of the enterprise at various levels of scope and detail [64]. FEA is maintained by the US Office of Management and Budget. FEA describes a suite of tools that enables to implement a common approach that enhances the effectiveness of the government by standardizing the development and use of enterprise architectures within and across federal agencies [55]. FEA can be used to represent SoS

architecture, however it is most useful for representing enterprise architectures.

- The Rational Unified Process (RUP) –Rational Unified Process (RUP) is a software development process that is developed and maintained by IBM [65]. Its primary objective is to ensure the development of high-quality software that meets needs of end users, within a specified budget and time schedule [65]. It is widely used to represent software enterprise architectures, but it is not useful for representing specific architectures.
- The Open Group Architecture Framework (TOGAF) – TOGAF is an Open Group Standard, which is a proven enterprise architecture methodology and framework [66]. It is used by world's leading organizations to improve business efficiency. The Open Group Architecture Forum, comprising of more than 200 enterprises, develops and maintains the TOGAF standard [66]. The first TOGAF standard was published in 1995 based on the US DOD Technical Architecture Framework for Information Management (TAFIM) [66]. TOGAF has a primary focus on the architecture methodology – the process of how to architect without prescribing architecture describing artefacts [55]. Hence it more suitable to represent enterprise architectures rather than SoS architectures.

Among the many architecture frameworks discussed, some of the architectures are most significant for representing SoS architectures. These architecture frameworks (DOADAF, MODAF & FEA) have a primary focus on the architecture description through a set of views, without a detailed description of methodology. They were all developed by government of United Kingdom and United States for their use within government agencies; however, they are freely available and also are well documented. Therefore, they can be used as standard architecture framework for representing SoS architectures across government organizations as well as private enterprises.

2.2.5 Modelling Language

Once the decision on selecting the architecture development framework and methodology is made, it is also important to select the modelling technique to

represent the architecture structure and processes. SysML (Systems Modelling Language) is a comprehensive modelling language used for describing systems. It is an extension of the Unified Modelling Language (UML) and is better at representing system related problems. The UML is a standard modelling language widely used in the software community to represent software-intensive systems. It is more suited for modelling software architectures than system architectures. Hence, the International Council on Systems Engineering (INCOSE) and the OMG (Object Management Group) joint with other industry partners (IBM, Motorola, Airbus, Boeing etc.) to define a general-purpose modelling language based on UML to address Systems Engineering needs, in order to bridge the semantic gap between systems, software and other engineering disciplines. SysML was officially adopted by the OMG in 2006 and there have been several updates since. SysML reuses a subset of UML2 and defines some new features. It introduces two new extensions namely requirements and Parametric diagram to address the limitations of the systems engineering in modelling non-software intensive systems.

Presently, SysML is the standard modelling language used by systems engineering community for representing systems. However, until now there is no formal semantics specifically for SoS modelling and design languages. The primary modelling techniques for SoS currently comprises the use of architecture modelling languages such as UML and SysML to represent various SoS aspects. SysML can be used to represent SoS, its constituent systems and other entities through following diagrams:

- Behavioural aspects
- Constraints on physical and performance properties
- Relationships between requirements
- Allocations between behaviour, structure and constraints
- Structural composition, interconnection and classifications

2.3 Methodology to Architect and Analyse SoS

The above definitions and design considerations for SoS help to illustrate the complex nature of these systems and suggest that using traditional approaches are inadequate

to define the problem space. Using the conventional means to model and analyse SoS will be unsuitable or inappropriate to provide tangible and verifiable results due to lack of availability of full details of component systems. SoS are likely to be comprised of legacy and new system. During the evolution of SoS through its lifecycle, while each of the component systems changes may be well understood, however it is not uncommon for the impact on overall SoS to be ignored. Hence there is an increasing requirement for new techniques to model and analyse SoS that will reduce the dependency on missing details of inadequately specified component systems within the overall SoS architecture.

The Danse project aimed to develop a cohesive methodology to support evolutionary, adaptive and iterative SoS life-cycle along with tools that support SoS analysis, simulation and optimisation [103]. The Danse methodology can be summarized based on use cases that provide a means for describing the solution methods and various tools that offer value from end user's point-of-view. The first use case is to develop SoS objectives/goals and models and enable simulation of multiple models with different levels of abstraction and fidelity at different phases of the SoS development in order to understand the SoS behaviour. This included using high fidelity component system models with ability to use different tools that enable co-simulation. The second use case was to develop new architecture views for the SoS to identify emergent behaviour and improve its responses is specific goals and contracts. The final use case is to check how the SoS and component systems meet their goals. The validation of the DANSE methodology was carried out through the use of a semi-theoretical concept alignment example and through three actual SoS test cases developed by the industrial partners [103].

In the DANSE methodology the challenge of investigating architecting and analysis of SoS was tackled with modelling approaches though the use of patterns [103]. Use of patterns is not new to certain areas of engineering, where they have been used in the past at different abstraction levels (design, interaction etc.) especially in software engineering and civil/building architectures to understand, communicate, and implement design concepts. In the same way, large scale systems can be managed by breaking them chunks for humans to understand, communicate,

implement and maintain such systems. The patterns which enable large scale system to be represented in structure and behaviour are called architecture patterns. The architecture patterns provide an ability to architect and analyse by breaking SoS into chunks but the process also maintain the characteristics, structure and relationships between the various components of the SoS. Chapter 4 provides more details on architecture patterns and their role in understanding and analysing SoS.

2.4 Air Traffic Management (ATM) as SoS

The global ICAO airspace can be viewed as an example of a system-of-systems based on the definition and characteristics of SoS described in the previous sections. The global airspace is composed of 190 National Airspace Systems (NASs), each of which is part of member nations National Transportation System (NTS). The NTS can be viewed as a collection of layered networks composed by heterogeneous systems, in which the Air Transportation System (ATS) and its National Airspace System (NAS) is a part. The individuals or groups operate within each ATS based on standard regulations and structure to provide synergy with global system enabling to achieve the desired overall system performance with a very high safety rate. Air Transportation System consists of airports, runways, airlines, cargo terminal operators, concourses, fuel depots, retailers, catering establishments, air traffic controllers, etc. The successful operation of this SoS requires standard communication protocols and procedures to be followed among individual and groups across enterprises. The International Civil Aviation Organization (ICAO), as a United Nations agency, manages the international Air Traffic Control (ATC) system since it has been founded in April 1947 based on already existing agreements and regulations agreed among the member nations.

The current National Airspace System (NAS) consists of a complex collection of facilities, systems, equipment, procedures, and airports that are operated by several people to provide safe and efficient environment for airspace users. The flow of air traffic is managed in the NAS by Air Traffic Management personnel based on demand and supply. They use a systems approach that considers the impact of allowing an airspace user or their individual actions on the whole air traffic flow to ensure equity in

the delivery of air traffic services. Air Traffic Management (ATM) is provided through the integration of humans, information, technology, facilities and services supported by air, ground and/or space-based communications, navigation and surveillance [10]. ATM as described by ICAO is defined by an aggregation of air and ground based functions required to ensure the safe and efficient movement of aircraft during all phases of operations. The primary goal of the air transportation sector is to provide capability to transfer people and goods from one place to another in a safe and efficient way. In the air transportation system, the various airspace users and ground-based elements interact to provide this capability [3].

UAS when integrated into the national airspace system will be part of the air transportation system. UAS is in itself a complex system which involves the integration of unmanned aircraft, various ground systems, communication link and human operators. There is a myriad of stakeholders such as UAS manufacturers, UAS operators and UAS standardisation bodies which are all part of the process to be able to operate UAS in the National Airspace System (NAS).

In a system of systems context, the introduction of a new technology or applications such as unmanned aircraft should contribute to providing the capabilities of the overall system-of-systems and not cause any negative impact on the provision of the system capability. One of the key aspects of an evolutionary system-of-systems architecture is that the introduction of new constituent systems into the system-of-systems must not increase the complexity of system or require re-engineering of other existing constituent systems to maintain the same performance levels as before [10].

In terms of integration of UA in current air traffic environment, when viewed from a SoS concept, the most important criteria would be that it must not cause any detrimental impact on the safety and efficiency of the current airspace users. This is one of the driving thoughts behind the views of the aviation authorities. According to them, UA will have to follow same rules and procedures as that of manned aircraft thereby no special provisions would be made for UA's [2]. Thus, UA flight must follow the principle of equivalence and transparency. UAS has to interact with other airspace users in the national airspace, without reducing the safety of the current airspace system. Also the interactions of the UAS with other airspace users also depends on

the size of the UAS and which category of airspace its flight operations are conducted.

One of the key aspects for UAS integration is also that the UAS have to fit in with the next generation Air Traffic Management Systems. The UAS as an airspace user must be part of the definition and design phase of the next generation ATM system [5]. Also, the UAS as a new type of airspace user must be recognised and a regulatory framework has to be developed balancing the need for following the current regulatory standards and also on the other hand not to overburden the industry with higher regulatory costs [7]

2.5 Scope

The knowledge gained from the background study and literature review of System-of-Systems enabled to scope the research. The previous section described the system-of-systems nature of the current National Airspace System and highlighted some important points to consider for integration of UAS into an already existing complex large-scale system which is evolving due to modernisation into next generation systems. The scope of the research into analysis of UAS integration into ATM as a SoS, is as follows:

- The research uses architecture patterns to analyse the current Air Traffic Management system as an SOS, and integration of UAS this SoS. The architecture patterns enable in capturing the SoS at an abstraction level which lends itself useful to architect and analyse SoS in order to compare different architecture solutions and provide guidelines for the development of future architectures based on the analysis of existing architectures. This research was a part of the DANSE project which was developing new methodologies, models and tools for architecting and analysing SoS so that they can be operated effectively. The focus of the research was only on capturing the architecture patterns to enable systems architect to improve SoS characterization and architecture analysis in order to provide improved SoS capability. Chapter 3 shows how architecture patterns were being used to characterise ATM system and also presents the architecture patterns that were mined. The chapter also

shows the key aspects to consider for the architecture pattern when integrating UAS in the national airspace system.

- The issue of integration of UAS into ATM system has challenges well beyond the technical and regulatory hurdles, to factors that are socio-political in nature. In order to understand the key challenges from important stakeholder's perspective the research uses 'wicked problem' analogy commonly used in social sciences. Chapter 5 describes the 'wicked problem' and its characteristics. It also presents the major stakeholders perspectives on the main challenges for the problem of UAS integration in ATM. This analysis provides a better understanding of the constraints and competing requirements of the major stakeholders involved. Thereby ensuring that needs and solution constraints are well understood in order to produce an effective design.

2.6 Summary

This chapter has provided an introduction into System-of-Systems (SoS), its characteristics and the architecture design process for system design. However, this chapter also highlighted the challenges presented with to a system architect when following the standard architecture design process for engineering SoS. A brief overview of the DANSE methodology to architect and analyse SoS was outlined. The SoS nature of the ATM system and the integration of UAS (a complex system on its own) into an existing SoS was outlined. Further this chapter provided the scope of the research related to SoS analysis of UAS integration into ATM system and the research aspects described in Chapters 3 and 4 were briefly mentioned.

Chapter 3: SoS Analysis of ATM and integration of UAS in ATM Using Architecture Patterns

3.1 Introduction

The inherent nature of a System of Systems (SoS) makes it very difficult to model and analyse it. An approach to characterize SoS to enable architecting and analysis is by using model abstractions. Modelling approaches using use of patterns may enable model abstractions to tackle challenge of SoS analysis. This chapter provides a brief overview of architecture patterns and how they would be useful in SoS modelling and analysis. It also describes the pattern mining process and contents of pattern template used to capture the architecture patterns. The verification and validation aspects of the patterns mined are also mentioned.

The reusable architecture patterns captured for the ATM System are detailed. Also, the key aspects to consider for the architecture pattern when operation of UAS is made possible in ATM in the future. This will enable system designers/architects to model SoS and analyse its behaviour to understand the impact on the overall SoS capabilities of the National Airspace System with the integration of UAS into the ATM.

3.2 Architecture Patterns

The use of patterns in certain areas of engineering such as software engineering or Information Technology, is not new as part of architecture and design process. Another field where patterns are important and used frequently is in constructing building and city architectures. It has been stated that “A pattern is the abstraction from a concrete form which keeps recurring in specific non-arbitrary contexts” [104]. The form that a pattern has is defined through its representation as a set of interacting components and their relationships. Thus, a pattern exhibits structural and dynamic properties, and the visible components within a pattern can range from software, services, and hardware, technical or non-technical entities. Traditionally design patterns have been used in the software community which represent the design structure of software components and their relationships. Expanding on this definition

of design patterns, architectural patterns exhibit architectural structure [103]. A pattern fundamentally can be thought of a set of guidelines that describes how to create the particular entity and the context in which it can be used. Patterns can exist at different levels of system hierarchy and when used correctly can provide an effective way to represent common concepts at the operational through to implementation levels. The use of patterns in support of architecting and analysing SoS is at an early stage [104].

An architecture pattern can be considered as a framework that provides a template for the structure and behaviour of an entire system within a domain [104]. At a system level the architectural model refers to the system requirements, its logical components and its physical entities. Architectural pattern when applied to SoS can support system designers working at higher abstraction levels rather than be constrained by specific limitations of a particular technological solution, thereby providing system designers the ability to see more clearly the system-to-system interactions at the top-level. Architecture patterns are concerned mostly with the top most level blueprints expressed in an architectural framework such as UPDM enables the systems architect to decompose SoS into manageable elements for analysis purpose, while still preserving the SoS capabilities in its entirety [105]. Architectural frameworks offer a huge number of different viewpoints and not all of these are relevant for the current situation and may be useful for other situations. It has also been clearly mentioned in Chapter 3 that different modelling languages can be used to model architecture patterns.

Architecture patterns provide a variety of patterns (operational, system and functional) to develop a SoS architecture description of SoS and its constituent systems. The DANSE methodology enables system designers to break down the SoS and its constituent elements into manageable parts through several views in UPDM. The operational, functional and system views captured in the DANSE methodology were used to form the fundamental architecture description. The various UPDM view used in the DANSE methodology are as shown in Figure 3.1. The primary tool chosen for modelling an SoS and its constituent parts in DANSE methodology is Rational Rhapsody (using SysML and UPDM profiles).

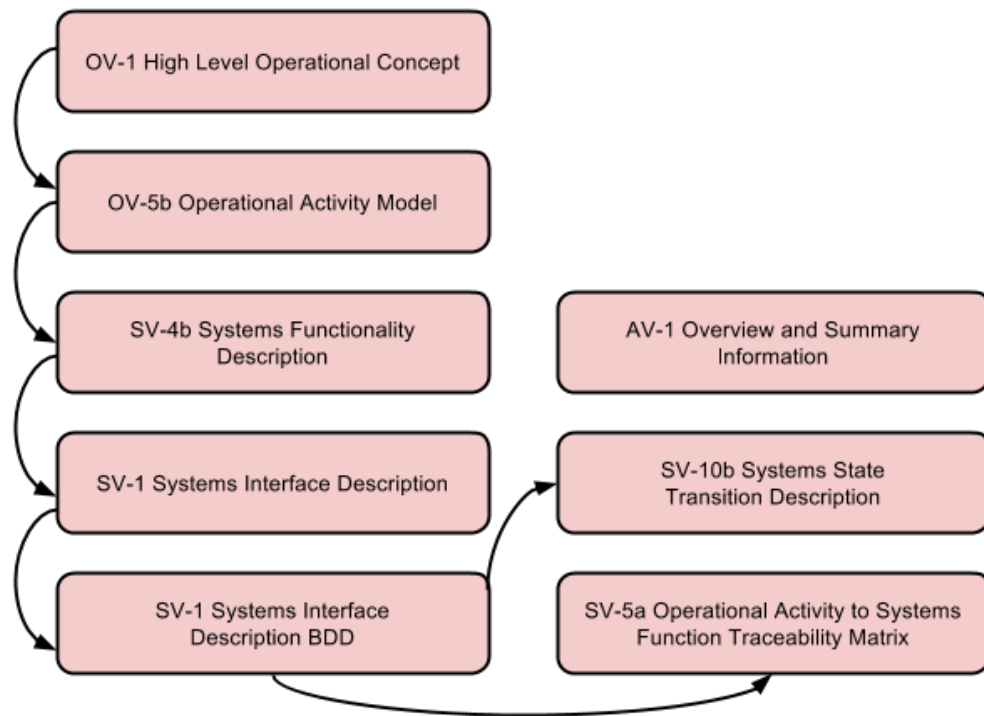


Figure 3.1 Overview of UPDM views used in DANSE methodology

3.3 Architecture Patterns Mining

The previous section provided an introduction to architecture patterns and outlined the benefits of using architectural pattern paradigm in SoS analysis. Here the anatomy of architecture patterns is looked at i.e. elements which make up the pattern template, creating architecture patterns and its verification and validation.

The pattern template used for capturing the architecture patterns in this methodology are as shown in Table 7. The pattern template consists of diagrammatical structure and textual elements which together provide important information regarding the pattern. The structure of the architecture pattern is a simplified model of the pattern and shows the various elements of the pattern at high levels of abstraction. As the architecture patterns are mined and their numbers increase it is imperative to have an online repository that provides an accessible and easier mechanism to share information.

Pattern Name & Classification		The name of the pattern
Keywords		Any key words that may appear in the pattern that will be useful when looking up the pattern in a repository.
Intent		This refers to the problem and why you would use the pattern to address the issue.
Also Known As		Common names referring to the same pattern, if any.
Motivation	Goals	Statement of why the pattern would be utilised to address the design problem or situation. It will help understand the structure and consequences later in the pattern.
	Capabilities	Describes what the pattern has to offer to the user and the characteristics which it possessed which will be of benefit to the pattern implementer.
	Limitations	Refers to the restrictions of the pattern.
Applicability		The level at which the pattern can be applied. In an architectural pattern the first Level, Level 0 ((L0) shows the pattern in its most basic form at the highest level of abstraction. Level 1 (L1) begins to show a little more detail in the different arrangements of elements that make the architectural pattern. And so on...
Structure		The general interconnecting arrangement between elements included in the pattern. E.g.
Participants		The units that are involved within the pattern. Possibly differing systems that make up the SoS, depending on the applicability level being shown.
Collaborators		Here, not only are the participants being shown that make up pattern, but also how, and with which other elements are interacting, describing briefly the relationship between elements which facilitate the tasks they need to conduct.
Consequences		The consequences refer to differing variables that may influence the usage of the pattern. What aspect of the pattern structure does it allow you vary in order to fit your specific application?
Known Uses/ Domain		Where the pattern has known to be used in real-life scenarios and in which domains. E.g. Military, Emergency Services.
Related Patterns	Parent Patterns	If the pattern has stemmed down from an original pattern, or patterns. Which are these?
	Child Patterns	Any patterns that may have been form from the pattern.
Implementation		Advice/Guidance on the usage of the pattern, providing some considerations to be undertaken when the pattern is applied.

Performance (Quality Attributes)	E.g. bandwidth, response time, cost, redundancy level, etc.
Model (e.g. SysML)	An applied model of the pattern as an example.
Example	An example

Table 7: Architecture Pattern Template

The creation of patterns does not have a single approach; however, a first stage of mining process is from existing systems. Legacy systems are the foundation of today's SoS and provide most of the SoS capabilities of the overarching SoS. The architecture pattern can be mined from legacy system by first determining if they have adequate system documentation for the SoS and its constituent components, which then could be used by stems architect to identify and extract the common patterns. The idea is to capture the architecture based on high level functional and behaviour aspects [104]. If the documentation is not available then it is necessary an equivalent architecture is developed using architecture framework such as UPDM and then reviewed by appropriate subject matter experts who understand the function and behaviour of the SoS under consideration. The next stage of the architecture mining process is to identify and extract candidate architecture patterns manually to compare them against existing patterns. If the pattern does not exist already then it is subjected to review by subject matter experts to ensure the pattern captured is indeed a pattern that can be used. The pattern mining process and its various stages are shown in Figure 3.2 [104]. There are two key aspects that have to kept in mind while mining architecture patterns. Firstly, the extracted patterns must be of a form that lends itself useful for reuse later. Secondly, the patterns must wherever possible be independent of the specific system implementation since this would lend them not transferable to other domains.

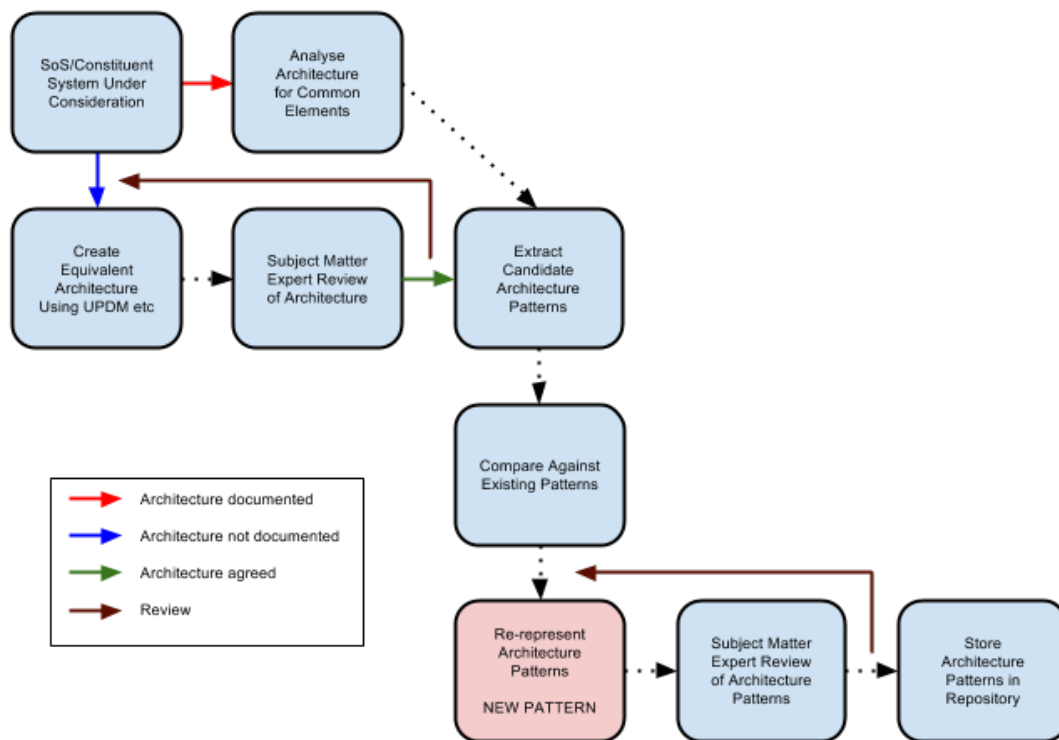


Figure 3.2 Pattern mining process [104]

3.4 Verification and Validation of Architecture Patterns

The verification and validation of architecture patterns extracted for SoS analysis is extremely challenging. The main reason being the abstract nature of the patterns makes it difficult to verify and validate. The constant evolution and lack of detailed information for all its constituent components makes it almost impossible to validate complete SoS. The use of architecture patterns is a starting point for architecting and analysing SoS by drawing upon existing knowledge about the systems. In order to have a robust architecture pattern, the architecture pattern can be mined or extracted by subject matter experts (SMEs) and then further scrutinised by other SMEs to ensure the pattern accurately captures the key elements of the architecture. At present the patterns are verified by the SMEs rather than validated, however in the future as specific patterns are re-used across domains, then a robust set of domain specialist architecture patterns could be obtained.

In this research, the SoS architecture patterns of the Air Traffic Management

system are identified and extracted based on the architecture mining process described in the previous section. The architecture patterns were reviewed by subject matter experts (SMEs) from Thales (industrial partner of DANSE project) to ensure the key elements of the architecture have been captured accurately. The SMEs only verified the correctness of the architecture pattern, however the SoS architecture patterns were not validated due the challenges mentioned in above paragraph regarding abstract nature of SoS.

3.5 Air Traffic Management (ATM) Architecture Patterns

The airspace in the present day is a combination of different airspaces with specific rules and regulations. The flight rules can be classified into two types, visual flight rules (VFR) and Instrument flight rules (IFR). The classification based on VFR and IFR varies depending on the weather conditions prevalent, airspace density as well as existence of infrastructure to provide this capability in the airspace region and so on.

3.5.1 Air Traffic Control Organisational Structure

United States

This is a generic architectural pattern of an air traffic control organisation structure for monitoring the overall air traffic flow in the United States National Airspace System.

This pattern enables to manage, organize and communicate between various control authorities in the air traffic control organisational structure, in order to provide traffic separation services to air traffic participants. The constituent parts and their control hierarchy are as shown below.

- The hierarchy enables air traffic management personnel (ATSCC) to analyse demand in the system and implement initiatives that are then relayed to the air traffic controllers (ARTCC).
- Air traffic controllers can relay information to traffic management personnel for use in their decision-making process.
- Air traffic command centre is the final authority on all national air traffic management initiatives and is responsible for resolving inter-facility issues.

- The centralised command and control structure provides ultimate authority to system command centre to balance air traffic demand with system capacity in the national airspace, especially during significant events such as adverse weather, equipment outages, runway closures, national emergencies.
- The command centre acts as a single point interface with its customers (aviation industry partners), and also maintains frequent contact with them to update on the air-traffic management issues in real-time.

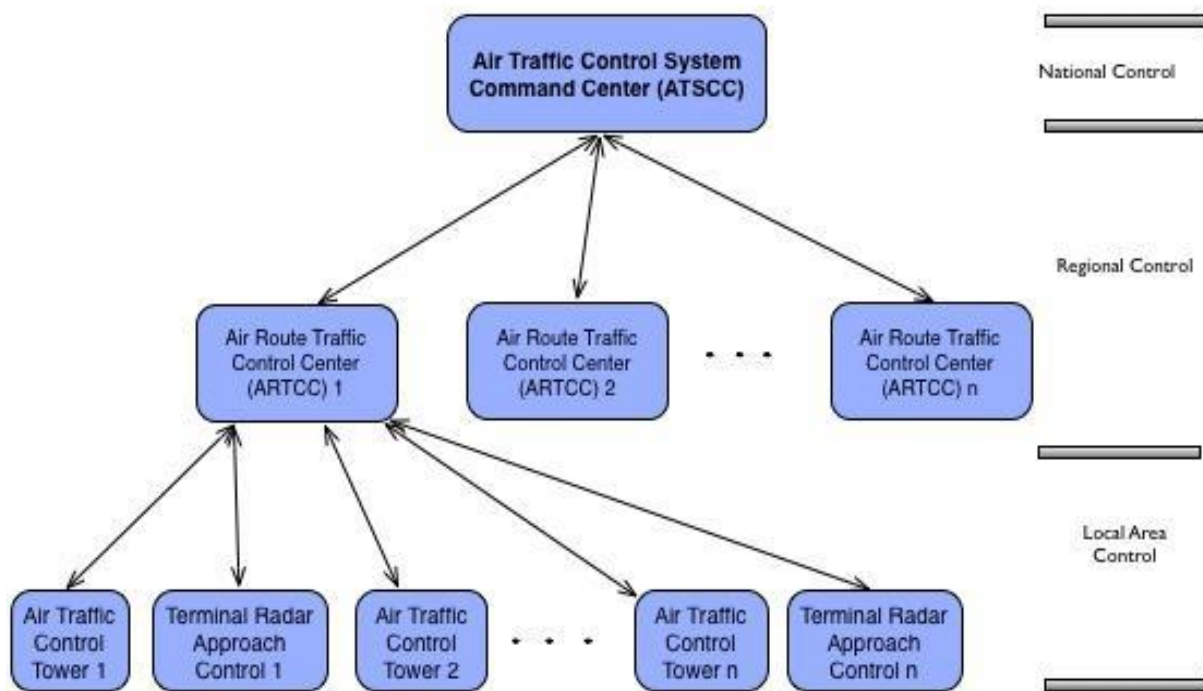


Figure 3.3 Air Traffic Control Organisational Structure (US)

The main participants or collaborators of the ATC organisation structure in the US are [67]:

- **Air Traffic Control System Command Centre (ATSCC)** – Provide oversight to air traffic management personnel. It has the final authority for all national management initiatives and is also responsible for resolving inter-facility issues. It also acts as a point of contact with customers for providing real-time air traffic management issues on a daily basis [68].

- Air Route Traffic Control Centres (ARTCC) – ARTCC coordinate with ATSCC to relay information on system demand and air traffic management initiatives. They are responsible for controlling air traffic over a large territory. Primary responsibility is sequencing of aircraft between waypoints.
- Terminal Radar Approach Control (TRACON) – TRACON exists at busy airports as a buffer between ARTCC and control tower. It handles air traffic operating in departure or approach phases of flight.
- Air Traffic Control Tower (ATCT) – It typically controls traffic immediately prior to landing or take-off within 10 miles of the facility. It performs specific tasks such as monitoring traffic, ensuring traffic separation and granting clearances for landing or take-off.

The implementation of this pattern in the current air transportation system depends on the national airspace region being managed and the various characteristics of the operating airspace i.e. air traffic density, controlled airspace volume, type of air traffic encountered. Also, the implementation of this pattern will vary based on the future demands of the national airspace. The increase in air traffic volume and the advent of new technologies in aviation would give rise to migration of air traffic controllers role from tactical control to strategic management.

The National Airspace System in US is managed by the Federal Aviation Administration (FAA). The FAA organisation structure comprises of an Air Traffic Control System Command Centre (ATCSCC) that manages air traffic demand with system capacity. The US national airspace is divided into 22 regional sectors, each controlled by an Air Route Traffic Control Centre (ARTCC) [69]. Every regional sector or ARTCC region is further partitioned into between 20 to 80 local sectors depending on the air traffic density and airspace volume. Each of these is controlled by a combination of Terminal Radar Approach Control (TRACON) or/and Air Traffic Control Tower (ATCT) [69]. Additionally, there are 15 local flight services stations (FSS) in the US and 61 Automated FSS.

Europe

This is a generic architectural pattern of an air traffic control organisation structure for monitoring the overall air traffic flow in the National Airspace System. This pattern enables to manage, organize and communicate between various control authorities in the air traffic control organisational structure, in order to provide traffic separation services to air traffic participants. The constituent parts and their control hierarchy are as shown in Figure 3.4.

The main capabilities of this architecture pattern are:

- Air Traffic Control service is provided by ground controllers who safely separate aircraft on the ground and through controlled airspace and can provide advisory messages to aircraft in uncontrolled airspace.
- In Europe, the control hierarchy is organised without a single Air Traffic Control Command Centre unlike US.
- European airspace is divided into cross-border sectors extending over a multinational airspace.
- European airspace is fragmented according to national borders rather than traffic flows.
- In each European nation, the control authority in the national airspace system is currently organised hierarchal with many Area Control Centres responsible for air traffic control in large airspace regions and each of those regions subdivided into aerodrome air traffic control services at airports [70].

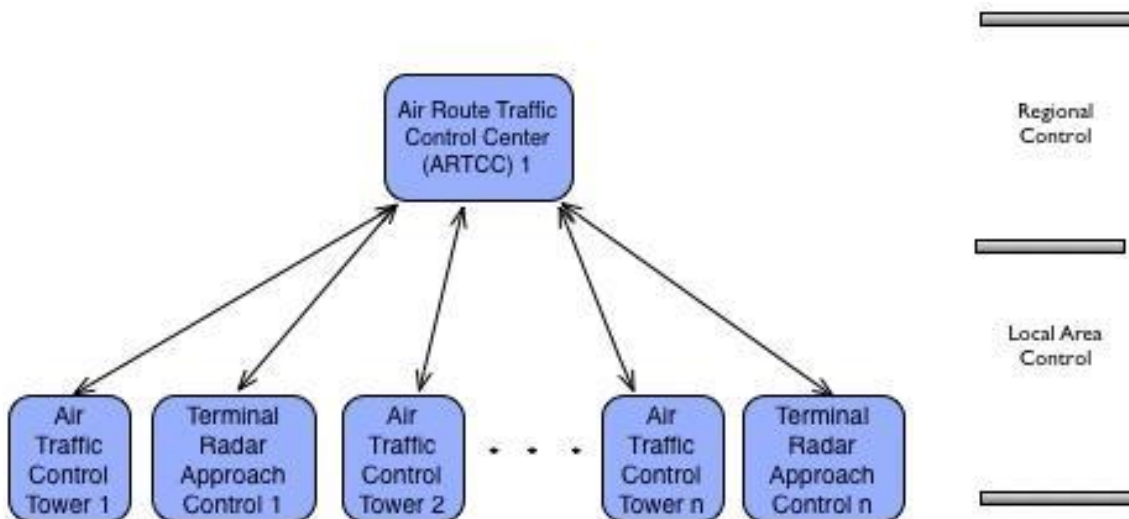


Figure 3.4 Air Traffic Control Organisational Structure (Europe)

The main participants or collaborators of the ATC organisation structure in the US are [67]:

- Area Control Centre (ACC) – They are responsible for controlling air traffic over a large territory. Primary responsibility is sequencing of aircraft between waypoints. There were more than 60 Air Traffic Control Centres in Europe before the transition towards Single European Sky programme.
- Terminal Radar Approach Control (TRACON) – TRACON exists at busy airports as a buffer between ARTCC and control tower. It handles air traffic operating in departure or approach phases of flight.
- Air Traffic Control Tower (ATCT) – It typically controls traffic immediately prior to landing or take-off within 10 miles of the facility. It performs specific tasks such as monitoring traffic, ensuring traffic separation and granting clearances for landing or take-off.

The implementation of this pattern in the current air transportation system depends on the national airspace region being managed and the various characteristics of the operating airspace i.e. air traffic density, controlled airspace volume, type of air traffic encountered. Also, the implementation of this pattern will vary based on the future demands of the national airspace. The increase in air traffic volume and the advent of

new technologies in aviation would give rise to migration of air traffic controllers role from tactical control to strategic management.

The national airspace in United Kingdom is managed by NATS (formerly National Air Traffic Services Ltd.), a public/private partnership, who are regulated by Civil Aviation Authority (CAA) [71]. The majority of activities in controlled airspace are managed from two air traffic control centres.

3.5.2 Airspace Classification Structure

The airspace classification structure aims to provide a high degree of safety and efficiency in the national airspace system. The pattern enables the management of air traffic safely and efficiently in the national airspace system, through an international standard of airspace classification system that controls the access of aircrafts into different flight regions.

The various capabilities of this architecture are:

- The airspace classes are fundamentally defined in terms of flight rules and interactions between aircraft and Air Traffic Control (ATC).
- Ensures separation between aircrafts to avoid collisions by requiring aircrafts to fly at different flight levels, directions or by controlling an aircraft's speed.
- Enables aircraft operation under different flight rules, Visual Flight Rules (VFR) and Instrument Flight Rules (VFR).
- Permission to fly in certain airspace regions where air traffic services are available has to be granted by ATC in order for pilot to proceed under certain conditions.
- The air traffic services provided and flight requirements vary for each airspace type.

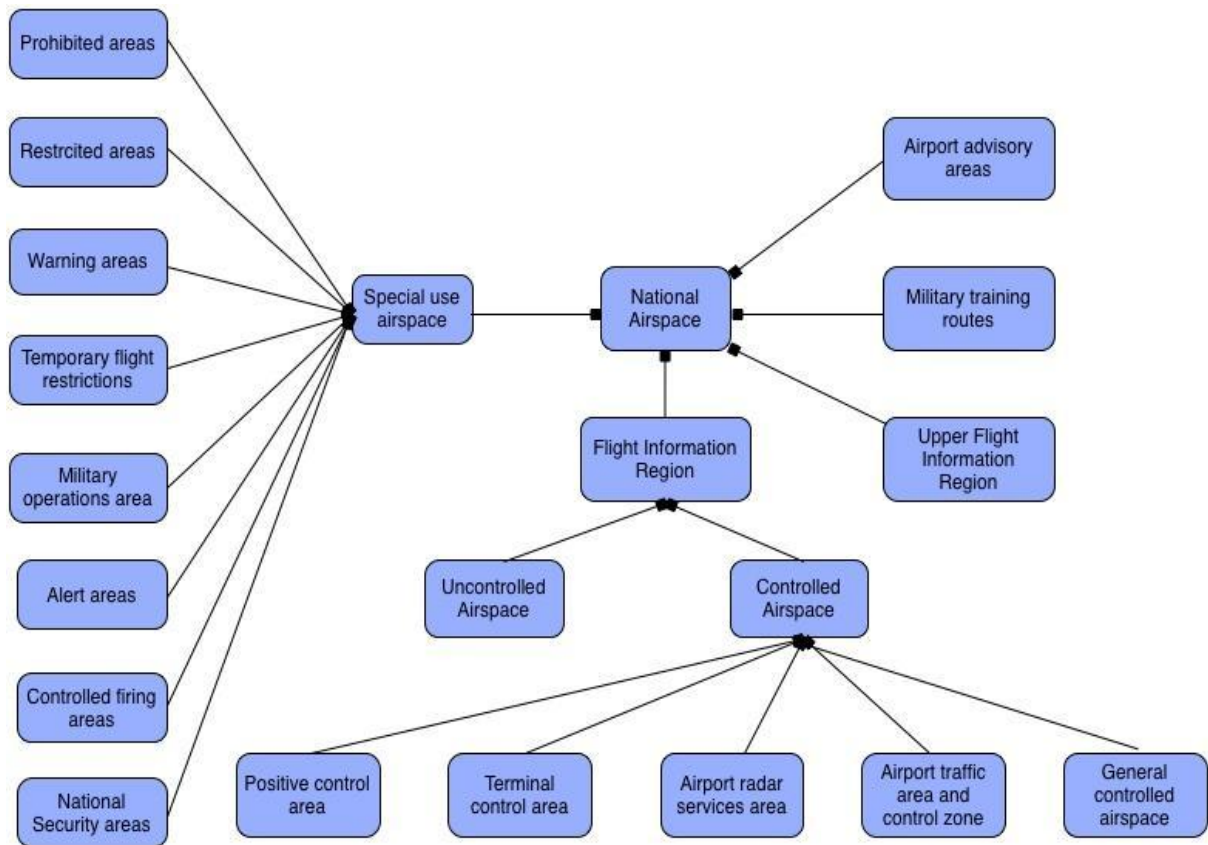


Figure 3.5 Airspace Classification Structure

The main regions/areas into which the airspace can be classified are [67]:

- Flight Information Region (FIR) – For organisation and management purposes, national airspace is divided into flight information regions. The division of FIR's of a national airspace varies among countries depending on volume of airspace, number and kind of air traffic movements expected in the national airspace. The FIR's are divided into different airspace type based on the ICAO airspace classification system. In the current ATM structure, the airspace is classified based on the air traffic services provided in it and on the meteorological conditions needed for visual flights. The airspace can be divided into basic types based on function of air traffic control in the airspace limit:
- Controlled Airspace: Controlled airspace is one in which air traffic control has executive authority over the aircraft flying in this airspace. The level of control exerted by air traffic control varies with different classes of airspace. Controlled airspace generally exists in regions where there is high-volume of air traffic

i.e.in the vicinity of airports during take-off and approach of aircrafts, and also at higher altitudes once aircrafts have climbed to cruise phase of flight.

According to the Annex 11 rules of the ICAO, the airspace is classified into five classes ranging from A to G, with Class A being most restricted and G being the least controlled. The ICAO provided a clear basis for different airspace classes in the airspace; however, the classification does not provide advice on location of each category in the airspace structure. The national regulations are responsible for the location of vertical and lateral limits of airspace categories within their countries airspace, because it may differ significantly for each nation

- Uncontrolled airspace: In this airspace, the air traffic control does not have executive authority, although it may provide advisory services to aircraft which are in radio contact. Aircrafts operating in uncontrolled airspace generally are conducted under VFR; however, some countries also allow IFR in uncontrollable airspace. IFR flight carried in uncontrolled airspace should not expect separation services from other air traffic, however advisory separation messages 'as far as practically possible' might be provided in certain uncontrolled airspace areas.
- Upper Flight Information Region (UFIR) – The airspace above the FIR is known as UFIR. The vertical separation between the FIR and UFIR in many countries such as UK, Spain, US is established at flight level FL 245.
- Special Use Airspace - Special use airspace consists of that airspace wherein activities must be confined because of their nature, or wherein limitations are imposed upon aircraft operations that are not a part of those activities, or both. Operations within special use airspace are considered hazardous to civil aircrafts operating in the area. Consequently, civil aircraft operations may be limited or even prohibited, depending on the area. Special use airspace is further divided into:
 - Prohibited - Areas where the flight of an aircraft is not permitted for reasons of national security. These areas are designated as prohibited areas and are depicted on aeronautical charts.
 - Restricted - In certain areas, the flight of aircraft, while not wholly

prohibited is subject to restrictions. These designated often have invisible hazards to aircraft, such as artillery firing, aerial gunnery, or guided missiles. Aircraft operations in these areas are prohibited during times when it is “active.”

- Warning - A warning area contains many of the same hazards as a restricted area, but because it occurs outside of national airspace, aircraft operations cannot be legally restricted within the area.
- Alert - Alert areas are shown on aeronautical charts to provide information of unusual types of aerial activities such as parachute jumping areas or high concentrations of student pilot training.
- Military Operational Area - Military operations areas (MOA) are blocks of airspace in which military training and other military manoeuvres are conducted. MOA's have specified floors and ceilings for containing military activities.

3.5.3 Air Traffic Surveillance

Surveillance is an integral part of the ATM infrastructure. The primary objective of the surveillance service is to provide a comprehensive and accurate picture of actual air traffic to ensure safe separation and efficient air traffic flow. The aircraft positional data acts as a primary means of surveillance of aircraft for the efficient provision of Air Traffic Control. The main function of ATM surveillance is to observe a region or area of airspace for the purpose of detecting aircraft or other air targets in that area of airspace. The tracking position and movement of aircraft or air targets in the area of airspace operating under, is used to enable the Air Traffic Control to maintain safe and efficient air traffic flow. The surveillance systems in the past and presently have relied primarily on ground based radar systems. However, there are other new technologies which have emerged in the last few years.

This is a generic architectural pattern of air traffic surveillance mechanism used by air traffic management systems to detect and track all aircrafts during all phases of their flight. The primary objective of the air traffic surveillance system is to provide a comprehensive and accurate picture of actual air traffic to ensure safe separation and

efficient air traffic flow.

The main capabilities of the air traffic surveillance architecture are:

- It provides the ability to accurately and reliably determine the location of aircraft.
- Surveillance systems detect aircraft and provide an accurate estimate of altitude, position and identity information of aircraft to the air traffic control system allowing the air traffic controllers to safely guide the aircraft.
- They also provide the ability to detect and monitor aircraft movements as well as other vehicular movement on the aircraft's surface to prevent runway incursions.
- At smaller airports having less air traffic movement, air traffic controllers use visual observations to detect airport surface movements on runway. In larger airports due to more air traffic movements, surveillance sensors are used by air traffic controllers to supplement visual observations.

The air traffic surveillance mechanism can be broadly classified into different types based on the capabilities of the surveillance sensors deployed as follows [72]:

- Dependant Surveillance – This is a surveillance type in which the position of aircraft is determined by aircraft data derived from on-board transponder.
- Independent Surveillance – This is a surveillance type in which the aircraft position is measured from the ground.
- Non-cooperative surveillance – The aircraft position is derived from measurement from a surveillance sensor not using the cooperation of remote aircraft. An example is a system using a ground based Primary Surveillance Radar (PSR) which determines the aircraft location but not the identity or any other aircraft derived data.
- Cooperative Surveillance – The position of air craft is derived from measurements from a surveillance sensor which cooperates with the remote aircraft to obtain this information from aircraft derived location data or through aircraft data transmissions from on-board transponder. Cooperative surveillance requires aircraft to be equipped with a transponder. Examples of such system are Secondary Surveillance Radar (SSR), Wide-Area Multi-

lateration (WAM), multi-lateration and Automatic Dependant Surveillance Broadcast (ADS-B).

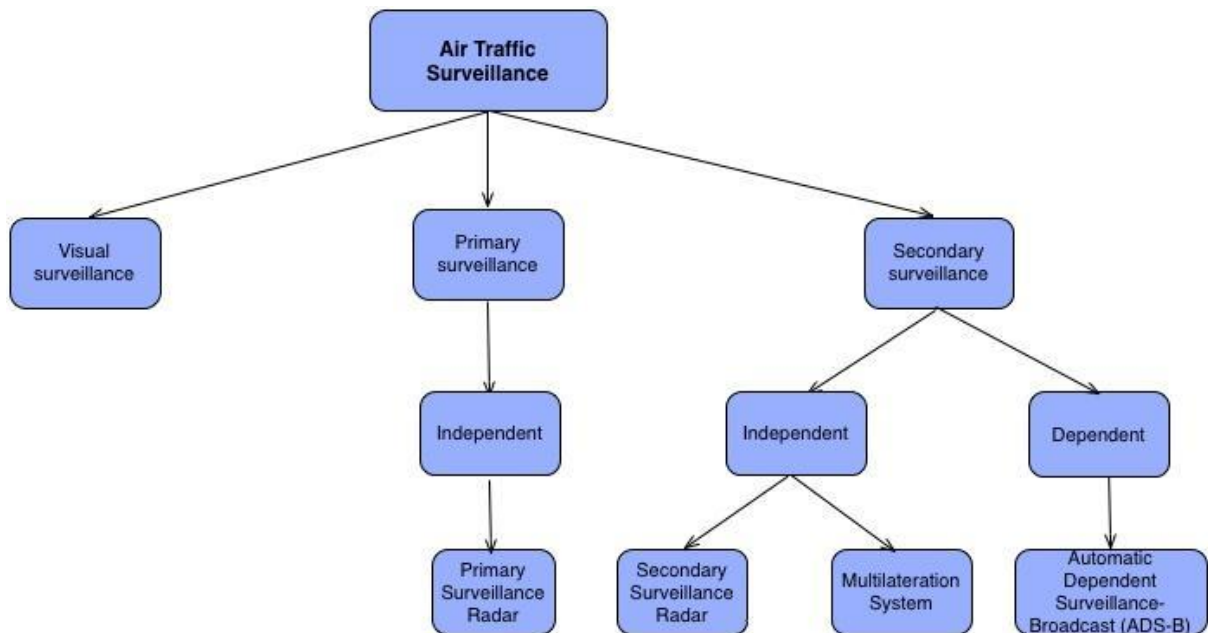


Figure 3.6 Air Traffic Surveillance

Air Traffic Management Non-Cooperative Surveillance

This is a generic architectural pattern of air traffic surveillance mechanism used by air traffic management system to detect and track all aircraft. The structure enables the detection and tracking of all aircraft's irrespective of whether they carry transponders, predominantly through the use of primary surveillance radar as well as other surveillance technologies. This will enable the ATC to have a complete air surveillance picture, thereby ensuring a secure and safe airspace.

The capabilities of this architecture are [73]:

- The non-cooperative surveillance architecture enables for detection and tracking of target aircraft independently i.e. no interrogation reply required from aircraft to provide a radar return.
- Non-cooperative surveillance carried out through the use of primary radar technology predominantly along with other technologies, presents a complete

air traffic picture to ensure security and safety of airspace regions especially at high airspace density regions or major airports.

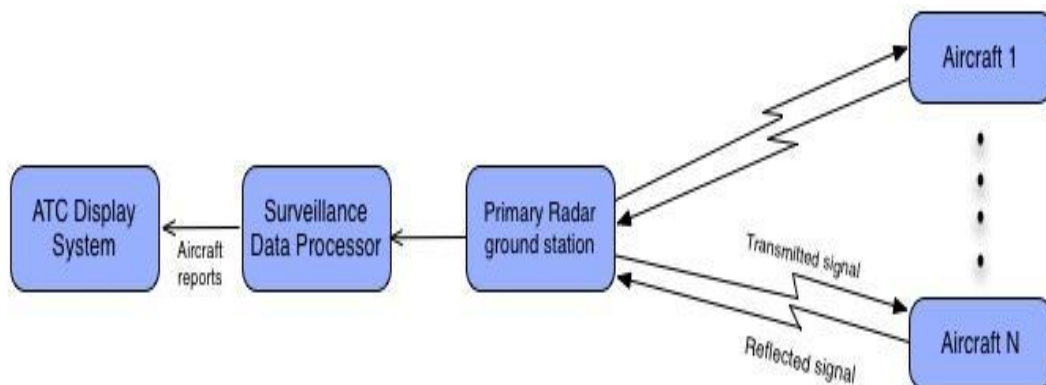


Figure 3.7 Air Traffic Management Non-Cooperative Surveillance

There are a few limitations of this architecture and they are:

- Primary Surveillance Radar does not provide aircraft identity and altitude. Although some primary radar has height finding capability but there are too expensive for civil ATC use and have poor altitude accuracy for civil aviation needs.
- Detection range is restricted by high transmitter power requirements and direct line-of-sight view of aircraft. Thus, restricted by terrain and obstacles surrounding the region where radar is installed.
- The performance of the primary radar can be affected by weather and ground clutter.
- It can often report false targets (such as windmills, ground vehicles, weather, birds etc.).

Air Traffic Management Cooperative Independent Surveillance

This is architectural pattern of a type of air traffic management surveillance system for identifying and locating positions of aircrafts in the airspace. The pattern enables the surveillance of aircrafts in an airspace coverage area thereby providing position and identity of aircrafts to the air traffic controllers. The surveillance mechanism is based on a cooperative system which implies that only aircrafts equipped with transponders are detected and controlled. The high integrity position and identity information of aircrafts provided by surveillance mechanism has increased safety and efficiency of

air traffic flow in the airspace especially in high density regions. Cooperative independent surveillance has been a principal component of ATC surveillance and is expected to remain so in the future.

The main capabilities of this architecture are:

- The transponders on the aircraft respond to ground interrogations from ground radar. The two-dimension information determined by ground radar and aircraft position as well as identity provided the aircraft together give high integrity position information of aircraft location to air traffic controllers.
- The two-way directional flow of information between ground station and aircraft enables additional information from aircraft to be used by advanced ATC automation tools to alert pilots of aircraft separation violation and other alerts. This in turn allows improved capacity and efficiency of air traffic flow safely in the airspace especially in high density traffic regions.

One of the main limitations of cooperative independent surveillance architecture is that it requires target aircraft to carry transponder. Hence when used as only ATC surveillance means, the aircraft not carrying any transponder cannot be detected. This increases the security risk and also negatively impacts safety of other airspace users especially in medium and high air traffic density areas.

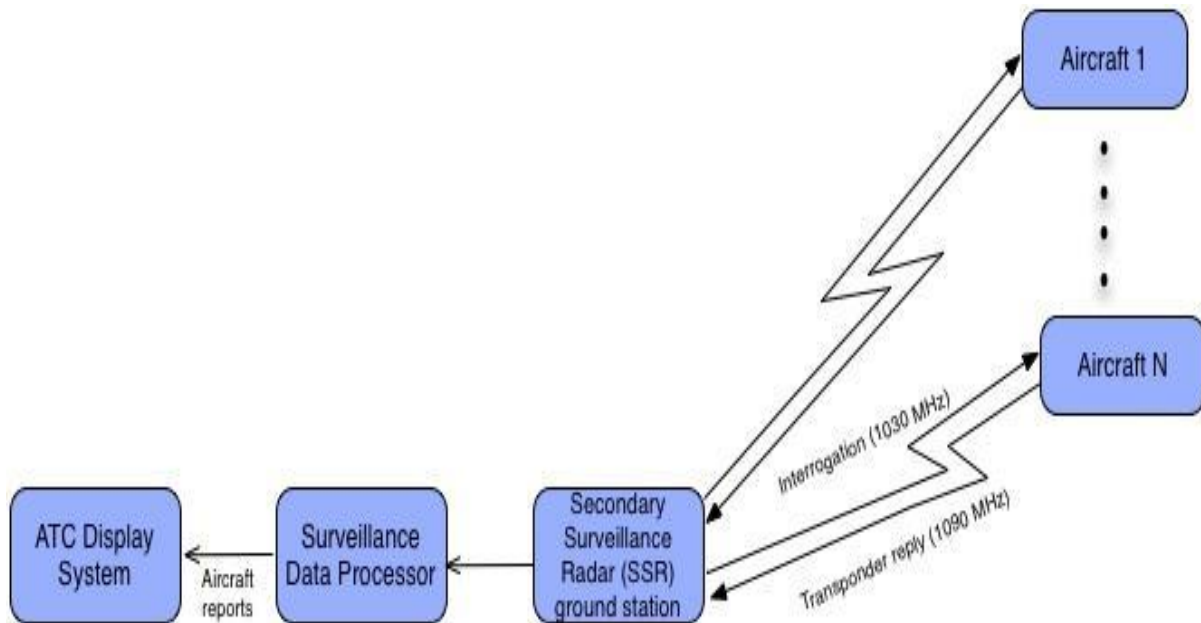


Figure 3.8 Air Traffic Management Cooperative Independent Surveillance

Air Traffic Management Cooperative Dependent Surveillance

This surveillance architecture pattern provides a mechanism for aircrafts to broadcast their position information periodically, enabling them to be detected and tracked by air traffic control and other surrounding aircraft. This surveillance architecture is an integral part of future ATM development initiatives and considered vital in ensuring the standards of safety and efficiency are maintained or even enhances as envisaged. This surveillance mechanism is set to replace secondary surveillance radar as the primary surveillance method for air traffic control worldwide in the future.

The various capabilities of this architecture are [74]:

- This surveillance mechanism is based on a cooperative system, which implies that only aircraft's equipped with transponders are detected and controlled by ATC.
- Automatic Dependent Surveillance - Broadcast is a cooperative surveillance technology which uses this architecture to broadcast an aircraft's position periodically.
- It allows ATC to monitor and control aircrafts with greater precision and over large areas of coverage on earth's surface which was not possible before.
- As well as position, aircraft also broadcast other information such as altitude,

speed and aircraft identity.

- The broadcasted position and other information is received and presented to air traffic controllers.
- The broadcast information is received, processed and presented to air traffic controllers so as to provide an air traffic picture.
- The ADS-B data broadcast by aircraft can also be received by other aircraft's, thereby enabling the pilot to view traffic information and other surrounding aircraft's.
- Unlike conventional radar ADS-B can operate at low altitudes and on the ground, thus vehicles equipped to transmit ADS-B data can be used to monitor traffic on the runways and taxiways of an airport.
- This surveillance technology is developed and certified as a low-cost replacement for conventional. The ground receiver stations are significantly cheaper to install and operate as compared to conventional radar systems.

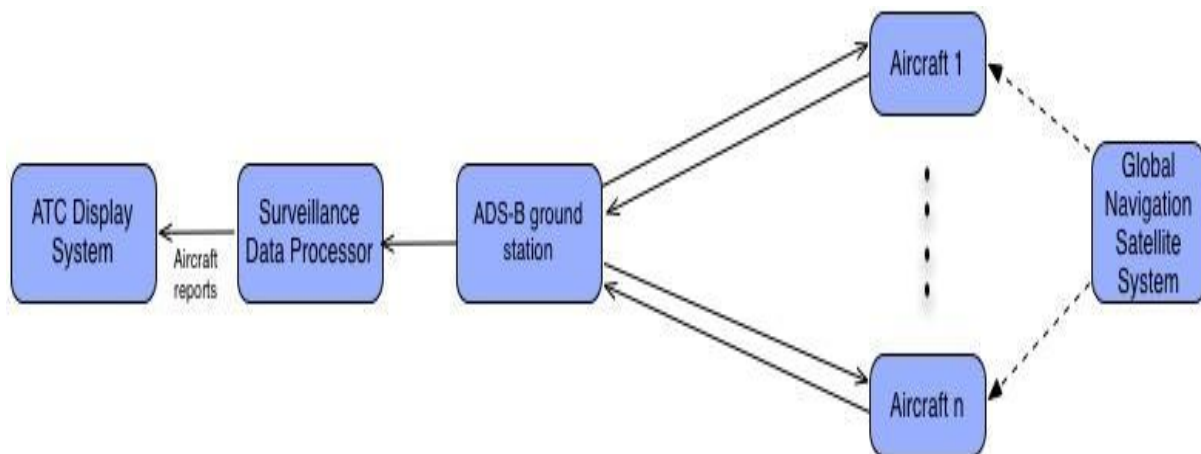


Figure 3.9 Air Traffic Management Cooperative Dependent Surveillance

One of the main limitation of this surveillance type is the integrity of the position information can be affected as the position information is derived from the global navigation satellite system. Hence any disruption in the satellite system can affect the accuracy and precision of position information thereby adversely impacting the safety and efficiency of the national airspace system.

The main collaborators of this architecture are:

- The aircraft determines its position information from Global Navigation Satellite System and broadcast it every second. ADS-B 'Automatic' refers to the fact that it requires no external input or pilot input.
- ADS-B has two different services, ADS-B IN and ADS-B OUT. ADS-B IN is the reception of FIS-B data, TIS-data and ADS-B data from other surrounding aircraft's. FIS-B and TIS-B surveillance mechanism are defined in separate patterns for each in the patterns database [75].
- ADS-B OUT provides a means of automatically broadcasting information periodically from aircraft equipped with this capability such as current position, altitude, velocity and identification, through an on-board ADS-B transponder. The ADS-B ground stations receive the ADS-B data, process and send it to be presented to air traffic controllers on a display screen. Thus, providing an air traffic picture of all aircraft's in the surrounding airspace thereby improving the situation awareness, of air traffic controllers.

Air Traffic Management Cooperative Independent Surveillance (Multi-lateration System)

This surveillance architecture provides a mechanism for detection and tracking of aircraft's over large areas such as airport approach and en-route areas through the use of multi-lateration techniques, for use by ATC to separate air traffic safely and efficiently in the national airspace. Multi-lateration system is an emerging solution to replace the secondary surveillance radar as the primary surveillance method for air traffic control in the future ATM system. Automatic Dependent Surveillance Broadcast (ADS-B) and Wide Area Multi-lateration (WAM) are key enablers of the future ATM network to achieve performance objectives such as capacity, safety, efficiency and environmental sustainability.

The capabilities of this architecture are:

- This surveillance mechanism is based on a cooperative system which implies that only aircrafts equipped with transponders are detected and controlled.

- This is a system that uses the aircraft transponder signals (Mode A/C, Mode S or ADS-B) signals to calculate an aircraft position in two dimensions or three dimensions.
- This system is based on the principle of multilateration, which comprises of several ground stations that receive the signals emitted by the aircraft transponder.
- The aircraft transponder signals are either unsolicited/unsynchronised squitters or responses (conventional Mode A/C and Mode S) to the interrogations from ground station of a multi-lateration system.
- Aircraft localization is performed by the Time Difference of Arrival Technique (TDOA) technique at the multi-lateration processing centre.
- Multi-lateration systems were initially deployed for airport surface surveillance, however they are also being used for airport approaches (MLAT) and for en-route surveillance (Wide Area Multi-lateration).
- Multilateration systems can be defined as being either passive or active systems. A passive system requires only ground-based receivers. It relies on other sources to trigger transmissions from aircraft. Whereas active systems require ground-based receivers and at least one interrogator. This system can trigger transmissions from aircraft using one or many interrogators depending on the coverage area requirements.
- Wide Area Multilateration (WAM) system is more accurate and can provide high update rate once per second as compared to conventional Secondary Surveillance Radar (SSR).
- WAM system comprises of multiple non-rotating sensors that are less affected by terrain or weather. Thereby providing surveillance coverage to remote and challenging areas as well as consistent, highly available surveillance capability.
- The capability of WAM system to detect both transponder and ADS-B out signals makes the technology an ideal solution for enhanced surveillance at present while also be operational during transition to ADS-B technology in the future.

However, there are few limitations with WAM system when used for air traffic surveillance purpose and they are:

- Multi-lateration can be costly when deployed for surveillance coverage of large regions. Due to the number of sensors and numerous sites required to install the sensors, this may lead to high infrastructure costs.
- For surveillance coverage over large regions, the complexity of the system to manage also increases. As the multi-lateration system will comprise of multiple interrogation stations and receiving stations, hence synchronization across the system is necessary to get accurate and highly reliable aircraft localization information.

One of the key collaborators of the WAM system architecture is a centralised processing centre which is referred to as Multi-lateration Processing Centre. The main objective of the multi-lateration central processing centre is to determine aircraft's position from the time difference of arrival (TDOA) of the aircraft's transponder signals at the various ground receiving station antennas. The TDOA between each receiving antenna pair corresponds mathematically to a hyperbolic surface on which the aircraft is located. When four antennas (3 distinct pairs) detect the aircraft's signal, it is possible to calculate the 3D position of the aircraft by calculating the intersection of the resulting hyperbolas. The central processing centre also performs key functions such as system time synchronization, target identification, target tracking and interrogation scheduling [76].

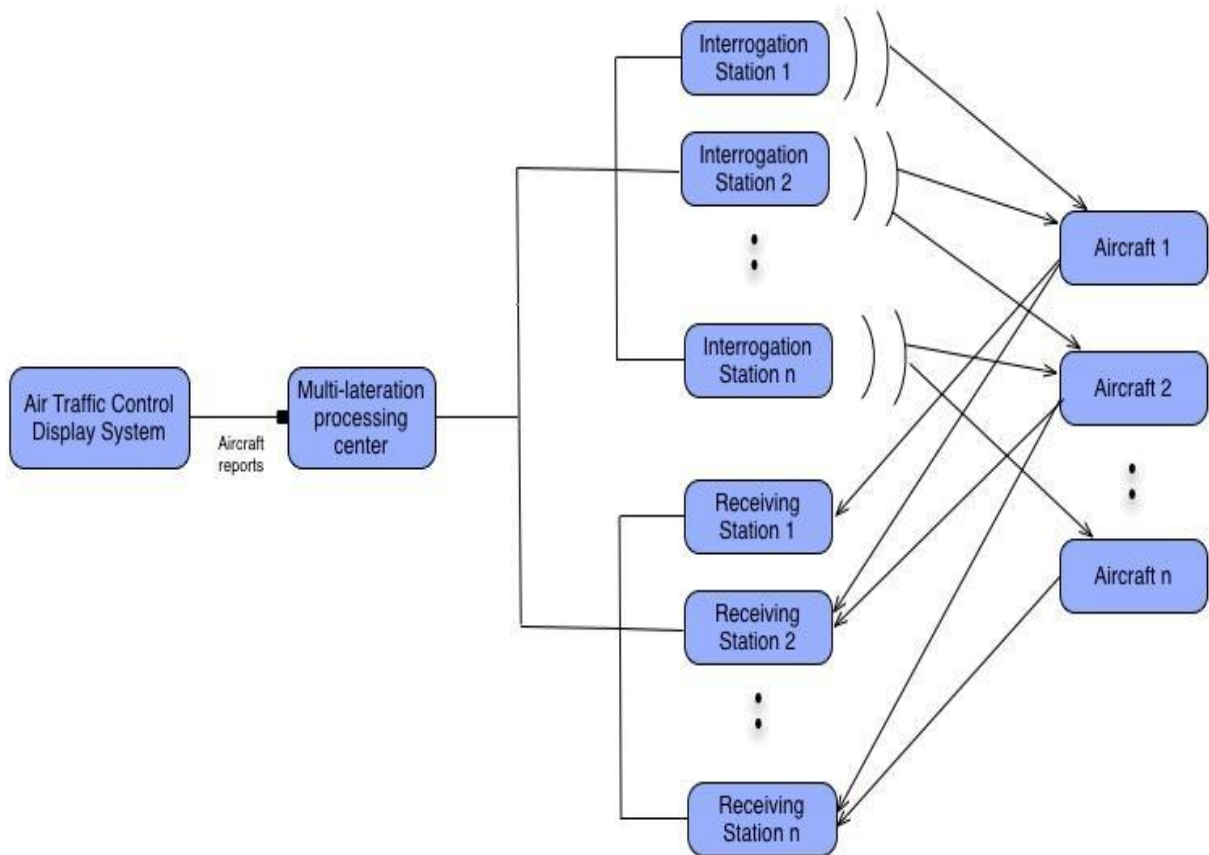


Figure 3.10 Air Traffic Management Cooperative Independent Surveillance (Multi-lateration System)

Multi-lateration system has a scalable architecture and is designed to meet the specific surveillance coverage requirements cost-effectively. This system can be implemented for use in various applications ranging from surface movement surveillance, airport approach and en-route/wide area surveillance. The configuration of the multi-lateration system is highly dependent on the terrain and environment in which the system would be deployed. To achieve highly accurate and cost-effective system, terrain and signal environment modelling have to be carried out to identify candidate sites for ground stations, in order to deploy multi-lateration system especially wide area systems.

3.5.4 Air Traffic Communication

Communication is a key element of the current ATM system and advances in

communication technologies are to be adopted in the future to support the new operational concepts which are envisaged to cope with the anticipated air traffic growth. The primary objective of the communication service is to provide a means for information exchange between the various ATM stakeholders (i.e. pilots, air traffic controllers etc.), meeting the communication capacity under an acceptable Quality of Service (QoS) requirement. In the past, voice radio communication has been the primary means of communication between the aircraft and controllers on the ground. However, in the future it is envisaged that, in order to meet the increasing demand for information exchange between the ATM stakeholders, a transition from analogue to digital communication means and technology would occur. Already digital communications (transmitting data between computers in binary signal format) have come in to use for ground-ground interaction by linking various ATC ground stations, but they have not been applied yet in the air-ground communication extensively. An exception is their use in the transmission of aircraft identity and altitude data between aircraft transponders and ATC Radar Beacon System (RBS) [77]. The aeronautical communication infrastructure can be basically characterised into two parts, the air-to-ground and ground-ground communication also referred to as mobile and fixed communication [78].

This is a generic architectural pattern of radio communication that is presently used for communication between the air traffic control centre and the aircrafts widely. The pattern enables the transmission of voice messages from air traffic controllers to pilots to manage air traffic safely. The safe operation of air traffic management system depends on a reliable and accurate means of communication between air traffic controllers and pilots.

The capabilities of this type of communication architecture are:

- Enables two way communications between air traffic controllers and pilots.
- A discrete frequency used by the transceiver system.
- Air Traffic Controllers can transmit instructions, procedures or clearances to pilots for separating air traffic through verbal communication.
- Enables pilots to verbally communicate with Air Traffic Controllers.
- Each radio transmitter performs half duplex communication, where each entity

can communicate to the other but not simultaneously. The communication is one direction at time.

The limitations of this communication architecture are:

- Radio frequency congestion can occur quite often in busy sectors when many aircraft attempt to communicate with an air traffic controller.
- Voice communication between pilots and air traffic controllers are prone to miscommunication and errors which may lead to adversely impacting the safety of the airspace.

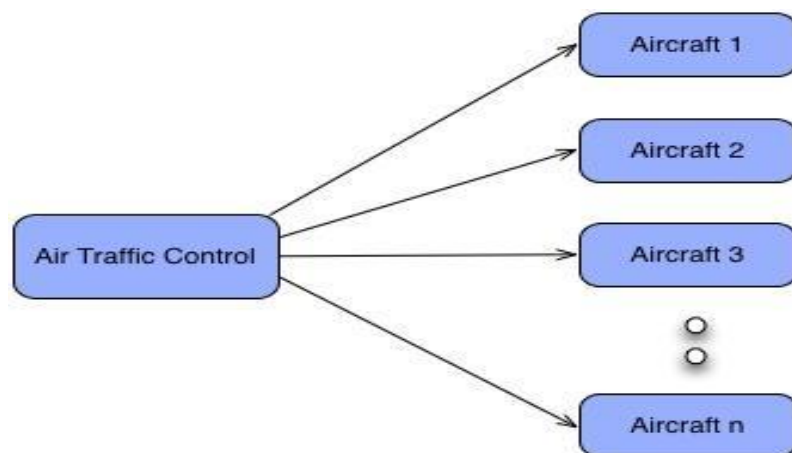


Figure 3.11 Duplex Radio Communication

The range from 118 MHz to 137 MHz in the Very High Frequency (VHF) has been allocated by International Civil Aviation Organization (ICAO) for radio communications between air traffic communications between air traffic controllers and pilots. ATC voice communication is via voice channels with a frequency spacing of 25 KHz or 8.33 KHz and uses [79]. Oceanic flight use HF (High Frequency) band for voice communication with ATC, using the long-range communication property of this frequency band. Military ATC takes place in the UHF (Ultra High Frequency) band from 225 MHz to 400 MHz [77].

To ensure that miscommunication is kept to a minimum when air traffic controllers are communicating with pilots, standard procedures and verbal phraseology have been detailed by ICAO. The communication procedures are laid down in the *Air Traffic Control Handbook* [78].

3.5.5 Air Traffic Navigation

Navigation is another integral part of the air traffic management system to ensure the safe and efficient flow of air traffic in the national airspace system. The main purpose of the navigation element of the CNS/ATM systems is to provide accurate and reliable aircraft position determination capability and also managing aircraft trajectory during all phases of flight. Navigation is a vital element for civil aviation and thereby aid to navigation was the first service provided to aircrafts by national governments when civil aviation flights began.

The air navigation aids have evolved over the decades, since the initial years of civil aviation when ground beacons were placed for visual guidance of pilots along the airmail routes. In the 1930's, the US Post Office replaced the ground beacons with a system of low-frequency radio navigation beacons along the airmail routes – namely non-directional beacons and four-course radio range stations. This essentially enabled aircraft flight at night and during times of poor visibility by guiding aviators along the air routes.

Currently, navigation during all phases of flight is provided by a large range of navigation services using conventional terrestrial systems and more recently global navigation satellite systems (GNSS). Apart from this airborne navigation capability also exists, in the form of inertial systems on-board an aircraft based on multi-sensor navigation systems. Hence a myriad of technologies exist that provide navigational aids to the pilots in order to navigate the aircraft safely under normal and poor visibility conditions safely. Dependant on the different phases of flight (En-route, approach and landing, airport surface movement), different technologies apply and the various technologies used in the current CNS/ATM architecture are briefly described below.

This architectural pattern represents the air navigation systems and aids that enable safe and efficient flight of aircrafts in the national airspace system. This pattern enables the movement of air traffic safely and efficiently in the national airspace system, through the use of technology, procedures and monitoring process to ensure that aircrafts can navigate and be guided safely and efficiently on the ground and in the sky.

The capabilities of this architecture are:

- Through the use of air navigation rules, procedures and technologies the pilots are able to plan and navigate the aircraft safely and efficiently through all phases of flight.
- Visual Flight Rules (VFR) navigation is carried out by pilots using combination of techniques, pilotage (aircraft position obtained by reading an aeronautical map and comparing it with surrounding terrain and landmarks) and dead reckoning (aircraft position obtained by using a compass, aircraft ground speed, a clock and an initial known position) .
- The air navigation technologies provide aircraft positioning and trajectory management in all phases of flight.
- Ground navigation aids act as a low-altitude navigation means with additional accuracy and reliability needed for landing aircrafts in conditions of low visibility.
- Aircraft navigation en-route is provided by a network of high frequency radio beacon system based on land. Whereas in oceanic regions, satellite based systems are used for aircraft positioning and its guidance.

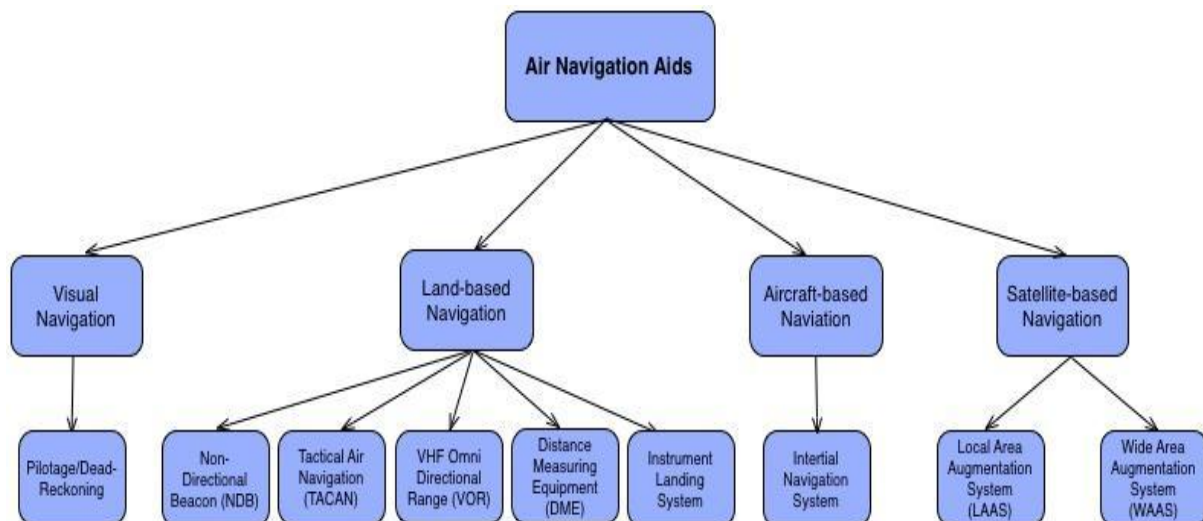


Figure 3.12 Air navigation Aids

The global air navigation system consists of several elements [67]:

- Terrestrial air navigation system – Primarily these systems are based on a

network of beacons/transmitters, which transmit signals continuously, thereby enabling the pilot of an equipped aircraft (aircraft direction finder) to navigate by determining bearings and/or by determining range from beacon while homing on the signal. The different technologies which operate on this principle in the national airspace system are shown below:

- Non-Directional Beacon (NDB) – A radio beacon system that transmits non-directional signals at low or medium frequencies ranging from 190 to 1750 KHz, enabling aircraft navigation by determining bearings.
- VHF Omni-directional range (VOR) – An Omni-directional transmitting station operating at very high frequency band between 108 to 117.95 MHz, which enables aircraft navigation by determining bearings.
- Distance Measuring Equipment (DME) – It operates based on line-of-sight principles to provide distance measuring information to aircrafts at very high level of accuracy. Operating frequency range from 960 to 1215 MHz. The DME and VOR combined together act as a primary navigation aid for civilian aircrafts for aircraft range and bearing measurement to a ground station.
- Tactical Air Navigation (TACAN) – It is specifically designed for military purposes thereby provides more accurate bearing and range measurement as compared to VOR/DME system.
- Airborne navigation system – Inertial navigation aids are used to provide long-range global navigation information to the pilots independent of external navigation aids. It acts as a backup in the event of loss of navigation signals from other external navigation aids.
- Satellite based system – En-route navigation is provided predominantly by ground based navigation aids. However global navigation satellite systems (GNSS) have been used for en-route navigation in the recent years especially as an oceanic air navigation service capability. The GNSS that is widely used is Global Positioning System (GPS). Other GNSS that are used / deployed soon for commercial use are Russia's GLONASS and the European Galileo system.
- Approach/Landing system - The landing//approach aids are primarily used under low visibility conditions when visual landing procedures cannot be

followed by pilots. The Instrument Landing system is the standard system widely used for navigation of aircrafts during their final approach to landing. The main components of a ILS and their functions are:

- o Localiser – Provides directional guidance in the horizontal plane along the extended runway central line. It transmits on a frequency between 108.10 and 111.95 MHz in VHF band.
- o Glide Path – provides directional guidance in the vertical plane along the extended runway central line. Glide path transmitters emit signals at UHF frequencies between 329.15 to 335 MHz.
- o Marker beacons – It provides the pilot of an indication of range information from the runway threshold while on final approach to landing.

Satellite-Based Augmentation System (SBAS)

The future air navigation system is aimed at providing flexibility in airspace navigational capabilities to aircraft in order to absorb the increase in air traffic flow in the future without having a detrimental impact on safety and efficiency of the national airspace [80]. This pattern aims to provide airspace users positioning and timing services with required accuracy, integrity, continuity and availability necessary to rely on satellite navigation system for all phases of flight, from en-route through to approach for all airports within the satellite navigation system coverage area. This type of system refereed by ICAO as Satellite-Based Augmentation System (SBAS) are an integral part of the worldwide effort to reduce dependency on ground-based infrastructure and leverage the precision and accuracy provide by satellite based technologies.

The main capabilities of this architecture are:

- The primary objective of the satellite based navigation system is to increase safety for aviation.
- SBAS increases the navigation capabilities for all classes of aircraft in all phases of flight by improving the accuracy, integrity, reliability and availability of global satellite navigation systems such as Global Positioning System (GPS),

Global Orbiting Navigation Satellite System (GLONASS) and Galileo system [81].

- It aims to achieve compatibility and interoperability among all the SBAS systems existing/in-work such as Wide Area Augmentation System, the European Navigation Overlay Service (EGNOS), the Multi-functional Satellite Augmentation System (MSAS) and GPS aided geo augmented Navigation (GAGAN), to enable seamless air navigation service across regional boundaries.
- It enables aircraft to fly any desired flight path between one airports to another, rather than constrained airway routes based on ground navigation signals. This greatly saves fuel and time for airline operators.
- The accuracy and system integrity capability provided by SBAS systems, that is provide information on accuracy of GPS satellite information and timely warnings to users when the system is producing hazardously misleading information, allows aircraft equipped with SBAS to operate at lower en-route altitudes than was possible with ground-based systems [82].
- SBAS offers opportunity for airports to obtain approach capability similar to an Instrument Landing System (ILS) without the installation of ground based navigation system at the airport. This provides significant cost benefits for airport operators.

There are several limitations in the use of satellite based navigation system and they are:

- The uncertainty in ionosphere delay and interference effects caused due it adversely impacts the accuracy and integrity of positioning information received from SBAS system.
- SBAS is not capable of achieving approach guidance accuracies required for Category II or III Instrument Landing System (ILS) approaches. In order to provide performance measure comparable to CAT II or CAT III ILS SBAS is not the solution, it would require existing ILS systems to be maintained or replaced by new systems such as Local Area Augmentation System (LAAS).

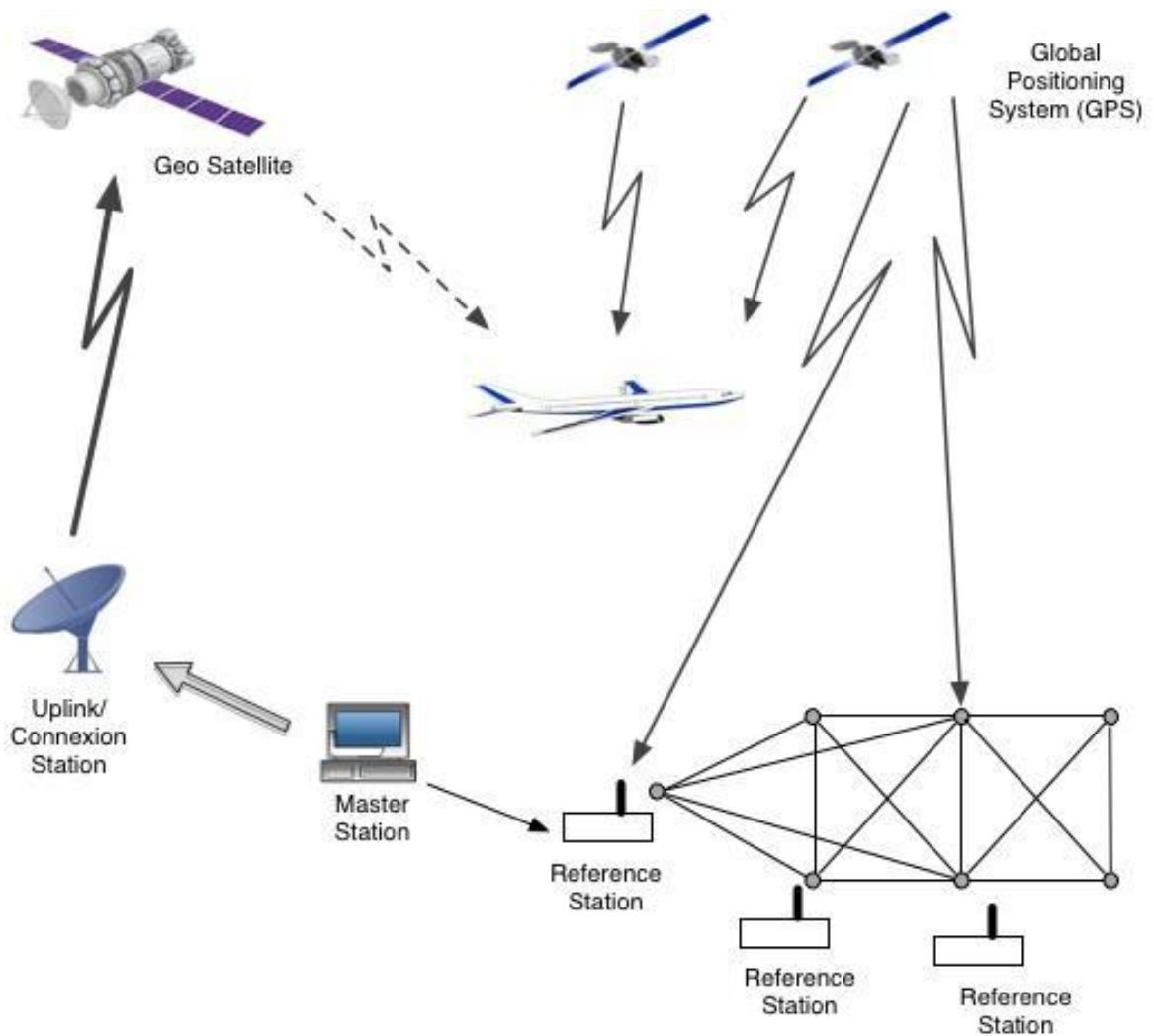


Figure 3.13 Satellite Based Augmentation System (SBAS) [67]

The SBAS system consists of several elements and they are:

- **Global Navigation Satellite System (GNSS)** – It is a system of satellites that provides precise geo-spatial location of a GNSS receiver anywhere in the world. The system enables the satellite receivers to determine their location using time signals transmitted over a large coverage area along the satellite’s line of sight. There are several GNSS systems in operation/being built such as GPS, GLLONASS and Galileo. The GNSS system aims to achieve technical interoperability and compatibility between various satellite navigation systems

in order to have a seamless global navigation service for users across regional boundaries.

- SBAS Reference Station – SBAS consists of a network of ground reference stations that receive and monitor the GNSS signals. The locations of the reference stations are precisely surveyed so that any errors in the received GNSS signals can be detected.
- SBAS Master Station – Master station removes the errors in the GNSS signal and corrections to signals are calculated, allowing for a significant increase in location accuracy and reliability. The GNSS information collected by the SBAS reference stations is forwarded to the SBAS master station via a terrestrial communications network. These messages contain information that allows GPS receivers to remove errors in the GNSS signal.
- SBAS Uplink/Connexion Station – Uplink/Connexion station transmits the SBAS augmented messages to navigation payloads on the Geostationary communication satellite.
- Geostationary Communication Satellite – Geostationary communication satellite rotate around the geostationary orbit thereby appearing motionless to observers on the ground. The navigation payloads broadcast the SBAS augmentation messages on a GNSS-like signal

3.5.6 Air Traffic Weather

Current Air Traffic Weather Service

This architectural pattern represents the structure of air traffic weather service system that provides air traffic controllers up-to-date and accurate weather information necessary to allow safe air traffic flow in the national airspace. This pattern enables to enhance the safety, effectiveness and efficiency of the national airspace system, through distributing weather forecasts and weather-related products and services to air traffic controllers that ultimately improve the pilot's awareness of weather conditions during flight in order to avoid adverse weather.

The capabilities of this architecture are [83]:

- The structure enables the traffic management specialists located in ATSCC to collect meteorological information from various sources and devise a suitable plan with air traffic facilities and airspace users to minimize the impact of severe weather on the national airspace system.
- The National Weather Service (NWS) specifically provides weather data, forecasts, advisories and warnings to support aviation community to reduce impact of adverse weather conditions.
- Through the national information database, infrastructure and meteorologists as part of the NWS, it develops forecast products that used by air traffic managers and controllers to enhance safety and efficiency in the national airspace.

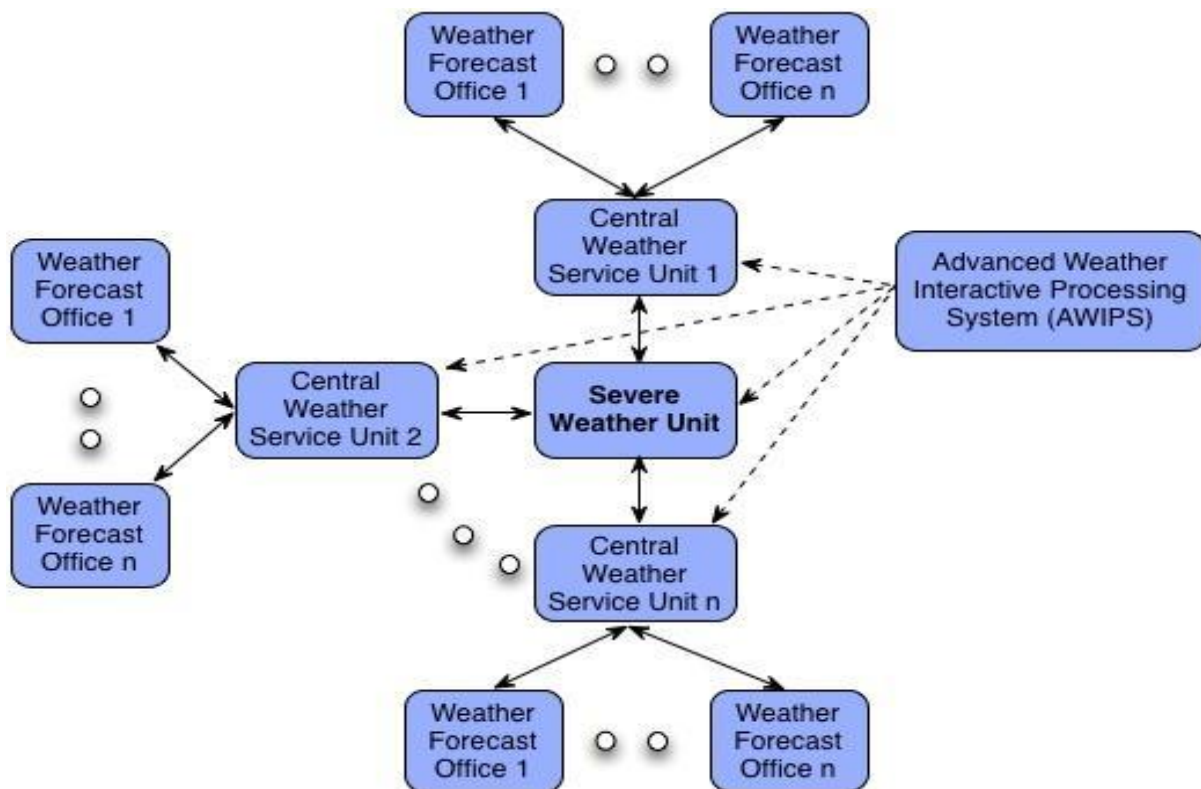


Figure 3.14 Air Traffic Weather Service

The various elements of the national weather service are [84]:

- Severe weather unit – It has the responsibility of minimising the impact of severe weather on the national airspace system. The unit is part of a national

weather service structure, located inside the Air Traffic System Command Centre. A team of traffic management specialists collect meteorological information from a variety of sources, and devise a suitable plan with other Air Traffic facilities and system users for routing traffic around the bad weather.

- Central Weather Service Unit – It is a part of the national weather service structure and is located inside each of the Air Route Traffic Control Centres. It has the responsibility of providing pertinent meteorological information for airports and airspace in the Air Route Traffic Control Centre’s area of responsibility. Each CSWU consists of onsite meteorologists to disseminate information to air traffic control area managers and occasionally to air traffic controllers directly on forecasts for weather front when it arrives in the ARTCC sectors. CSWU meteorologists also provide information directly to pilots of aircrafts in distress due to hazardous weather conditions.
- Weather Forecast Office (WFO) – It is a multipurpose local weather forecast office that produces aviation weather-related products. Each area WFOs has the responsibility for the issuance of Terminal Aerodrome Forecasts (TAFs) for airports within its control. TAFs are coded, concise 24-hour forecasts for specific airports, reviewed every six hours and amended if needed. TAFs contain aviation related weather elements such as wind shear, wind, visibility level and cloud cover.
- Advanced Weather Interactive Processing System - It is a system to replace the obsolete and expensive-to-operate Automation of Field Operation and Services (AFOS), that provides forecasters a very effective and efficient means to prepare accurate weather predictions and issue timely, highly reliable advisories and warnings. AWIPS is a high-speed technologically advanced information processing, display and telecommunication network that is cornerstone of the National Weather Service (NWS) operations. It is an interactive computer system that integrates all meteorological, hydrological, satellite and radar data into a single computer workstation. It enables weather forecasters the interactive capability to view, analyse, combine and manipulate large amounts of graphical and alphanumeric weather data. AWIPS is an

integral part of the National Weather Service enabling the provision of data and products that form a national information database and infrastructure. National Weather Service (NWS) provides weather data, forecasts and warning for the United States, its territories, coastal waters and ocean areas that can be used by public agencies, private sector, the public and the global community. The AWIPS is used by several offices of NWS to process and distribute weather products to support air traffic controllers and the national airspace system.

- Aviation Weather Centre – It is a Meteorological Watch Office (MWO) for the International Civil Aviation Organisation (ICAO). It issues following products in support of air traffic controllers:
 - Airman’s Meteorological Information (AIRMETs) – Information on surface wind speed, surface visibility, thunderstorms, severe turbulence and icing.
 - Significant Meteorological Information (SIGMETs) – Information on thunderstorms, cyclones, dust or sand storms, volcanic ash, severe icing, severe mountain waves.
- Flight Service Station (FSS) /Automated FSS – It provides pre-flight weather briefings for pilots, en-route weather, flight plan processing, relay ATC clearances and Notice to Airmen (NOTAMs). They also provide assistance to distressed pilots of aircraft and to lost aircraft, as well as conduct VFR search and rescue services.

Future Air Traffic Weather Service

This architectural pattern represents the future structure of air traffic weather service system that provides air traffic controllers up-to-date and accurate weather information necessary to allow safe air traffic flow in the national airspace. This pattern enables to enhance the safety, effectiveness and efficiency of the national airspace system, through distributing weather forecasts and weather-related products and services to air traffic controllers that ultimately improve the pilot’s awareness of weather conditions during flight in order to avoid adverse weather.

The capabilities of this architecture are:

- The structure enables common weather situation awareness and a single authoritative source of NAS weather information.
- A service oriented Architecture enterprise service provides dissemination of common weather observations and forecasts.
- Through the use Weather Information Data Base (WIDB) containing constantly updated weather observation and forecast information delivers common weather operational picture.
- It enables the direct integration of weather information into operational decision-making process.
- Weather information is translated into operational decisions for human/automated systems.
- A concept of this structure is a network enabled capability of weather observational systems so that weather data ranges from raw, quality controlled data to processed data form a single authoritative source.

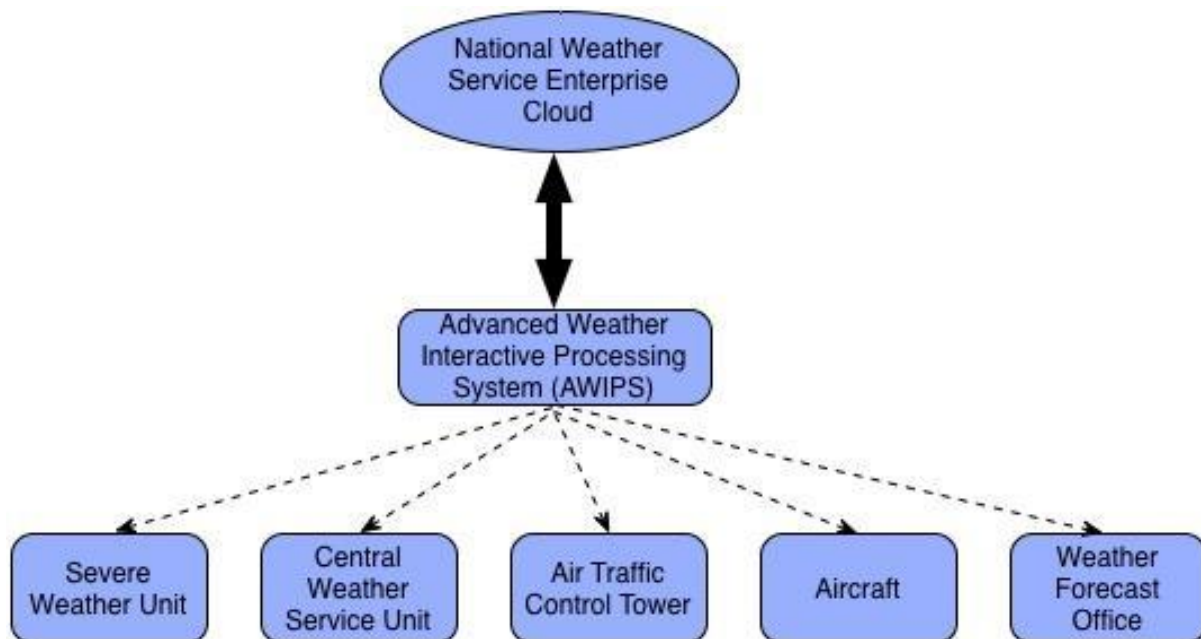


Figure 3.15 Future Air Traffic Weather Service

Advanced Weather Interactive Processing System II - It is a next-generation system

which will bring advanced functionality to weather forecasters [84]. It will also simplify code and consequently strengthen system performance while reducing the maintenance burden. All of this will be achieved while retaining a system look and feel that will make the AWIPS evolution appear similar to the user. The AWIPS II is built on service oriented architecture and based on evolution of AWIPS architecture.

3.5.7 Future Air Traffic Management Structure

The future air transportation system is based on transforming the way the National Airspace System (NAS) is managed, thereby increasing the capacity of the system to meet growing air traffic demand. The future air transport system aims to bring a transformative change in management and operation of national airspace system, through the integration of existing and new technologies, to reduce delays, save fuel and lower carbon emissions.

The capabilities of this architecture are:

- The ATC system is envisaged to change from a ground based system of air traffic to more air and space centric system that takes full advantage of advanced avionics and satellite based navigation.
- A key aspect is the transition to a net-centric model for transferring information of all types. The transformation to future air traffic management involves moving away from systems interacting point-to-point to a system based on the idea of system wide information sharing bus [85].
- Performance Based Navigation (PBN), which uses satellite-based guidance to route aircraft and improve approaches to aircrafts [86].
- Provide enhanced airborne and surface traffic management, which includes tools that help air traffic controllers merge and sequence planes in the air and on the ground.
- Shift from clearance-based to trajectory-based air traffic control that will enable aircraft to fly negotiated flight paths, taking both operator preferences and optimal airspace system performance into consideration [87].

The main collaborators in this architecture are Aircraft, Air Traffic Control System

Command Centre, Air Route Traffic Control Centres, Terminal Radar Approach Control, Air Traffic Control Tower, Navigation aids, airspace surveillance, airport airlines and Distributed system services as shown in Figure 3.16.

Distributed system services - The shared information service is implemented based on the principle of a service-oriented architecture. In the SOA model, a set of loosely coupled services that interact using standardized data models provide the basic building blocks for a modular, composable system that can be adapted over time to meet changing requirements [88].

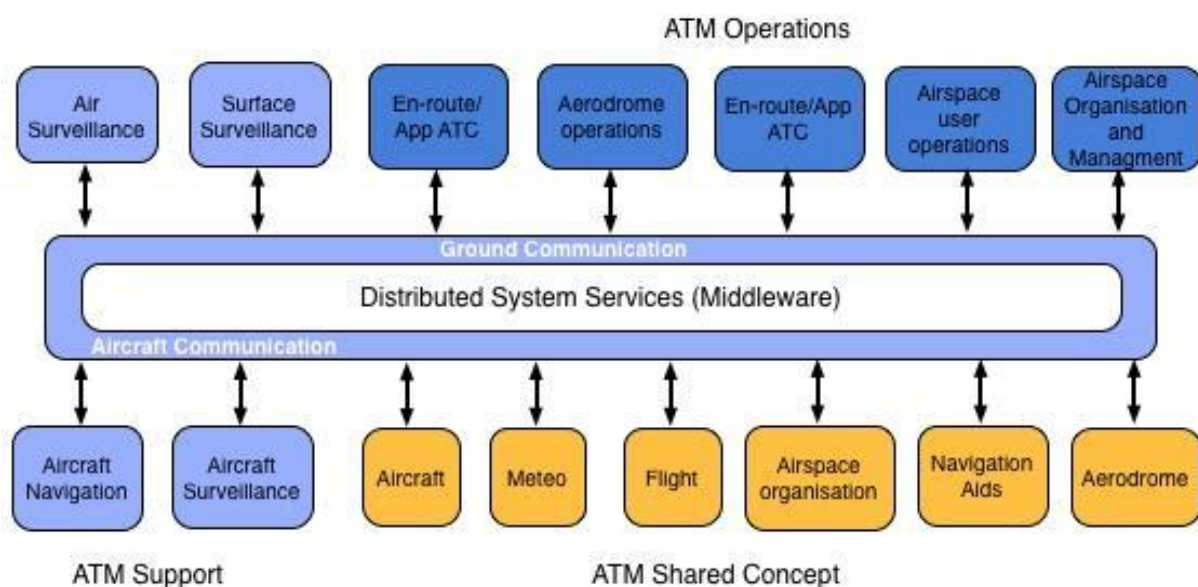


Figure 3.16 Future Air Traffic Management Structure [88]

There are two major future air transportation system initiatives carried out in US and Europe which are namely NextGen by FAA and SESAR (Single European Sky ATM Research) by EUROCONTROL. The FAA's NextGen service-oriented architecture has three primary tiers. At the lowest level, a set of core services provides functionality that is shared by all services in the network, such as security and basic messaging capabilities. In the next tier, services that are common to specific communities of interest (COIs) exist, providing, for example, higher-level building blocks for the weather community. In the highest tier the services that exist are more

application specific. These tend to be highly specialized services that provide a customized end product for a small set of end users [88].

3.6 Summary

This chapter has detailed the architecture patterns identified and extracted for ATM system to enable SoS architecting and analysis of integration of UAS into the ATM system. The key aspects to consider for the specific architecture pattern when UAS are an operational user in the ATM system. This will aid the systems architect when using the architecture patterns for SoS analysis of the ATM and integration of UAS into the national airspace system. The architecture patterns were verified by subject matter experts to ensure the key elements of the architecture were captured accurately. This chapter also gave a brief overview of what architecture patterns are, how they are captured and the validation and verification of the patterns extracted.

Chapter 4: Integration of UAS in National Airspace System – A Complex SoS problem

4.1 Introduction

The use of Unmanned Aircrafts has increased in the last decade especially in the military domain. However, both military and civil Unmanned Aircraft Systems (UAS) are currently subjected to restrictions that inhibit their operations in non-segregated airspace [1].

The current operations of UAS are allowed in certain segregated areas of the airspace only after they have acquired a Certificate of Authorization (COA) for their flight [2]. The COA is issued on a case-by-case basis and valid for a year. The COA is issued after the submission of required documentation and an analysis performed by the aviation authorities to determine whether an equivalent level of safety to a manned aircraft has been achieved [2].

Unmanned Aircrafts provide major benefits when compared to manned aircraft. Unmanned aircrafts provide typical operational abilities to perform missions that are considered “dull, dirty or dangerous” for manned aircraft [3]. The three most important capabilities achieved by operation of UA’s are; they can fly at high altitudes for several days, they can perform missions which are high risk or are considered to be dangerous to human operators, and finally they can perform the tasks at much lower costs compared to a fully piloted aircraft [4].

Although the flexible and unique operational capabilities of unmanned aircrafts provide major benefits, however these characteristics also provide unique challenges for integrating them in the current airspace environment. The whole range of sizes and shapes, different operating speeds and altitudes as well as payload carrying capability that UAS come in, will require airworthiness regulations and operating standards and procedures for ensuring safe operation of UAS in National Airspace System [5].

Apart from the certification standards and operating procedures, other major issues in the integration of UAS in non-segregated airspace that have been identified

are sense and avoid ability to avoid collisions with other aircrafts as well as obstacles in its vicinity i.e. buildings, terrain, power lines etc., UAS equipage with radios and transponders for flight in the airspace and finally pilot qualification requirements [5]. Aviation is a risk-free and safety conscious domain. Hence introducing a new form of system into this domain is a slow and difficult process since it must be introduced in such a way that it does not have any detrimental effect on the safety of the ATM system and this must be proved before allowing uninterrupted access to the national airspace environment [6].

The history of introduction of new technology has shown that the greatest obstacles have not been technical in nature but are related to their integration and acceptance to society [7]. There are many issues related to political, economic and social in nature, which govern the integration and acceptance of new technology [7]. The objective of this paper is to present that the problem of integration of UAS in non-segregated airspace is a complex system-of-systems problem with challenges that are well beyond the technical and regulatory hurdles. The paper proposes that this complex and multi-faceted problem has many characteristics similar to a wicked problem. The phrase wicked problem refers to those problems that are difficult or impossible to solve because they are not understood until after the solution is found because of incomplete, contradictory and changing requirements of problem nature [8].

The wicked problem as an analysis tool is used to perform further analysis of two-example case study in order to show approaches taken to solve the problem have not yet been adequate for such types of problems. Based on the analysis key aspects to focus on are proposed, which will support the process of integration of UAS in non-segregated airspace as viewed from a wicked problem perspective.

4.2 Wicked Problem

Even though large resources and funding have gone into solving the problem of UAS integration in civil airspace over the last decade, there has not been much progress made in terms of access of UAS into national airspace [4]. Although the actual problem seems to be one of a typical system-of-systems problem, however when looked at

closely the problem has similar characteristics to that of wicked problems. The wicked problem analogy is used to analyse the unique characteristics of the problem that make it a difficult problem to solve easily.

A wicked problem is the phrase used to describe a problem that is difficult or impossible to solve because of contradictory, incomplete and changing requirements [8]. Hence such problems are not understood entirely until after the solution is found. Rittel and Webbers formulation provided ten characteristics that best described such problems in the area of social planning [8]. Jeff Conklin in order to generalize the concept of problem wickedness into other areas had identified six characteristics of wicked problems [8].

In the previous section the systems approach was used to describe the system-of-systems view of the problem, where UAS would be part of a collection of systems operationally and managerially independent but are within the entire air transportation system. The systems approach also allows the author to analyse their competing requirements. However, beyond the competing requirements, a detailed analysis of the problem shows that the requirements are not only competing but are also contradictory and changing as well as in some instances they are incomplete. Thus, a closer look at the problem shows that the complexity involved is well beyond that for which the traditional systems engineering techniques could be used for developing a solution.

The perspectives of the major stakeholders involved are widely varied. Hence to better understand the constraints and competing requirements, the research has used the analogy of a 'wicked problem' as an analysis tool to better understand the problem. As mentioned earlier wicked problems have six generic characteristics that can be used to classify them. The design, acceptance and integration of UAS in non-segregated airspace have several common features to that of a wicked problem.

1. Problem not understood until the formulation of a solution

A characteristic of wicked problems is that every solution proposed to a wicked problem exposes new aspects of the problem, requiring further adjustments to the proposed solution. Moreover 'what the problem is' depends on who you ask – different

stakeholders have different views on what the problem is and what would be an acceptable solution [8].

This can be readily noticed in the problem of UAS integration in national airspace system. One of the solutions to sense and avoid could be to use co-operative sensors on-board the UA to be able to detect all other transponder-equipped aircrafts. However, the problem would be that the UA's would not be able to fly in VFR (Visual Flight Region), as not all aircraft are equipped with transponder in this airspace region [11]. Other problem that arises from UA required to carry transponders is that small UA's would not be able to carry such transponder, as they would have to compromise on payload capability [11]. Thus, there is no single solution to the problem that fits all classes of airspace and all types of unmanned aircrafts [5].

The UAS operators can learn and explore the various civil and state applications of UAS operations in the national airspace only when they are integrated in the national airspace. Only when UA's are allowed access to operate alongside manned aircrafts with the full extent of safety and risk assessments would be well understood. Even though a comprehensive safety assessment would be carried out before the integration process, however the various risks to the airspace cannot be fully understood as long as UAS are segregated to restricted areas of the national airspace [7].

2. Different stakeholders have different views of what the problem is and what constitutes an acceptable solution to the problem.

This characteristic is evident from the different views on the airworthiness regulations of UAS from the different stakeholders [12]. Although there has been much effort that has gone into the definition of standards for UAS, the current proposal is to apply the similar airworthiness standards to that used for commercially piloted aircraft (CPA) [12]. This default view of the authorities has been based on fact that following equivalent level of airworthiness standards will lead to equivalent level of safety (ELOS) to CPA's, despite UAS being described as having fundamentally different risk paradigm [13]. The current CPA safety regulations primarily aim to reduce risk to people on board and secondarily to those over-flown [13]. However, for UAS as there

are no people on-board, the primary risks are to those over-flown or those who are external to the system. Hence this fundamental dissimilarity can lead to airworthiness regulations that do not result in effective management of risks across all types of UAS and their operations; potential over-regulation and thereby higher costs for the industry; or potentially worse effect of the airworthiness regulation not really ensuring to satisfy the objective of an equivalent level of safety [12].

The perception of risk by the public is also much different to those of CPA's. The perception of risk by society is quite different to other areas because the benefits of UAS operations are not directly visible [7]. However, the public are the primary individuals at risk due to the operation of UAS.

3. Have no stopping rule

As there is no one definitive stated problem due to different views from the stakeholders hence there is no definitive solution [8]. Hence the search for solution stops when resources, money or energy run out and not when optimal or 'final correct' solution emerges [8]. Thus, it has been referred to as a 'satisficing' solution – stopping when there is a solution that is 'good enough'.

These similar characteristics apply to the problem of UAS integration in national airspace. Firstly, the problem differs according to who the stakeholder is and therefore differing view on the problem definition means there is no definitive solution. According to the aviation authorities the major problem for integration of UAS has been the inability of UAS to demonstrate that they can operate similar to manned aircraft in all airspace classes, however the UAS operators believe the current view of authorities is that UAS must follow manned aircraft standards in all airspace classes is not justified and also not viable [12]. Also, there are several limitations of current manned aircraft operations in some airspace classes, thereby applying those principles for UA operations will lead to predictably less safe air traffic environment [7].

It is difficult to attain a point where it can be said the UAS integration in non-segregated airspace has become safe. There is a constant process of trade-off between the system safety, system performance aspects and cost benefits [12]. Even through exhaustive analysis of the trade-offs there is no definitive certainty at which

one can say all the safety related aspects have been identified, there may be some instances that could occur during operation of the system. Hence a decision has to be made at some point on the solution to the problem. There is no stopping point for the goal of increasing safety. The process stops when resources such as time, money, energy etc. have been exhausted to a point that the process can no longer continue. The solution is said to be satisficing and it the best possible solution available at present. For example, the answer to make integration of UAS safe and efficient, there is no objective point at which one can say the UAS flight is now completely safe and efficient. There has to be a time when the solution seems to be 'good enough'. This situation has come into force.

4. Solutions are not right or wrong

The solution to wicked problems cannot be measured objectively and there are no right or wrong solution but an 'optimal' solution [8]. The perception of benefits and risk to the problem of UAS integration in non-segregated airspace is varied among the stakeholders; hence a solution to the problem cannot be right or wrong, as the perception of risk is subjective. There can only be a solution that could be perceived as less or riskier as the other.

5. They are unique and novel

A key characteristic of wicked problems is that the varying factors and conditions make no two wicked problems alike and solutions to them will always be custom designed and fitted. Although one may use wisdom and experience acquired over time to approach a wicked problem however he/she is a beginner with regards to a specific wicked problem [8].

Although the introduction of any new technology into aviation is a slow and difficult due to highly safety conscious nature of the domain, integration of UAS in non-segregated airspace is unique and novel not only due to the technical complexity but the configuration of issues and stakeholders that make it so. The perception of a new technology such as pilotless aircraft by society, the practical and commercial limits of technology along with the political and social environment in which regulatory

decisions have to be made makes it different to other problems in the past [14].

6. No opportunity to perform trial and error

As presently the operation of UAS is not allowed in non-segregated airspace, there is no way to gain operational data on safety and performance of Unmanned Aircraft Systems (UAS) alongside manned aircrafts. The current restricted access has given only operational data from large UAS used for very few state applications. Hence the aviation authorities do not have a way to get a large amount of operational data to decide on the acceptance of these systems in the national airspace system [15]. Hence testing sites must be provided as well as phased entry into non-segregated airspace through entry initially by allowing access to UA's in uncontrolled airspace [5], [16].

7. Every solution to a wicked problem is a one-shot operation

This characteristic of wicked problem is a typical “catch 22” situation, where learning about a problem can only be achieved by trying out solutions, but every solution to try is expensive and has lasting unintended consequences which may likely spawn new wicked problems [8]. The integration of UAS in national airspace also has such a situation wherein the necessary operational safety data required to prove reliability of UAS operations can only be obtained by operating UA's in non-segregated airspace, however a single incident or accident involving a UA may actually derail the whole process due to the negative perception such an unintended consequence would portray [17]. Thus, the trying of solutions may lead to unintended consequences that may delay or curtail the process else the solution could lead to full integration thereby creating a paradigm shift in the industry.

Hence any solution should ensure that there are no unintended consequences that may lead to accident or incident when the UAS are allowed access partially or fully into non-segregated airspace. Thus, solution to the problem is a one-shot operation whenever the operation of UAS is allowed in non-segregated airspace.

4.3 UAS operations in ATM: A Wicked Problem Analogy

Several previous works have outlined the technical issues and concerns involved with the integration of UAS in national airspace. However, among them there are a few major issues that are key barriers towards certification and finally achieving regulatory approval. Considering the problem as just a complex technical design issue has not yet been sufficient to resolve these issues. There appear to be much wider constraints that need to be understood from a broader stakeholder requirements perspective. Thus, in order to understand the wider stakeholder constraints, the research problem is defined in terms of a complex System of Systems problem. Well beyond just being a System of Systems problem from a technical design perspective, the wider constraints of other stakeholders lend itself to being mentioned as a complex system of systems problem.

A system engineering approach is used to better understand the problem by analysing the different requirements and constraints imposed by the stakeholders that are impacting the major system design issues at present. Only the high-level stakeholders are considered here as lower level stakeholders views are represented through the primary stakeholders. The high-level stakeholders represented here are the aviation authorities, UAS end users, UAS manufacturers and operators. Each of the major issues and concerns, which at presently are hurdles towards allowing the integration of UAS in national airspace, are analysed from the point of view of main stakeholder's requirements.

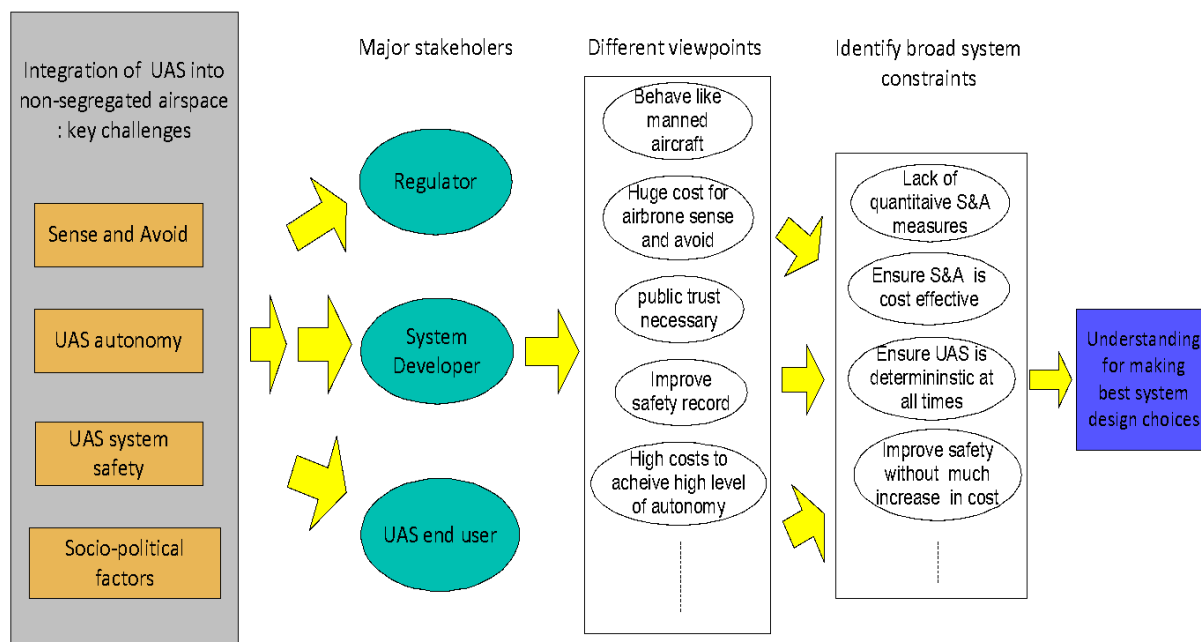


Figure 4.1 An overview of systems approach used to identify and analyse the key challenges of UAS Integration in ATM

In the following discussions, the UAS end users point of view is captured here as commercial perspective, UAS manufacturers and operators view are captured through system developer's perspective and the aviation authorities' viewpoint is captured via the regulatory perspective. The regulatory perspective will also include the interests of other pressure groups such as general public, politics etc. Three views will be analysed in how they impose requirements and constraints on the major system design issues faced presently. A better understanding of the system constraints will help in building a solution for the integration of UAS that could be certified by the aviation regulators. The four major issues and analysis of the stakeholder's constraints imposed on them is discussed here.

❖ **Sense and Avoid**

Among the many technical issues involved in the integration of UAS into non-segregated airspace, collision avoidance is a major issue [34]. The current collision avoidance capabilities of UAS are not adequate for them to be allowed to operate alongside manned aircrafts [89].

A major part of operational concept of the air traffic services provision is conflict

management [34]. Conflict management functionality in the current ATM system is carried out in a three-layered approach namely strategic conflict management, separation provision and collision avoidance [34]. To be integrated into non-segregated airspace, UAS operations must fit into this layered approach and be able to follow the procedures and standards in place as well as cooperate and participate with the separation provision rules followed by other manned aircrafts in the national airspace. In instances where the separation provision fails, the UAS must be able to employ a collision avoidance function, which will provide an acceptable level of safety [34].

In the current context of manned aircraft, the pilot is central and ultimate authority responsible for the whole collision avoidance process in all categories of airspace. The primary means the pilot of manned aircraft discharges the collision avoidance responsibility is through the 'see and avoid' procedure [34]. However, the 'see and avoid' procedure is not adequate due to many of its limitations and to aid the pilot in the collision avoidance process an airborne collision avoidance system (ACAS) has been developed. Currently in European airspace ACAS II is mandatory for all fixed wing aircraft above maximum take-off weight of 5700 kg or passenger approved seating configuration of over 19 [34]. However other light aircrafts are exempt from this rule and also in uncontrolled airspace these rules do not apply. Hence in these circumstances only means of collision avoidance is 'see and avoid'.

1) Regulator's view

According the current view of aviation authorities UAS operations in non-segregated airspace should not in any way have a negative impact on the safety of the airspace [31]. This underlines the fact that, basic tenets for the deployment of UAS in non-segregated airspace must be based on UAS properties such as equivalence and transparency [31]. This means a UAS must behave like a manned aircraft.

In terms of collision avoidance procedure for UAS, this means that UAS must be able to have a sense and avoid capability that is similar or better than a pilot of manned aircraft especially for detection and tracking of non-transponder equipped aircraft. And for detection of transponder equipped aircraft, the UAS collision avoidance function

should be able to generate avoidance manoeuvres that are as much or more effective than that of ACAS II in manned aircraft [34]. And there would be a size threshold for UAS above which those UAS will need to carry collision avoidance function equivalent to ACAS II or not [34]. Also, another important factor is that UAS collision avoidance function must be interoperable with ACAS II or consider the fact that ACAS II equipped aircraft will create coordinated avoidance manoeuvres with other similarly equipped threats.

2) System Developer's View

Sense and avoid is a challenging complex design problem in itself. The design problem is further complicated by the fact that the UAS collision avoidance performance measures are not clearly defined yet. The performance measures that are available at this stage are more qualitative in nature [34]. The system developer's currently having to work with the basic performance requirements that the UAS collision avoidance must be equivalent or more effective than collision avoidance function of manned aircrafts. The base level performance requirements seem straightforward; however, defining the performance metrics based on these baseline requirements is a challenge.

The challenge arises due to several issues. Firstly, the human skills and ability vary from pilot to pilot [3]. The visual perception and processing varies significantly and all the pilots do not have the same visual scanning pattern. The frequency of scanning also varies from pilot to pilot. Apart from this the pilot's see and avoid process is affected by physical and psychological issues [34]. The external environment especially the weather conditions have a considerable effect on the performance of the human visual range. The pilot's view is also affected by the size of the cockpit and the aircraft type. In order to factor in the degradation caused due to each of these factors and develop equivalent performance metrics for sense and avoid for UAS is a complex task.

There have been several working committees, which have been looking at the issue of collision avoidance. And the proposed solution so far has been based on ASTM (American Society for Testing and Materials) F-38 committee published

standard, which most of the system developers are following for developing sense and avoid system for UAS. The standard is based on the manned aircraft pilot maximum viewing angle of $\pm 15^\circ$ in elevation and $\pm 110^\circ$ in azimuth and also being able to respond to avoid a collision within 500 feet [3]. However, analysis of data available from mid-air collisions shows that they occur near an airfield where traffic volume is high and mainly at lower closing speeds. Most mid-air collisions occurring at low speed happen when two aircrafts are travelling roughly in the same direction when a faster aircraft is overtaking a slower aircraft. This situation may arise in case of UAS as cruising speed of many UAS are less compared to other manned aircrafts. Hence considering this limitation the standards based on limited field of view may not be enough. However, in UAS the backward-looking capability is achievable by placing sensors in such a way that full 360 degrees is possible [90].

The research on mid-air collisions also reveals that most of the collisions occur when visibility is normal during day and in uncontrolled airspace [90]. This also outlines the inherent limitation of the 'see and avoid' procedure and in the future with the increase in traffic of lighter aircrafts this might become a serious limitation. Hence to base the UAS collision avoidance performance on a standard that has many limitations may not guarantee certification of UAS sense and avoid systems.

Systems engineers' tend to follow the 'V' model of systems engineering, where at each stage the system concept is tested and validated [91]. However, the challenges that exist in translating the baseline performance measures to quantitative performance metrics make it difficult for the systems engineers to follow the systems engineering process during design and development of UAS sense and avoid systems. Hence the design problem is further complicated due to these challenges.

3) Commercial viability view

In providing a solution for the UAS sense and avoid system a major consideration would be cost apart from other factors such as weight and power consumption. If the sense and avoid system cost is high enough contributing to a major cost of the UAS, then the UAS manufacturers would not be able to justify the business case of civil UAS operations to the UAS end users.

To improve the reliability of UAS sense and avoid system there would have to be redundant systems on board the UAS and this means more additional cost [90]. However, the costs could be lowered in case the sense and avoid system was placed on the ground. But according to the current standards of the aviation authorities it appears that airborne collision avoidance would be needed for last ditch attempts to avoid collisions when other collision avoidance provisions fail [34]. Hence an acceptable collision avoidance solution will have cost as an important issue.

❖ UAS autonomy

An autonomous system unlike an automatic system has various choices available to it to perform a particular task and it has the capability to reason on the alternative choices available to it before it makes a decision [31]. It has the ability to constantly perceive the outside environment and take action according to the effect of current state of environment on its ultimate and in making this action it ensures that its actions are safe enough while achieving its goal. Hence autonomy range from the capability of system to be fully autonomous that is a system without any human oversight, to semi-autonomous where there is sharing of decision making between the humans and system and finally those with no autonomy that is the system is just able to provide information to the operator on a timely basis and all decision making is left to the operator [31].

The level of autonomy in a system also gives rise to many human factor issues. For a system where human-UAS collaborative decision-making is necessary, there are several human factor issues that are safety critical. Some of these issues are UAS pilot skill levels, UAS pilots and ATC controller situational awareness and also their workloads. Hence providing the right kind of information and at right time is crucial for safe operation of UAS [3]. Also, considerable analysis has to be done to determine how this information has to be presented in raw or processed form so that the UAS operator has the correct amount of information so as not to increase workload of the UAS pilot.

1) Regulator's view

The first and foremost requirement for the aviation authorities in terms of UAS autonomy is that the system must be fully deterministic in nature [31]. That is the decisions made by the system must be on a rational basis. An autonomous system must also be consistent and repeatable. By ensuring consistent behaviour at all times the system will in turn encourage human trust. Consistent behaviour can be achieved by making decisions that are repeatable. That is, the system should not in any circumstance exhibit unexpected or emergent behaviour. Without these characteristics, the system would not be able to be certified.

Another major factor to consider when certificating autonomous system is data integrity. In a manned aircraft, the pilot is presented with sensor data (altitude, air pressure, airspeed etc.), which he then interprets for its validity before taking any action [31]. An autonomous system also perceives its environment through a large amount of sensor data on board, databases or messages; however, there is no human oversight provided by the pilot. Hence UAS are prone to incorrect or erroneous data [31]. Thus, ensuring that the data on which the UAS bases its reasoning and makes decisions is of high integrity is necessary to ensure system certification.

2) System developer's view

The issue of UAS autonomy is a complex design problem. An autonomous system with higher level of autonomy will be very difficult to design, verify and finally to certify. The decision making in an autonomous system should be collaborative, that is the human and UAS must together work as a team with however the human having the ultimate authority [34].

One of the ways of sharing the decision-making would be by determining the time criticality of making the decision. That is decisions, which are safety critical and require immediate action, in those instances the UAS could act autonomously without much human oversight. Example of such instances are the UAS making a last-ditch attempt to avoid a collision in case the other collision aversion provision fails and also during a loss of communication link between the UAS pilot and the UAV, the UAS must be able to follow contingency plans and reason independently of the UAS. However,

in other occasions the UAS could share decision making with the UAS pilot but with human oversight and UAS pilot having ultimate authority. By using these methods, the UAV system could become more deterministic for most part of its flight. This will significantly ease the difficulty in certification of these non-deterministic systems. The control algorithms of the UAS should be robust and provide consistent behaviour. The UAS health should be monitored at all times and in case of any malfunction with the major flight systems the control algorithms should be able to revert to emergency conditions and land the flight to safety without causing any detrimental effect on the safety of the airspace.

In a human and UAS collaborative decision-making system, two concerns that have to be addressed are data fusion and UAS pilot interface. To determine what all information available from sensor data need to be processed and reasoned on the air vehicle and also which information have to be communicated to the UAS pilot in a form so that decision making processing of those data takes place on the ground. This also impacts the situational awareness of the UAS operator. As the unmanned aircraft has a better situational awareness as compared to the UAS pilot far away on the ground, it will be necessary to provide on-board sensor information as well as other systems on the ground in a form that increases the situation awareness of the human [3]. Also, the system should be careful not to overload information on to the UAS operator, which may lead to mistakes by the human pilot.

Apart from these challenges, the biggest issue to consider for certifying UAS is the verification and validation of these systems. To prove that UAS are able to operate without any emergent behaviour and make decisions that are consistent and repeatable at all times is difficult. The more and more decisions are taken by the UAS without human oversight, the less predictable will be the UAS behaviour. Hence ensuring human oversight during all phases of flight will be vital to proving the system consistency.

3) Commercial viability view

In terms of commercial viability, the costs have to be compared for UAS having varying levels of autonomy. In a system where UAS is highly autonomous, it would

mean more complex software process on board and also increase in hardware to ensure high degree of reliability. This in turn will lead to higher cost of UAS. It is envisaged that lower cost could be achieved where the decision-making is shared between the UAS and UAS pilot working as a team [31].

❖ System safety

In civil aviation, safety is paramount and it is a highly risk averse domain. So, the introduction of any new form of technology should be such that it does not have a negative impact on the safety and efficiency of the overall Air Traffic Management System [4]. For successful integration, UAS should prove that they can operate safely, i.e. they must not pose any undue hazards to other aircrafts or to persons on the ground under any circumstances [31].

Although UAS have been operating in the military domain for a long time, there are major concerns regarding their safety. From the UAS use in military sphere over the years, the reliability analysis study shows that UAS have a poor safety record. According to a 2002 US congressional service report the current UAV accident rates were 100 times more than that of manned aircrafts [27].

In the past several years the US government agencies have been using UAS increasingly for a few state civil applications. These UAS are restricted to certain segregated areas of the airspace and they do not have jurisdiction to operate beyond those areas. The US Customs and Border protection agency has been using unmanned aircrafts for monitoring illegal border activity. A recent figure reported by them on the accident rate of unmanned aircrafts suggests that they are 353 times more accident prone than manned commercial aircrafts [27].

1) Regulator's view

According to the aviation authorities, the limited operational and safety data that is currently available from use of UAS in state civil applications do not support their full integration into the national airspace [3]. The UAS accident rates are very high compared to that of manned aircrafts. A huge improvement in safety and reliability is required to be able to allow unmanned aircraft to operate alongside manned aircraft.

In view of the current safety record the UAS operation in non-segregated airspace is not possible.

A key to ensuring system safety of UAS would be effective collision avoidance and terrain warning systems. Apart from this other highly safety critical factor to consider for certification would be ensuring data security of UAS. A highly secure communications link between the unmanned aircraft and UAS pilot would be necessary to prevent any intentional data manipulations [7]. The major threats are unauthorised commands, false or misleading data. Although UAS would have certain ability to reason on misleading data, however they are highly dependent on a secure communications link [31].

Human factors are a very important safety issue as far as the UAS operations in national airspace is concerned. Thus, ensuring that the UAS pilot has the right amount of skill level and also adequate situational awareness for operating unmanned aircrafts will be important from an overall system safety point of view [3].

2) System developer's view

The safety criteria for UAS may vary based on unmanned aircraft characteristics and its operational capabilities. Some of the characteristics that may affect safety are size of UAV, maximum cruising speed, category of airspace it's operating in and kind of applications it's used for [3].

It would be inappropriate to compare safety record of unmanned aircraft to those of its manned counterparts at this stage [3]. UAS use in the military domain started with the idea of saving human lives in battle space and was primary developed as expendable vehicles. The systems were not developed with reliability or safety in mind; other functionalities such as cost, payload capacity and performance were major criteria's in mind during their development. As the system size and power requirements varied for different type of unmanned aircrafts, the UAS manufacturers tended to use commercially available components which are not certified according to aviation standard [3]. These were some of the reasons for high degree of unreliability of UAS operated in the military domain.

In case of deployment of state UAS in a few civil applications, the UAS used

were a spin off from UAS technologies and flight systems from the military domain. Hence that may also have been a contributing factor in UAS operations for state civil applications.

System safety has to be improved not only by improving reliability of individual system components but also by ensuring human-UAS interactions are safe and build enough safety nest in order to prevent failure events occurring due to inadequate UAS operator actions.

Most of the safety metrics for the UAS safety critical systems are not clearly defined yet. The system developer has to rely on baseline performance requirements that have been outlined by the aviation authorities. Hence this situation also makes the design for safety more technically complex.

3) Commercial viability view

Usually two methods are possible for improving system reliability, which are increasing reliability of individual components/systems and build in redundancy or duplication [3]. However, improving reliability using these methods will invariably lead to higher costs. These costs could be justified by the fact that system unreliability can lead to high costs as well when UAS crashes to ground or during any other catastrophic event. Along with the air vehicle platform, the payload could also be damaged which in some instances may cost more that damage only to the UAV platform itself [3].

From the UAS manufacturers point of view, as various technologies in UAS evolve they could also be used in manned aircrafts to improve safety. For example, development of a cost effective UAS sense and avoid system could be very useful in improving situational awareness of pilots and also avoiding collisions in light aircrafts. Hence a wider customer base could compensate for higher costs involved with improving system reliability.

Ensuring safety standard for small UAS would be difficult to balance against the cost benefit in their operation. However, by sharing of decision-making processing on board unmanned aircraft and the ground control station, few of the systems redundancy can be placed on the ground. Thus, using the new business models, the

cost could be shared between the UAS operators and the UAS end user.

❖ Socio-political factors

Socio-political issues will play a major role in deciding whether to allow or restrain access of UAS in non-segregated airspace [3]. The shaping of public perception towards UAS will be a crucial factor for UAS acceptance in national airspace. Depending on how the public perceives UAS operational as being beneficial when compared to the potential costs of developing these systems. This perception is also shaped by any catastrophic events that occur or may happen in the future that may be reported by the media [3]. Public and media perception in turn most probably shape the political will on such issues.

According to several surveys conducted, the primary reason for public anxiety towards UAS has been job loss that will arise due to increased automation and other main factor is the uncertainty with regards to the technology itself [3]. However, a majority of the respondents were happy for use of UAS in cargo and civil applications [3].

1) Regulator's view

However safe the UAS become; eventually the decision of aviation authorities to allow UAS integration in national airspace will be swayed by public acceptance of autonomous systems.

Public trust in UAS can be built in several ways. Firstly, by comprehensively demonstrating that UAS are safe, cost effective and act in a responsible way. This will take a lot of time and effort [3]. Secondly by changing the taxonomy of the term used to refer to these systems. Also educating the people about the fact that human is the ultimate control authority in UAS operations.

The aviation authorities have already been using the taxonomy of Remotely Piloted Aircrafts (RPA) instead of the term UAS to provide the public with clarity. Also, to allay the fear of job losses, the military have been trying to educate the public that RPA fleets also requires a considerably high manpower to operate and maintain [92]. However, with these entire efforts one stray incident where an accident involving UAS

occurs that may lead to loss of human lives, can have detrimental impact on public perception. Hence it is envisaged that for the civil UAS market to open up, the UAS may have to prove a high level of safety as compared to manned aircrafts.

2) System developer's view

UAS industry has to provide confidence to the public by ensuring they are acting credibly in every step [3]. Build technologies that will have least environmental impact and also demonstrate socially responsible actions of UAS. The dilemma in the mind of the system developer's is when full integration could be achieved. This will postpone several new product development initiatives for the civil UAS market. There may be a need to prove that UAS is more reliable and safe than manned aircraft will be difficult and consume more resources as well as effort.

4.4 Discussion on ways to address airspace integration

Presently, the perspectives of the major stakeholders on the most important issues involved with the integration of UAS into civil airspace are varied. A stakeholder analysis of the problem has shown that the stakeholders have a wide range of views and also seem to have different frames for understanding the problem. As has been discussed earlier, such problems cannot be tackled through the traditional engineering approach in which problems are defined, analysed and solved in sequential steps.

There have been several strategies proposed in the past for tackling wicked problems in different subject areas. Generic sets of strategies to cope with wicked problems are identified in Roberts (2000) [8]. Among these proposed strategies there are a few which are suitable and need to be applied to the problem of UAS integration into national airspace. A set of strategies are identified and discussed here which are well suited and tailored towards tackling the problem of allowing routine operation of UAS in non-segregated airspace.

□ Collaboration

This approach is aimed at achieving closer collaboration by engaging all the major stakeholders in order to find the best possible solution for all stakeholders. As

indicated in Rittel (1972) and in Roberts (2000) [8], the collaborative approach attempts to make all major stakeholders along with those who are being affected as participants in the process of formulation of a solution to the problem [8].

The greatest impediment to the routine flight of UAS in non-segregated airspace has been the regulatory environment in the countries, which have the greatest interest for using UAS for civil and state applications as well as R&D activities. There has been more demand for UAS in scientific missions and monitoring of natural disasters.

A recent example for the use of UAS in monitoring scene of disasters was when unmanned aircrafts were used above the failed nuclear power station in Fukushima, Japan to assess the damage to the reactor buildings [33]. Another example of UAS applications is, the British Antarctic Survey have been using hand-held small UAS for conducting scientific studies and are keen to use them in place of manned aircrafts in several scientific purposes widely [33].

However as with the national airspace, the international airspace regions are also bound by the rules and regulations. Hence to carry out mission in international airspace regions, the users have to comply with the ICAO (International Civil Aviation Organisation) rules and regulations, which are enforced by the nation states along with their national regulations when flying under their airspace regions. This also creates a large degree of hurdles for the UAS operators, as they have to navigate through the regulations of each states under which they are operating. Even the limited access to UAS operations by some countries as an initial entry level for UAS developers has also been inconsistent from country to country along with the overall regulatory approach adopted for UAS access [17]. Apart from common regulatory approach between countries, there has been a lack of global initiative for an approach to develop a harmonised regulatory framework [17].

A UAS working group was established within ICAO with the goal of supporting the regulation and guidance development based on the work of rulemaking committees such as RTCA, EUROCAE and other similar bodies in 2007. However there needs to be greater integration among the several aviation authorities [33].

In order to tackle wicked problems there needs to be more collaboration and

engagement among the various stakeholders. There has been lot of co-operation with the various stakeholders and airspace regulators in the process of solution formulation in countries that have seen great demand for operating UAS in non-segregated airspace. But the solution also involves co-operation at the intra-regulatory level [34]. It is also necessary to leverage UAS standards and airspace integration work from other countries in order to develop further set of performance requirements and standards at a global level. For instance, the future ATM architecture framework initiative in Europe and US represented by NextGen and SESAR, have now been actively involved in establishing UAS operational environment in future ATM architectural goals. The process would lead to a determination of the airspace classes, ATM systems and Air traffic services units that the UAS will interact/interface with in the future ATM. These activities could be better harmonized at a global level to truly achieve a seamless integration of UAS in non-segregated airspace across boundaries, nations and oceans.

□ Change in Mindset

A problem whose solution requires a great number of people to change their mind-set and behaviour is likely to be a wicked problem [8]. As has been noticed in many standard examples of wicked problems in the area of public planning and policy, such as global climate change, natural hazards, nuclear energy, healthcare etc. [8].

Similarly, UAS are transformational and thereby requires a large number of people to change their mind-set to be able to integrate them in civil airspace by managing safely. Over the last several years there have been huge sums of money invested in research and development for solving the problem of UAS airspace integration; however, the progress so far has been limited. [1]. The analysis of the challenges and issues involved with the problem in the context of wicked problem analogy has shown that there is a need for change in the mind-set of the major stakeholders. The wide viewpoints of the various stakeholders on the solution to the problem and also having a default position have meant that there has not been much progress until now [12].

One of the key areas where this change is needed is in the perception of UAS

operational risk by the aviation authorities [12]. Operation in non-segregated will require an ELOS to that of civilian piloted aircrafts operating in the same airspace. The efforts involved so far in the definition of standards. The current view of the aviation regulators is that the standards specific to UAS has given little considerations on how these standards and regulations will be applied across diverse UAS types, their operational capabilities and various mitigation strategies deployed [12]. The proposed approach has been to apply regulatory framework for civilian manned aircraft to that of UAS [4]. The fundamental basis behind such an “off the shelf” approach has been that applying equivalent regulations leads to an ELOS, despite UAS having a different risk paradigm [13]. The underlying principle of the civilian piloted aircraft regulatory is based on the primary risk to people on-board the aircraft, however the primary risks governing the development of UAS regulatory framework is different as they are external to the aircraft [7].

One of the main principles of regulations is to ensure that the safety objectives can be met but at the same time minimising the regulatory costs to meet the standards by the industry [14]. The approach to the definition of part 1309 regulations for UAS has been to assign system failure probabilities as used for the civilian manned aircraft except the JARUS group which has proposed a draft kinetic-energy based approach [34]. Hence the approach to assign average system failure probability similar to manned aircraft could lead to a situation in which the safety metrics could not be achieved for small UAS where the greatest demand for integration in non-segregated airspace is present. And also, the principle of using equivalence failure probability may not lead to equivalent level of safety. In view of these factors, there needs to be a major shift in thinking on the way the regulations and standards defined for UAS so that the unique operational capabilities and diversity of UAS are considered along with the fundamental difference in the nature of risks associated with UAS from civilian piloted aircrafts [12].

An alternative approach for UAS could be risk based models that relate the safety metrics to the potential for a flight critical failure event. There has been research work on model based approach to assess the risks associated due to the operation of UAS in non-segregated. Example model-based approach is presented by Weibel

McGeer *et al.* (1999), Grimsley (2004), Weibel and Hansman [37], Clothier and Walker [13], Clothier *et al.* (2007), and Dalamagkidis *et al.* [4]. Clothier and Walker [12] propose a framework for defining airworthiness regulations for UAS using a risk matrix based approach. They point out that the quantifiable specification of the framework makes it possible to establish a transparent and justifiable basis in terms of the overarching requirement for an ELOS [12]. A risk matrix model is used to determine an airworthiness certification matrix. The airworthiness certification matrix is a systematic method for partitioning the numerous possible types of UAS and operations into a finite number of scenarios [12].

Also, there have been other research studies in statistical modelling of encounters of conventional and unconventional aircraft, which provide a basis for rigorous analysis of the risks associated and also risk mitigation effects with the introduction of UAS in non-segregated airspace [36]. These statistical models provide a collection of tools and methodologies for risk assessment that could provide a basis for a fundamental shift in the approach taken by the aviation regulators and rulemaking bodies to assess the demand for operating UAS in non-segregated airspace safely and routinely [36].

The process of integration of UAS in non-segregated airspace has to be on a step-by-step basis providing incremental access. A step-by-step approach will enable restricted access initially which would lead to more learning and information on the operational performance of the UAS [16]. This operational data could be useful in providing further access to the UAS or plug any loopholes in the safety aspects of their operations in the restricted airspace. This procedure of providing incremental access from very low risk airspace to a high-risk airspace where safety systems have to be precise and efficient to avoid collisions will enable in breaking down the catch 22 situation that exists at the moment between the regulators and potential UAS operators.

4.5 Summary

The integration of UAS into the national airspace system brings a fundamentally new aviation technology which has several benefits to society. However Unmanned

Aircrafts also introduce a risk paradigm that has to be managed to ensure safe operations in non-segregated airspace. The varied requirements and perspectives of different stakeholders make the problem more complex that can also be defined in terms of a wicked problem.

There are several limitations in the current with regards to solving the major issues of UAS integration. Hence an analysis of the whole problem as a wicked problem lends itself to suggest few techniques of tackling such problems need to be adopted in case of UAS integration also. Primarily a key aspect is the fundamentally new technology of UAS means there needs to be a paradigm shift in the mind-set of the aviation authorities in terms of development of regulations and standards for UAS operations in non-segregated airspace. Also, other aspect which is lacking is the high level of collaboration between the major stakeholders to an international regulatory framework that would lead to similar rules across national boundaries.

The systematic approach to analysis of the problem and suggestion of different approaches proposed in the paper will aid in further discussions on the integration of civil unmanned aircraft in non-segregated airspace.

Part III: Unmanned Aircraft System (UAS) Sense and Avoid

Chapter 5: UAS Sense and Avoid Overview

In an Unmanned Aircraft (UA), the pilot is not on-board the aircraft to perform the task of seeing and avoiding aircrafts which is the case in a manned aircraft [9]. Hence this becomes a significant issue when the cockpit and the pilot are placed remotely on the ground away from the flight deck of the aircraft.

ICAO Annex 2 [10] lays out the 'Rules of the Air', and within which it states that: "An aircraft shall not be operated in such proximity to other aircraft as to create a collision hazard and the statement that It is important that vigilance for the purpose of detecting potential collisions be exercised on board an aircraft, regardless of the type of flight or the class of airspace in which the aircraft is operating..."

The exercise of this vigilance, for the purpose of seeing and avoiding collision hazards, is referred to as the 'See and Avoid' principle [10]. In manned aircraft, the pilot in the cockpit exercises the 'see and avoid'. The corresponding function in UAS as coined by the UAS community is the analogous principle of 'Sense and Avoid' [9,10]. Thus UAS 'Sense and Avoid' system is the technical capability to be developed in order to mitigate the lack of an on-board see and avoid capability for UAS [10].

There are no formal definitions of the term 'sense and avoid' apart from the high-level requirement as mentioned in the quote above. There is no particular method, technology, functionality or performance that is required for the Sense and Avoid principle apart from the high-level requirements. In manned aircrafts, the pilot exercises the 'see and avoid' other aircrafts that is inherently independent of the avionics systems providing both separation provision and collision avoidance capability [10]. As a high-level requirement, Sense and Avoid is 'the capability of UAS to stay well clear from and avoid collisions with other airborne traffic' [9]. It consists of two parts [9], [10], as shown in Figure 5.1:

Separation provision: Separation provision is a second layer of conflict management as per the ICAO ATM concept. Separation provision is the process of keeping well away from other aircrafts and also other fixed obstacles, by at least a certain separation minima, by way of tactical intervention. The separation provision function

takes into effect when just the first layer of strategic conflict management can no longer avert the separation conflict and the responsibility may be of the ATM service provider or airspace user or both. And the rules, procedures and roles of the actors are clearly decided before the separation provision process needs to take over.

In the case of non-cooperative aircraft or in regions where there is no separation provision service provided, the separation has to be maintained by the airspace user alone and is referred to as self-separation. Similarly, a UAS sense and avoid system should be able to keep well clear of other aircrafts so as to maintain a safe separation.

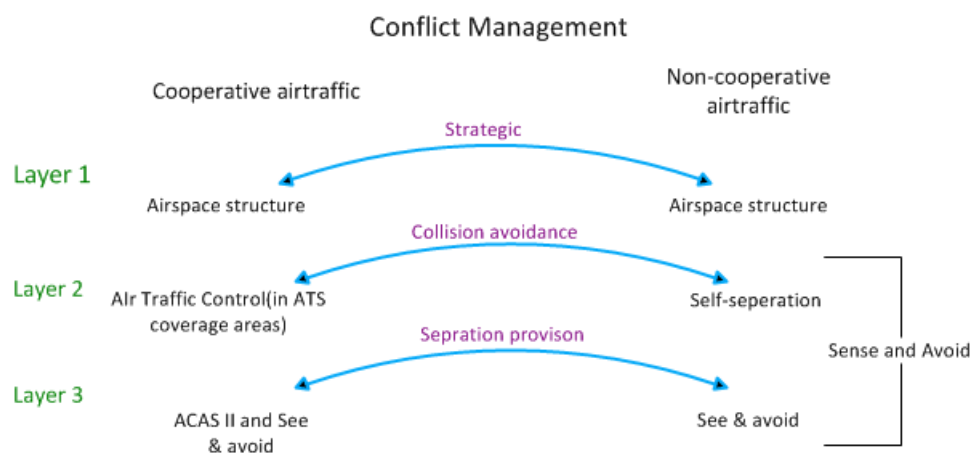


Figure 5.1 Airspace Conflict Management

Collision avoidance: Collision avoidance process takes over only when the other two layers in the conflict management layer have failed to remove conflict to a point where the flight crew or on-board systems perceive there is a risk of collision. The collision avoidance manoeuvres are taken on-board the aircraft in response to alerts and advisory from on-board system i.e. ACAS, instructions from controllers (based on alerts from ground based safety nets such as STCA) and finally the pilot’s visual acquisition resulting from constant visual scanning or by voice communication on traffic information by ATC or via cockpit display of traffic information.

The pilot carries out the responsibility of maintaining vigilance at all times by exercising the see and avoid procedure. However, see and avoid procedure has many limitations related mainly to the flight crew and the weather conditions prevailing. Therefore, to aid the pilot to perform collision avoidance process an Airborne Collision

Avoidance System (ACAS) safety net has been developed [10]. Currently in European airspace ACAS II is mandatory for all fixed wing aircraft above maximum take-off weight of 5700 kg or passenger approved seating configuration of over 19 [10].

However other light aircrafts are exempt from this rule and also in uncontrolled airspace where transponder carriage for airspace users is not mandatory. Hence in these circumstances only means of collision avoidance is see and avoid. Thus, see and avoid procedure is a very important function and UAS sense and avoid must have a similar ability to 'see and avoid' capability of manned aircraft for them to carry out collision avoidance manoeuvres.

Thus, the two components function of self-separation and collision avoidance together provide the UAS sense and avoid capability. These component functions operate in a layered approach to maintain safety and efficiency of the airspace. According to the ICAO concept, the conflict management process is applied in three layers: strategic conflict management, separation provision and collision avoidance. The layered approach ensures that only when failures occur in all the three layers would result in a collision [10]. The layered approach to safe and efficient ATM is as shown in Figure 5.1.

5.1 Current Progress

The UAS 'sense and avoid' is an important factor for the integration of UAS in national airspace system. There are many organisations and programs around the world working on this important technology.

In manned aircrafts, the pilot on-board are able to ensure self-separation and see and avoid other aircraft. However, for unmanned aircraft pilot is remotely located thus an alternative means of compliance is necessary. There are several alternative approaches that are possible which could in a phased manner reduce the restrictions on the operations of UAS in non-segregated airspace from the current situation.

According to the current rules of CAA, If the UAS does not have sense and avoid system, the UAS could be flown outside segregated airspace only in uncontrolled airspace and within visual line of sight of the UA operator. And other

restrictions include that the maximum height of operation should be less than 400 feet and they should not be operated near aerodromes or within 150 metres of any congested area of a densely populated region [11]. A small aircraft (20 kg or less) as defined in the defined in air navigational order can operate under the above-mentioned operational procedures without complying with any airworthiness or flight crew licensing requirements. However, a special permission from the CAA is necessary when flight is used for purposes of aerial work.

Currently it appears that the introduction of UAS will be through a step-by-step approach, as the technology needs the time to mature and also to learn from the restricted access to the UAS.

5.1.1 Airborne Sense and Avoid (ABSAA)

Airborne Sense and Avoid (ABSAA) is the approach to locate sensors on-board the unmanned aircraft to sense and detect other aircraft in the vicinity of its flight [9]. Most of the research in the UAS community has been mainly focussed on the ABSAA approach to gain routine access of UAS in the airspace system.

An ABSAA solution development must have the ability to sense and detect both co-operative and non-cooperative air traffic type in the airspace. A significant concern is the development of an ABSAA system that will sense and detect non-cooperative aircraft in the vicinity of the UA. However, the complexity would be minimised if all the air traffic were co-operative, which is not the case [9].

The implementation of an ABSAA solution for UAS sense and avoid requires a major-architectural trade-off. This trade-off involves the role of the pilot in performing sense and avoid function. There are two possible implementations with regards to the role of the pilot: pilot-in-the loop and autonomous operation. The two of the architecture differ in the decision-making role for sensing and avoiding functions [9].

A pilot-in-the-loop operation involves the use of sensor on-board the aircraft to send all the traffic information to the pilot on the ground to make decisions and take manoeuvre action of the unmanned aircraft if necessary. The pilot may be warned by an automated alert or conflict also may suggest manoeuvres to be taken to avoid conflicts, similar to ACAS today. This architecture is heavily dependent on

characteristics of the command and control link between the UA and UCS such as the latency, availability, integrity, reliability etc. [9].

In autonomous S&A operations, still the sensors on-board the aircraft collect the traffic information and autonomously detect a conflict and determine a manoeuvre execute the manoeuvre and determine when to return to the original flight path. The action or manoeuvre to be taken may be informed to the pilot and he/she could override a manoeuvre if necessary. This architecture will be least affected by the vulnerabilities of the command and control link between UA and UCS.

An airborne sense and avoid ability must be developed for detecting and avoiding both co-operative and non-cooperative type of air traffic. Although the implementation of cooperative sensors for sense and avoid is less complex to develop and certify, not all air traffic is cooperative thereby making non-cooperative sensors necessary [9]. In the following section advantages and disadvantages of both cooperative and non-cooperative ABSAA are described along with their approximate implementation timeline.

Cooperative ABSAA: In a cooperative ABSAA, the sensors on board the aircraft receive information about the relative or absolute location of other aircraft carrying similar sensors. Thus aircraft, which carry such transponders for transponding or reporting location information, are called cooperative aircraft. Currently there are two cooperative capabilities namely the Mode-C transponders or Automatic Dependant Surveillance Broadcast (ADSB) [10].

However, the Mode-C transponders and ADSB-OUT capability are not mandated for use on all types of aircraft and in all categories of airspace. Although the Mode-C transponders are mandated for certain areas of the airspace, they not directly appropriate for use on unmanned aircrafts. However, an adequate sense and avoid capability could be developed by using ADSB as the surveillance information source.

It appears that Mode-C interrogation would not have the adequate position accuracy for an ABSAA; hence an ADSB-OUT capability will be required for ABSAA [9]. However, ADSB-OUT capability in the process of being rolled out and the aviation authorities in Europe and US have mandated the deployment of ADSB-OUT capability

in all regions of airspace where the Mode-C transponders are required today.

The cooperative capability of ADSB-out is not planned to be mandatory for non-commercial aircraft intending to operate in uncontrolled airspace (class E and G airspace). However cooperative ABSAA brings many advantages over a non-cooperative solution [9]. Firstly, cooperative ABSAA would work on a surveillance technology whose integrity, accuracy and failure rate are already known. Secondly, the conflict detection and resolution algorithms are inherently simpler compared to non-cooperative sensors due to known accuracy and integrity of information. Thirdly, there is no need for multi-sensor fusion algorithms and associated processing thereby leading to lower power consumption that has an impact on the weight, power and size constraints of an unmanned aircraft [9]. Finally, the development and certification risks for the cooperative ABSAA are less due reduced complexity of the system.

It is widely estimated the cooperative ABSAA solution would be operationally viable in the next ten years emerging through existing research, current deployment timeline for mandatory ADSB-out equipage and ongoing efforts on the development of standards for UAS operations [9]. Although the development and validation costs are less compared to non-cooperative ABSAA due to reduced complexity of detecting and sensing operation, there would be a cost in equipping the aircraft potentially operating in regions where UAS will be operating.

The implementation of ADSB-out would enhance the safety of the airspace; it is unlikely all the airspace users can be mandated in equipping their aircrafts. There may be resistance from some of the user community. The development of a successful cooperative ABSAA for unmanned aircraft may also lead to technology transfer to manned aircraft operation to improve the overall safety of the airspace system.

Non-cooperative ABSAA: The non-cooperative ABSAA principle of operation is similar to cooperative ABSAA, however the difference is that apart from detecting cooperative traffic (carrying Mode-C or ADSB transponders) they should also detect those aircrafts which do not report their position information via transponders. The detecting of such aircraft called as non-cooperative aircraft provide many complexities due their several attributes such as detecting in visual or Instrument Meteorological conditions; at all

time of the day; through ground clutter; varying dimensions, sizes, speeds and climbing rates; using multi-sensor processing and at a sufficient range so as to avoid collisions [9,12].

The non-cooperative ABSAA solution has added complexity in view of development and certification due to the complex nature of avoidance and resolution algorithms, lack of know accuracy and integrity of sensor information and need for multi-sensor fusion algorithms on such kind of information [9]. There has been much research in the area of non-cooperative ABSAA many of which were analysed in detail in the second-year annual report, however much of the technology is at relatively low maturity levels. It is envisaged that the development of a commercially viable non-cooperative ABSAA capability is 12 years or more away [9].

The added sensor and processing capabilities required on-board the aircraft give rise to increased cost as well as other constraints such as larger size and higher power consumption. The complexity of a non-cooperative ABSAA is significantly greater and the overall costs for development and certification are set to be much more expensive than a cooperative ABSAA solution [9]. The development and implementation of a successful non-cooperative ABSAA could potentially be used in manned aircraft that may reduce the number of mid-air collisions leading to a safer national airspace system [9,10].

5.1.2 Ground Based Sense and Avoid (GBSAA)

As has been described in the above section, the development and validation of a non-cooperative ABSAA solution is at least ten years away [9]. Other drawback of such an ABSAA could be their usage in small UA (less than 30 kg) due to their much larger size and high-power requirements that may not be available on small UA [12]. Hence to enable operations of UAS beyond line of sight of a pilot on the ground, in the near to medium by providing a capability to detect air targets in the vicinity of UAS is needed. Thus, providing this capability by means of using off board sensors on the ground as an alternative approach to UAS sense and avoid is widely referred in the UAS community as ground based sense and avoid (GBSAA) system [8,12].

GBSAA is seen as a near term solution which would become element of an

integrated sense and avoid system finally to enable uninterrupted access to entire national airspace [8]. An integrated sense and avoid system consisting of both the ground and airborne S&A elements is seen as the eventual solution. Hence GBSAA system will form a key part of the entire sense and avoid function [9].

The FAA has provided an interim guidance for the operations of UAS through an alternate acceptable means of compliance which states that *“if special types of radar or other sensors are utilized to mitigate risk, the applicant must provide supporting data which demonstrates that: both cooperative and non-cooperative aircraft, including targets with low radar reflectivity, such as gliders and balloons, can be consistently identified at all operational altitudes and ranges, and, the proposed system can effectively de-conflict a potential collision.”* [12]

Hence alternate means of complying can be achieved by using already mature technologies such as 3D surveillance radars, other primary radars.

Dedicated sensors: Dedicated ground based sensors, which can provide surveillance coverage over an area where the UAS operations are carried out. The air traffic information can be presented to the UAS pilot who can take any manoeuvring action if necessary. Although the technology exists, still research work has to be carried out to develop operational concepts, procedures, separation criteria and decision support tools for UAS pilot to ensure that the UA remains well clear of any intruding aircrafts that may cause potential conflict situation. As the sensor technologies already exist this kind of a solution could be implemented in the next one or two years [9]. The UAS operations have to be restricted to the areas of airspace where the surveillance coverage exists, hence limiting the operational flexibility of the UAS operations.

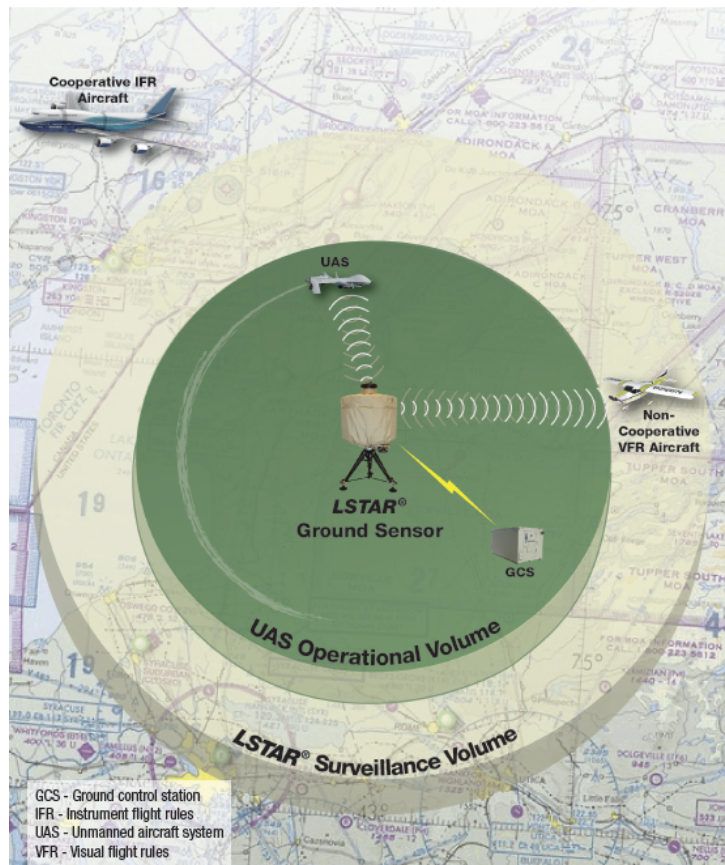


Figure 5.2 Ground Based Sense and Avoid (GBSA) dedicated sensor

Repurposed sensors: However, a way to increase the operational flexibility could be look at existing air surveillance radars and other air traffic control radars for potential use as GBSAA. Existing surveillance radars are developed with signal processing techniques to reduce the clutter on the primary targets displayed. However, in order to ensure that all non-cooperative aircrafts are detected modifications have to be made in the signal processing aspect. Primary radars are normally two-dimensional radars providing no altitude information of the detected targets, thus post-processing algorithms would have to be used in order to provide a better estimate of the altitude of the primary radar targets. Repurposing the sensors would lead to additional development risks thereby delaying the operational implementation by further one or two years as compare to those for dedicated sensors [9]. While the operation of UAS is more extensive and the long-term lifecycle costs are low by opting for repurposed sensors, however the development risks associated with radar processing make this

alternative less desirable as compared to using dedicated sensors for GBSAA operation [9].

The GBSAA is a relatively unexplored concept in the UAS community and there are only a few locations in the world, which are currently close to performing a basic version of GBSAA in non-segregated airspace [9,12]. However, GBSAA is widely seen as a short to medium term certifiable solution for UAS integration in national airspace [8]. The GBSAA concept has also been approved by the US congress for technology development and validation as a near term solution for the UAS access needs in national airspace system.

The US army has successfully tested and certified a ground based sense and avoid system at one of the army sites in order for UAS operations to take place during night times especially for training purposes [13]. This is a basic GBSAA implementation in which two ground based radar systems were connected and the traffic information provided to UAS observers who were responsible for landing the aircraft in case of any intruding aircraft entering the monitored airspace [13]. This effort is part of ongoing development that will lead to an eventual demonstration of an integrated ground based and airborne S&A system.

Apart from this major development program, there is also a major research collaboration project in Australia called Smart Skies where one of the research areas for demonstration has been a Mobile Aircraft Tracking System (MATS) similar to the GBSAA concept [12]. The primary objective of MATS is to detect and track all airborne targets in the local airspace and provide this traffic information to the UAS operator. The MATS use low cost portable radar sensor to provide air traffic information of the local airspace in order to enable safe operation of UAS [12].

Chapter 6: Ground Based Sense and Avoid (GBSAA) System Concept Overview

6.1 Introduction

The civil UAV market has been difficult to develop in the National Airspace System (NAS), this is primarily due to the restriction on the routine flight of UA. UAS can be flown only in certain segregated areas on a 'file and fly' basis, which requires a prior permission from the aviation authority for operating UAS. There are number of factors which are responsible for the restriction of UAV operation in the national airspace and they vary depending on the size of UAV concerned:

- For Large UA (above 150 kgs), integration into national airspace requires that they are highly reliable and follow the same rules as manned aircraft.
- For smaller UA (between 15 to 150 kgs) different rules and regulations apply.
- Even smaller UA (below 15 kgs), have to follow regulations and standards that are more aligned to radio controlled aircraft models rather than complex commercial aircraft.

This idea concentrates on the small UA part of the UAS market and should allow them to be practically used by a broad range of end-users. It will allow small UAVs to be flown at relatively low altitudes, out of line of sight, outside controlled airspace (in fact one of the main product features is the ability to ensure that the UA does not fly in controlled airspace). The one important thing to consider is that the range of operation will be limited by the system performance and conditions, likely to be 10 to 15 miles radius of the system. This should not be a major limitation as small UA have short ranges at low altitudes. The system would not be restricted only to small UAS operation but it could be extended for operation of larger UAS if a number of systems were daisy chained together.

Problem

The major issue to resolve for small UAS is collision avoidance, which mainly focuses on collisions with manned aircrafts and incursion into the controlled airspace. This product will ensure that small UAVs stay within a predefined area well clear of controlled airspace and if any air vehicle fly into the predefined area then the UAV could be redirected.

Small UAVs are inherently safe due to their low mass and kinetic energy. However this gives them two major drawbacks:

- The UAV cannot carry significant avionics suite including for example a radar altimeter and collision avoidance systems.
- It is difficult to duplicate or triplicate the systems that are on-board a small UA. This is also driven by the requirement to make them simple and affordable.

The small payload means that two major safety aims cannot robustly be met, that is to avoidance of the ground and other air vehicle.

Solution

The solution to the problem is to place the collision avoidance and terrain avoidance system on the ground. At its simplest level a UA developed collision avoidance system could merely be used on the ground. The placement of the equipment on the ground however would afford a number of advantages in the design of the equipment as mass and power would not be considerations. The system design would also allow in operational calibration of the sensors. Therefore a more tailored solution could be developed. Additionally the decision-making aspects of the system could bring human into the loop and use other ground based surveillance systems such as primary and secondary radar.

The idea of the system is to monitor an area of airspace and give to the UA operator an area, which is safe to fly in. If another vehicle is detected then the UA flight path can be altered if any condition is anticipated.

The system has an added benefit of increasing the overall integrity of the air vehicle, as the system will monitor the position of the UA independently of the UA GPS system. By correlating the positions from the GBSAA and UA GPS it will be possible to assess the condition of the overall system. As the number of UAVs deployed is increased so the integrity level will increase, as more sources of position will be available. It will also place the system in a good position to manage the overall operation of the UA, especially if a number of CA ground stations are networked together.

6.2 GBSAA System Concept

6.2.1 System Requirements

Given below are some of the system requirements that have been identified at this stage:

- Primary requirement of the system is to provide aerial surveillance capability.
- It should be able to detect aerial obstacles such as UA, balloons, parachutes, birds, light aircrafts and also big commercial aircrafts.
- Typical range of the system would be 15 to 20 miles radius of the system. This is limited by the system performance and conditions.
- Provide operational calibration of the sensors by correlating the positions of UA from the GBSAA and UA GPS.
- Many GBSAA ground stations to be networked to maintain overall operation of UAS.
- Allow flight of UAS only in uncontrolled airspace and ensure they do not enter controlled airspace.
- Small UAVs to be flown beyond line of sight
- Allow small UAVs to be flown at low altitudes

6.2.2 Stakeholders

An initial stakeholder analysis has been carried out in order to capture the potential stakeholders of the system and also to determine the basic interactions/influences that exist between each of them. The stakeholders have been identified and grouped as show in Figure 6.1.

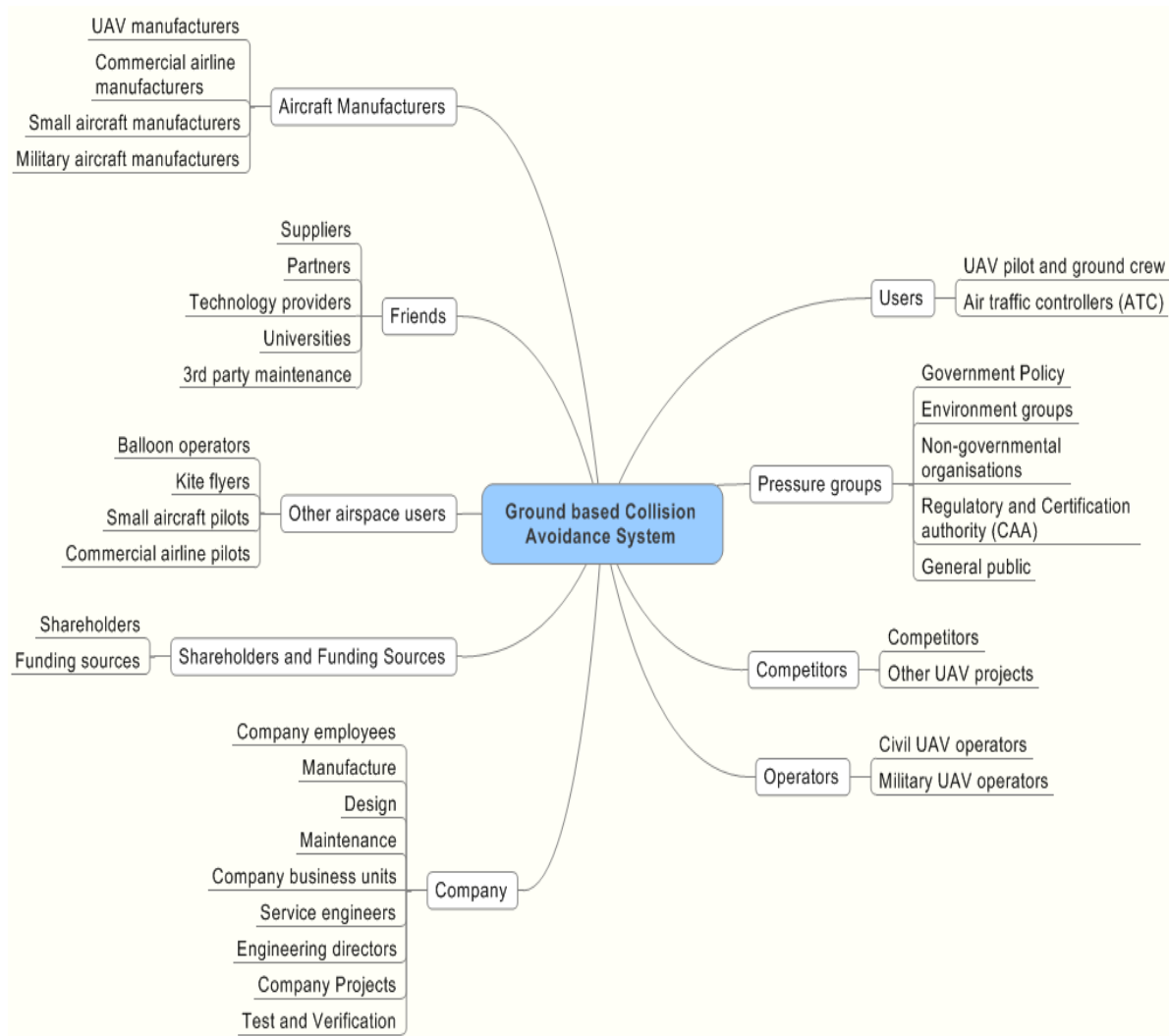


Figure 6.1 Potential Stakeholders and their Grouping

Between the stakeholders many interactions occur which affect the successful development of the system and its entry into the market. The main stakeholder's influences have been identified in Figure 6.2.

There are many influences taking place between the stakeholders and it is

important to identify the level of influence that each of the stakeholders will have on the development of the system, which has a profound effect on the success/failure of the project. Stakeholders can be further categorised into their degree of importance (i.e. the degree to which the stakeholder is to gain/lose with the success/failure of the project) and the degree of influence (i.e. the ability of the stakeholder to affect the project) according to a binary scale.

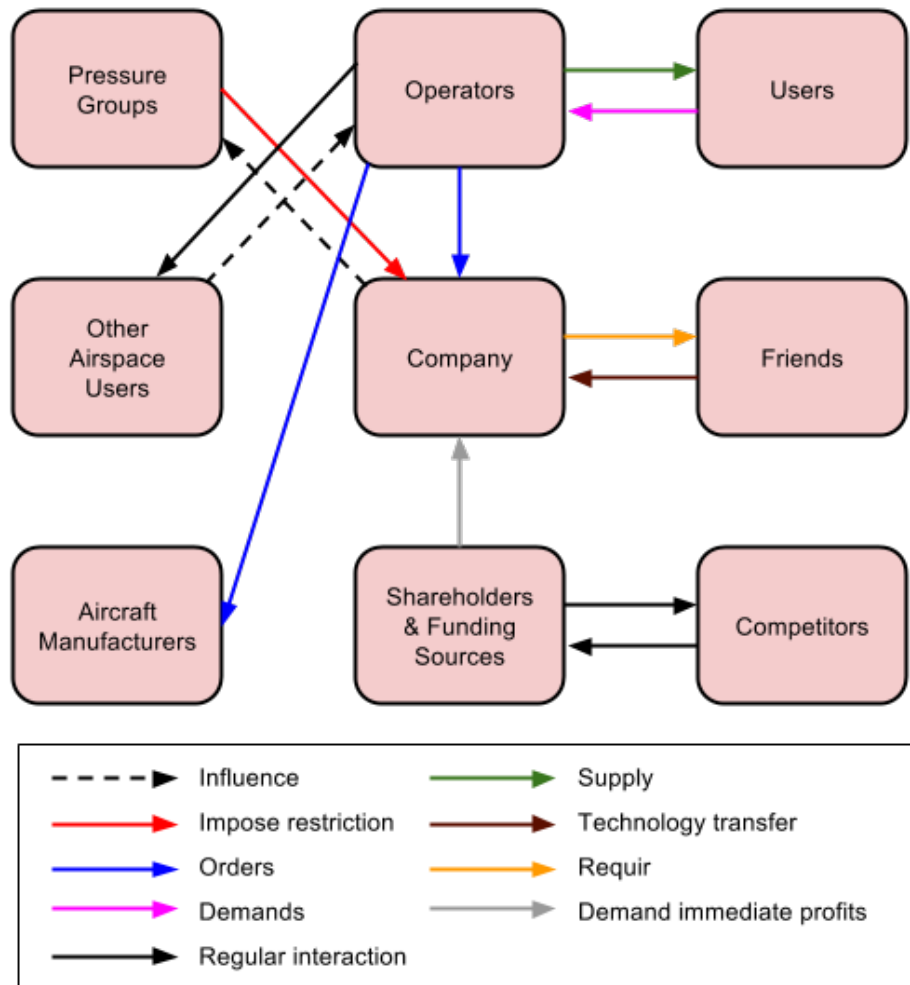


Figure 6.2 Stakeholder Influence Map

6.2.3 System Definition

6.2.3.1 *System Description*

A ground based UAV collision avoidance system comprises of a ground-based sensor

or combination of sensors, the output of which is then signal processed to detect the presence of targets in a confined area scanned by the sensors. The detected targets are then tracked continuously with the continuous scanning of the sensors. Overall integrity of the system can be improved by correlating the location of UAV from the ground-based sensor and the GPS location from the UAV. The calibrated tracks and the original tracks are fused to display on to a monitor, which can be used by the UAV controller to monitor the airspace where the UAV is operating in. The system could be programmed to trigger warnings in order to inform UAV pilot in case of potential conflicts with other airborne targets.

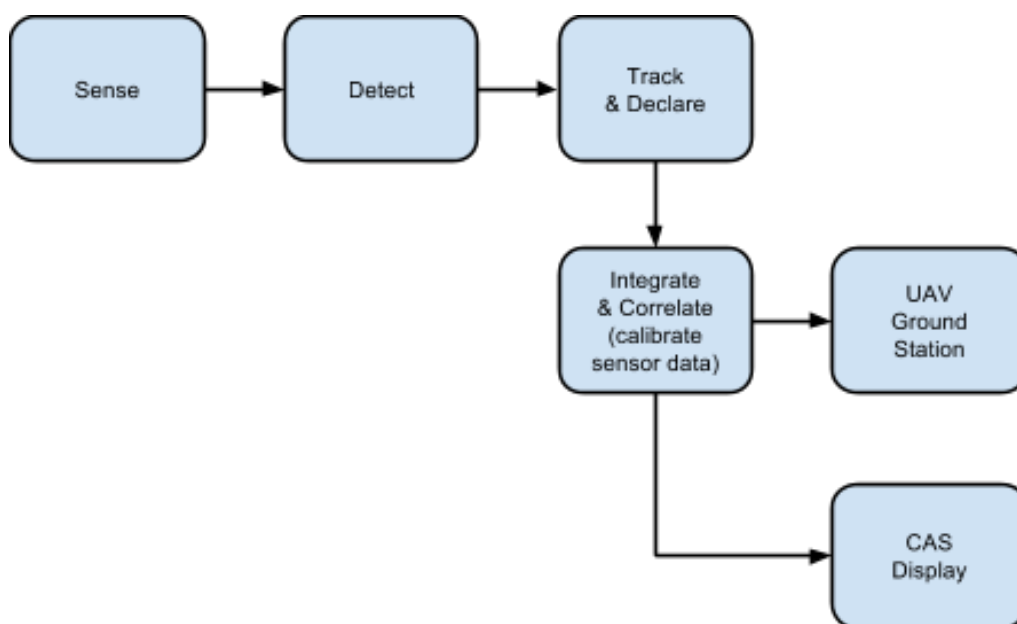


Figure 6.3 Ground based UAV Collision Avoidance System

6.2.3.2 Use Case

The use cases represent the functionality of the actors in the system. The users of the Ground based UAV collision avoidance system are UAV operator, ATM system and the Weather monitoring system as shown in fig 5. UAV operator utilises the ground based UAV CAS to perform tasks, such as monitor area of airspace, detect potential conflicts and also monitor weather and ATC information. ATM system performs the task of providing the ATC information to the UAV operator. And the Weather Monitoring system performs the task of providing weather information to the UAV

operator. The Figure 6.4 also shows the dependencies between the various functionalities of the UAV CAS system.

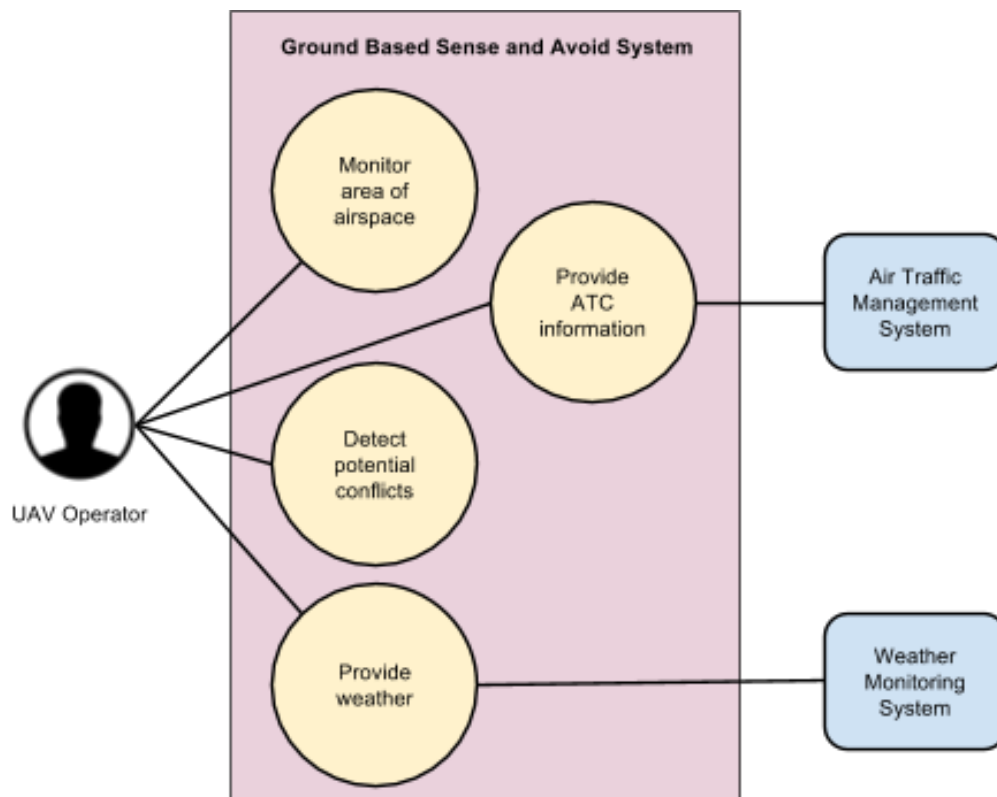


Figure 6.4 Ground based UAV CAS use case diagram

6.2.3.3 System Overview

The current position of the CAA is that sense and avoid system developed for UAV must be able to achieve the same level of capability and safety which is equivalent to the existing ‘see and avoid’ concept for manned aircrafts. In view of this requirement, the UAVs must show adequate capability to avoid non-cooperative targets in uncontrolled airspace. The obvious way to achieve a solution is by placing airborne sensor on the UAV, which can sense and avoid other air obstacles. However, in the near term i.e. in the next several years the technologies that will enable the UAVs to sense and avoid similar to manned aircrafts does not seem to be available in the foreseeable future. Hence the other possibility to develop a reliable sense and avoid system is by looking at a ground based collision detection solution. In order for the sense and avoid mechanism to meet the safety standards as required by the CAA,

developing a sense and avoid system, that is only based on the ground would not be sufficient.

One of the major drawbacks of using only a ground based collision avoidance system means that the air surveillance information has to be available to the UAV at all times to autonomously avoid other airborne targets. This in turn implies the dependence of the ground based sense and avoid system on the communication link between the UAV and ground control station to be highly reliable. Hence it would not be possible to a guarantee a highly reliable communication link; there might be instances where the communication link might be lost due to technical malfunction or weather conditions etc. Therefore in case of a failure of the communication, the UAV flight in non-segregated airspace will affect the safety of other aircrafts in the airspace even if contingency plans have been put in place. During the period when communication link is down between the ground control station and UAV, the UAV would have to operate without any form of a sense and avoid system. This situation would lead to the non-compliance of the safety standards as per the requirement of the CAA.

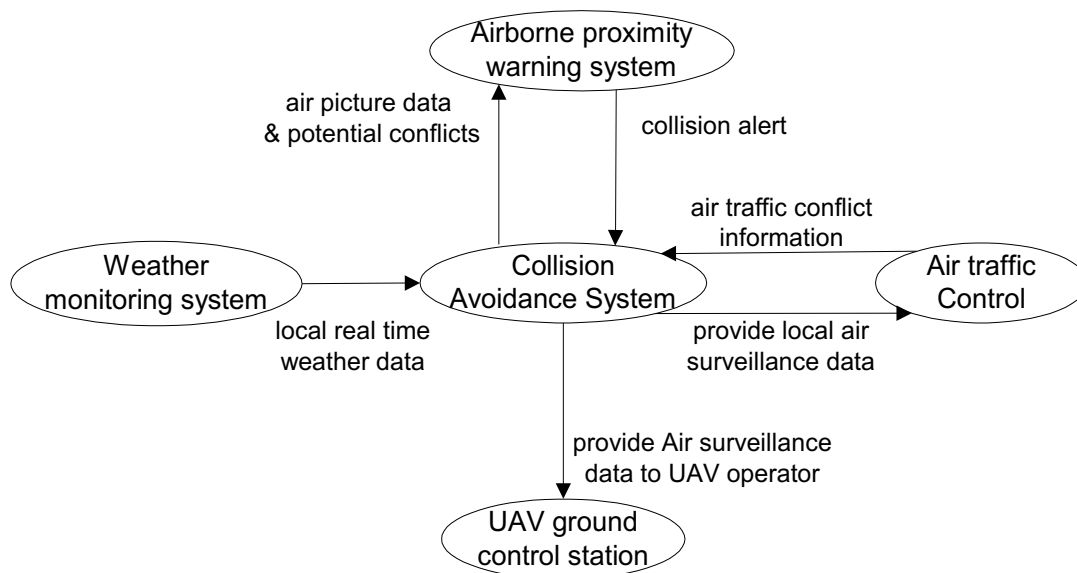


Figure 6.5 System level interactions of Ground based CAS

Other drawback of the ground-based system is that the safety of the airspace would

be severely hampered due to the lack of local situational awareness of other air obstacles around it that is available to the UAV. Thus in the instance of ground sensor sending incorrect information to the UAV, the UAV does not have the ability to check the integrity of the data available from the ground system. Hence apart from a ground based collision avoidance system there is a need for an airborne system, which acts as a last line of defence for the UAV to avoid it from colliding into other aerial obstacles especially manned aircrafts.

The airborne sense and avoid system, would be used only as a secondary system that would be complementing the ground based collision avoidance system. Hence the requirements and performance specifications of the airborne sensors would be less demanding compared to the ground based sensors. In this way, the use of airborne proximity warning system will greatly improve the integrity of the UAS sense and avoid system.

The overall system for the operation of small UAS in uncontrolled airspace is as shown in Figure 6.6. The ground based sense and avoid system interacts with other systems in order to provide the efficient and safe flow of air traffic in the uncontrolled airspace. Apart from interacting with the UAV ground control station, the sense and avoid system gathers information from the weather monitoring system in order to represent the areas of severe weather conditions on the sense and avoid display. This will help the UAV pilot to steer clear of harsh weather conditions that could affect the operation of the UAV. The UAV ground control station should also be able to communicate with Air Traffic Control (ATC) in order to provide information on system failure of any UAV. Also, the ATC could provide information on any commercial aircraft that might be heading towards the uncontrolled airspace where the UAV is operating due to a system flaw or error. Figure 6.6 also shows the additional uplink data that has to be transmitted to the UAV when sense and avoid system is based on the ground.

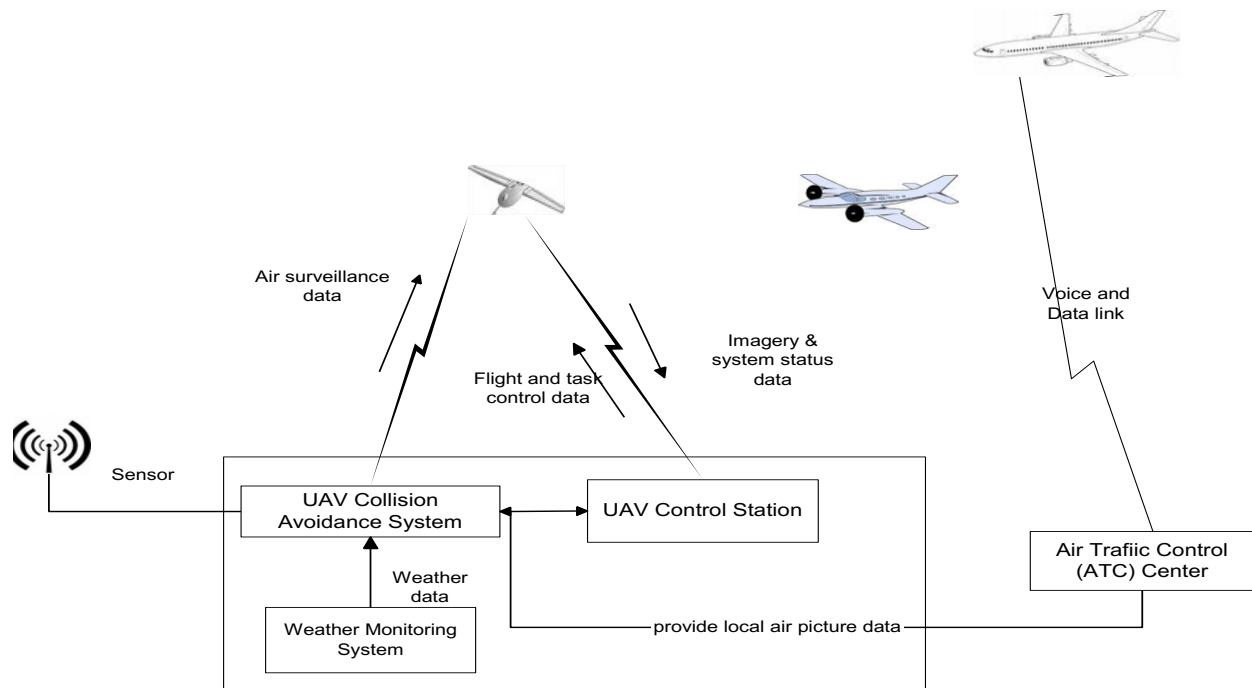


Figure 6.6 Overall system Overview

6.2.3.4 System Operational Aspects

The air target information obtained by the ground based CAS could be used in several ways by the UAV ground control station. The operational requirement of the collision avoidance system should be able to adapt its operational aspects depending on the mission of the UAV or if the situation of the UAV flight demands be in case of failure of other UAV systems. The ground CAS could be used for providing the following primary system operational requirements:

Strategic Collision Avoidance System (CAS): (verification of navigation accuracy) this is one of the most important and primary operational aspects to be provided by the ground CAS. The air surveillance data obtained from the ground-based sensor would be available on a display in the UAV ground control station. The sense and avoid system will not only fuse the air surveillance data and display it but it will fuse the position of the UAV obtained from the ground based sensor and the corresponding location obtained from the GPS placed in the UAV. Hence the comparison of the

location from two different sensor sources will improve the integrity of the data. Also the necessary correction can be made and fused with the airborne target data, which would provide more accurate information display to the UAV ground control station. Thus the strategic CAS could also improve the data integrity of the GPS obtained information that is vital part of the navigational system in a UAV.

Pure Navigational System (Duplicate or secondary system): In small UAVs the primary system used for navigation is a GPS. But the disadvantage is that they cannot carry redundant systems to improve reliability as is done by the larger UAVs. In the event of failure of the GPS or instances where the satellite constellations are invisible to the UAV (due to terrain or weather conditions prevalent), the navigational capability of the UAV could be severely hampered. This produces a massive risk to the safety of the airspace and may well lead to the UAV colliding into other airspace users. In such an instance, the ground based CAS could act as a secondary navigational system by transmitting the current UAV location to the aerial system. The air vehicle data obtained from the ground-based sensor could be transmitted to the UAV via the air surveillance data uplink. The UAV location data messaged could be updated very frequently in such a case so that UAV could use this information as a pure navigational system. Hence this would act as a redundant navigation system for the UAS flight in non-segregated airspace.

Tactical Mobile Sensor: Another operational use of the CAS could be as mobile sense and avoid system for rapid deployment of UAVs. If the sensor could be such that it could be configured for use on mobile platforms, this would provide a great advantage especially in search and rescue operation where rapid deployment is imperative. The sensor placed on a vehicle could be driven to any location as when the need arises or it could place on a temporary basis anticipating any incident may occur that may need quick deployment.

Covert Operation: For the military use of UAVs, it is necessary that UAV flight in UK airspace must be conducted in a covert manner. Under normal operation, the military

UAVs use transponders to broadcast their location information every few seconds for their entire flight in the UK airspace. Hence without the transponder, the ground controllers would not have any idea of the location of the UAV in the airspace. In such circumstance, the ground based CAS could provide the UAV operator with the position of the UAV.

Integrated Surveillance Architecture: The passive sensor could be part of future integrated surveillance architecture for the non-cooperative air traffic users. In several years air travel is projected to rise steadily and this means a crowded airspace. Hence to allow all the aircrafts to efficiently fly in a crowded airspace, there would be a huge requirement for reducing the separation distance between the aircrafts. In order to operate these aircrafts close together without compromising on safety and efficiency of airspace would be a major challenge to address in the future. One of the ways to address such concerns is by using technologies that will improve situational awareness of the aircrafts in the airspace. Also enabling the ATC operator to better understand the nature of airspace in which the aircraft is operating. Passive sensor technology is one such system, which would help the UAV operator to identify the non-cooperative targets in the airspace. With the ability for the ATC operator to see both cooperative and non-cooperative technologies, it provides a better situational awareness for the ground operator.

Portable air traffic control sensor system: The ground based sense and avoid system when integrated with other surveillance mechanisms such as ADSB (Automatic Dependent Surveillance Broadcast) and other flight information services broadcasts, could provide a better situational awareness of the air traffic in the local airspace. In this way, the information on position and heading of the airspace users could be used to maintain the separation between the manned and unmanned aircrafts as well as between all other airspace users. Hence the capability to detect both cooperative and non-cooperative air targets the portable system could be used in providing aerial surveillance in several applications involving both manned and unmanned aircrafts.

Integrated Portable Collision Avoidance System: An integrated solution could be developed for coastal surveillance applications. The existing coastal radar infrastructure could be used as illuminators of opportunity for a passive collision avoidance system on the air. When the UAV is operating in an area with radar coverage, the passive sensor on the UAV could receive the reflected signals from nearby air targets to determine the characteristics of air obstacles around the UAV. The air traffic data could be used by the UAV itself to make decisions or it could be sent to the UAV ground operator who may then direct the UAV on possible actions to be taken.

6.2.4 GBSAA Functional Overview

The USAS functions can be divided into two categories as pre-flight functions and flight operational functions. A brief description of the USAS functionalities is as given below:

1. *Pre-flight functions:* The various functions, which are carried before the unmanned aircraft starts its flight procedure, are referred to as pre-flight functions. Below are the pre-flight functions of the GBSAA:
 - *Deployment planning:* This is an important pre-flight function, which provides a profile of the sensor coverage and communications link availability for a requested flight path. It validates that the system integrity will be maintained throughout the flight operations by being within the coverage area of the GBSAA and thereby able to maintain separation standards at all times except during situation of loss of communication link.
 - *Flight plan validation:* Flight plan validation function checks the flight intentions against the existing airspace structure resolves any inconsistencies and authorises the flight plan. It uses information from the ATC centres to get latest updates on any restriction for the area of uncontrolled airspace currently under surveillance by the GBSAA. The flight plan validation functionality is somewhat similar to the flight plan processing performed in the current ATM environment.

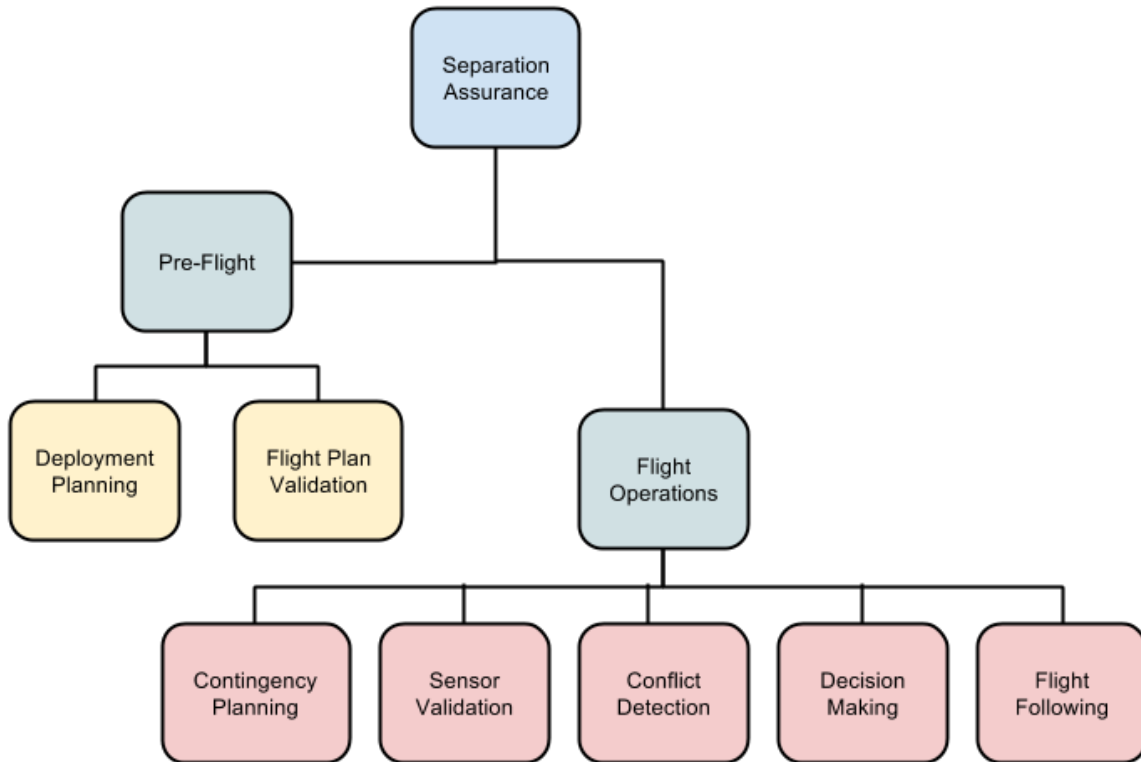


Figure 6.7 GBSAA functional block diagram

2. *Flight operational functions*: These functions are carried out during the flight operations of the unmanned aircrafts and they are all safety critical in nature that is any failure in their performance can be detrimental to the safety of the airspace.
- *Sensor validation*: Sensor validation is the most important functionality for the UAS operation and it is highly safety critical in nature. The sensor validation system compares the position data received from the on-board air vehicle to the location information coming in from the ground-based sensor. It checks the deviation in correlated data between them is above a certain standard required navigation performance level, the system can be shutdown to avoid further degradation of the overall system.
 - *Contingency planning*: The contingency planning function consists of a set of possible emergency landing points that are closest to the UAV when it goes into an emergency mode. Depending on the flight plan of the UAV, a set of contingency plans is generated before pre-flight and during an emergency

situation the contingency planner provides a set of options to the UAS operator.

- Flight following: This function is real time flight path validation system that it checks the flight intentions in the original flight plan against the actual flight path taken and confirms that the flight is following its original flight plan or it alerts the UAS operator of the violation of the flight plan of the aircraft.
- Conflict detection: Conflict detection is a key function of GBSAA as it is responsible for maintaining safe separation between the unmanned aircraft and other airspace users. The de-separation algorithm receives the air surveillance picture data from the ground based sensor and determines the potential aircrafts that may led to violation of separation. It then computes a safe manoeuvre to be taken or area where the unmanned aircraft can operate in order to maintain the safe separation distance from the threat aircrafts. This way any possible conflicts with other airspace users in the monitored area is avoided and ensured that unmanned aircraft stay well clear of threat aircrafts so that there is no possibility of a near mid-air collision.
- Decision-making: The decision-making function is a support tool which enables the UAS operator to make the decision on the overall condition of the system and perform actions if the system performance is below a certain required level. It integrates the system performance across all the GBSAA flight operation functions and presents an overview of the overall condition of the system. This whole system condition-monitoring picture aids the UAS operator to making critical decisions on operating the system at the current performance levels.

6.2.5 GBSAA System Elements

The architecture of GBSAA concept of operations consists of several key elements. Several aspects of these elements are interdependent and have an impact on the operations of the whole system. The elements also vary depending on the several factors such as the location of sensor, operating airspace and a given unmanned platform. Hence it is important to determine the how the GBSAA system aspects vary based on these various factors. There are five main elements that will impact the overall operation of the GBSAA system.

The first element is a ground-based surveillance sensor. It provides a local capability for the detection of cooperative and non-cooperative aircrafts flying in the surveillance region in order to support UAS operations in the operating airspace. The surveillance sensor will form a key element of the sense and avoid architecture as it determines the time required to detect and track a target. The detection and track times of the surveillance sensor are highly dependent on the probability of detection of the sensor at the target intrusion point. The probability of detection in turn depends on several factors such as terrain obstacles in the local environment, target characteristics and its location. It is important to determine the site-specific factors of the surveillance radar that impact the detection and track acquisition times of the radar. For safe operation of UAS in non-segregated airspace, the UAS must operate at a safe separation distance above the bottom of radar coverage and also within the horizontal coverage area of radar, such that the intruding aircraft can be detected and tracked in time to avoid the collision risk.

The second element is the separation strategy. Separation strategy refers to the separation procedures and margin of separation from the traffic encountered. The margin of separation aspect is determined by evaluating the time take to evaluate all the stages involved in the sense and avoid encounter process. A typical sense and avoid encounter consists of following stages: detect and track, evaluate collision potential, prioritize threat to raise alert, evaluate avoidance manoeuvre and finally execute the manoeuvre. Currently, the separation measure used by the ATC (Air Traffic Control) for manned aircraft separation conflict alerting is based on a vertical separation of 1000 feet and a lateral separation of 1 nautical mile [11]. However, these are for manned aircraft operation as well as in regions where there is ATC control. Thus, these measures would not be suited for UAS and especially those operating in uncontrolled airspace. In order for UAS operations in uncontrolled airspace supported by USAS on the ground, there is need to understand and examine the margin of separation for various traffic situations.

The third element is the GBSAA display. The GBSAA display acts as an interface that provides the air traffic information to the UAS operator. The primary objective of the GBSAA display is to provide the UAS operator with an air situation

picture, so that the operator has the situational awareness information to ensure safe UAS operations. The GBSAA system will provide level 2 situational awareness to the UAS operator. Hence the pilots need to be presented with the information in an effective way so that they take evasive action when separation violation is predicted. The final element is the crew workload level. Depending on the several variations of the locating the GBSAA display (in GCS or separate ground observer station for GBSAA operator) a UAS pilot/observer will have the task of monitoring the GBSAA display and taking manoeuvring actions in the event of a potential collision. The separation procedures will have an impact on the crew workload level and it is critical to determine a set of separation procedures that will be able to manage the crew workload to an acceptable level.

6.3 GBSAA Systems Operation

6.3.1 GBSAA Concept of Operation

The primary objectives of the GBSAA system are; firstly, to be able to detect and track both cooperative as well as non-cooperative aircrafts that may intrude in the operational area of the UAS, and secondly the ability of the GBSAA system to effectively de-conflict a potential collision.

In a GBSAA system operation, a ground-based sensor continuously detects and tracks the UA under the control of GCS and also other aircrafts within the sensor surveillance region. The detected air targets are then displayed to the UAS operator present on the ground. In case of a loss of separation between the UA and any other intruding aircraft that may lead to a potential collision, an alert is generated and displayed. Based on the alert the UAS operator decides the necessary manoeuvre to be taken and executes it so that UA moves to a safe location. Hence the GBSAA sensor continuously provides situational awareness information to the UAS operator. Apart from detection of UA by sensor, the UA position information is also available at the GCS as it tracks the UA through its GPS position received via the telemetry link continuously.

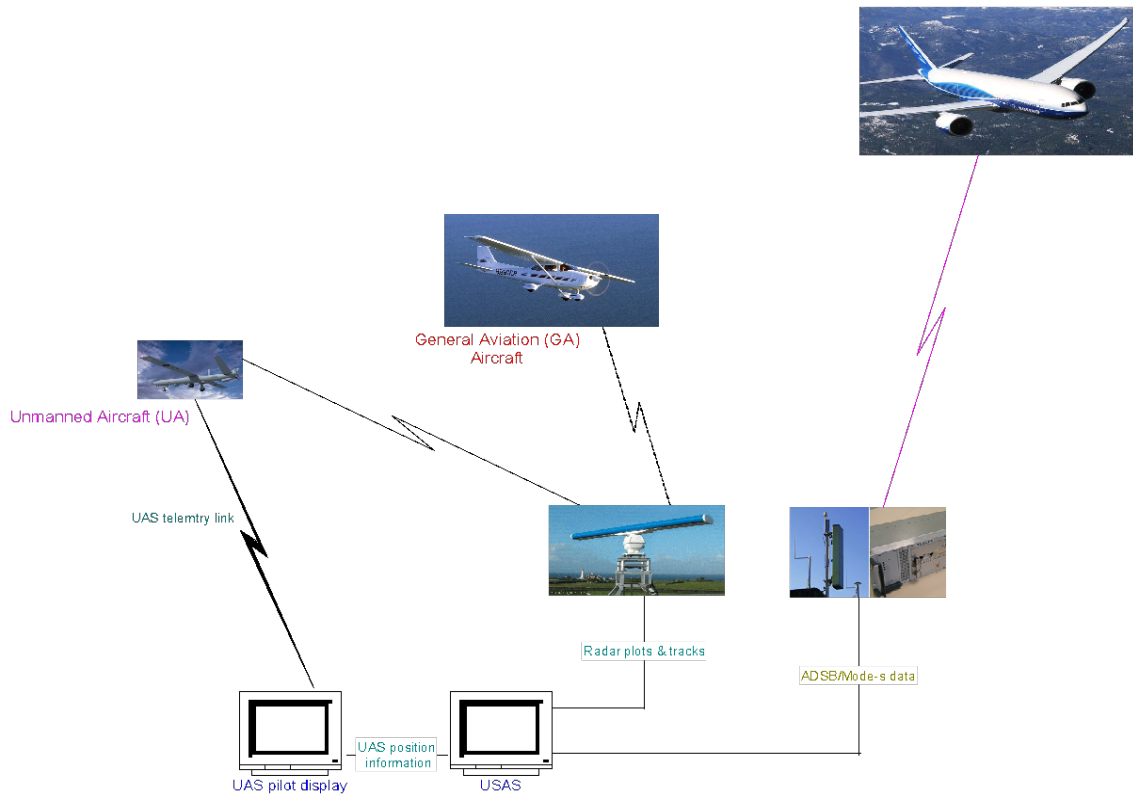


Figure 6.8 Concept of using GBSAA for operations of UAS in non-segregated airspace

The initial GBSAA implementation is envisaged for UAS operations in the non-segregated airspace and an incremental access procedure would be followed. Hence the GBSAA system being discussed here is aimed at UAS operations in uncontrolled airspace. However, the concept of operations does not change when the operations are carried out in controlled airspace and for different operational scenarios to access the airspace in the future.

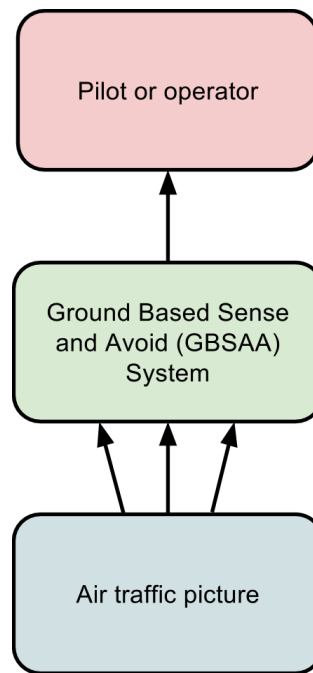


Figure 6.9 GBSAA service level view

6.3.2 Operational Level Description

At the service level, the GBSAA acts as a stand-alone system that provides a service to the users (in this case UAS pilot). In order to provide the service, GBSAA has to interact with the users as well as with external systems in the overall system-of-systems and its external environment. The several interactions of the GBSAA with the outside environment to provide the service are shown below through the external view.

Operational Scenarios

The operational concept of GBSAA has been developed by using scenario-based analysis of the operational needs of GBSAA from UAS pilot's perspective in case of an intruding aircraft about to enter or within a defined threat volume.

There are two proposed scenarios that are as follows:

- Air traffic situation display
- Intruder alert

Scenario 1: Infringement of intruder aircraft

Context

GBSAA provides air traffic situation awareness all the air targets both cooperative and non-cooperative aircraft in a surveillance region. The surveillance region covers an area for air traffic from the ground level up to 3000-4000 ft. and a radial distance from the radar of approximately 15 –20 nautical miles.

Trigger Event

An intruding aircraft enters the threat volume that may result in separation violation between the UA and the intruding aircraft.

UAS operator Actions

The actions taken by the UAS operator provided with the GBSAA are following:

- Determine the position, speed and altitude of the intruding aircraft
- Initiate a landing of the UA or a separation manoeuvre depending on the current position of intruding aircraft.

Impact on UAS Operator

The impact of the UAS operator actions for an infringement in the surveillance area is as follows:

- Loss of critical oversight of UA monitoring
- Workload of UAS operator increases: situation monitoring

Scenario 2: Track quality or uncertainty information

Context

Similar to Scenario 1

Trigger Event

The uncertainty in the position of UA is above a specified threshold. The uncertainty information is obtained by correlation of position of UA from its radar track information and GPS position on board the UA.

UAS Operator Actions

The actions taken by the UAS operator with the GBSAA are as follows:

- Wait for 5 seconds or until next refresh time of radar
- If uncertainty still above allowed threshold, then land the UA as soon as possible

Impact on UAS operator

The impact of the UAS operator actions for an uncertainty threshold warning:

- Increase workload – situation monitoring for more than normal time
- Loss of critical oversight of UA monitoring

Operational Services

This section provides a description of the services provided by the GBSAA from a user perspective using the operational scenarios presented in the previous section.

Air Traffic Situation Display

Through the detection of all air targets it is aimed to provide the traffic situation picture to UAS operator for adequate monitoring of aircrafts within the surveillance zone.

Service Description

Definition: Provision of position reports of CT and NCT targets in a pre-defined surveillance zone.

Operational range: The service shall be available in a pre-defined surveillance zone, in all traffic densities and primarily for uncontrolled traffic region.

Dependencies: The performance of the radar will be affected by surrounding environment and prevailing weather conditions.

Quality of service parameters	Details	Performance characteristics
<i>Detection range</i>	Effective range of radar based on local constraints	Typical values: Horizontal: 15 to 20 NM radius Vertical: from ground to 5000ft.
<i>Probability of detection</i>	Probability of target detection based on target characteristics (mainly RCS)	>99% for targets greater than RCS of 2m ² >96% for targets less than RCS of 2m ²
<i>Probability of false alarms</i>	Probability of false alarms raised against total number of target detections	
<i>Position accuracy</i>	Horizontal Vertical	
<i>Speed vector accuracy</i>	Horizontal speed Vertical speed	
<i>Update rate</i>	Maximum time allowed between two position reports	Between 1s and 5s

Table 8: Quality of Service Aspects [15]

Threat area infringement warning

The threat area infringement warning service provides warning to UAS operator in the event of a target aircraft entering the threat area.

Service Description

Definition: Provision of warnings to UAS operator for airspace infringements caused by target aircraft. The warnings are provided with a parameter time to infringement or after entering the threat area (selected by the user).

Operational range: The service shall be available in the entire threat area and in uncontrolled airspace under all traffic densities.

Responsibilities: Significant change in responsibility of UAS operators as they have to react to warning.

Dependencies: The service depends on the target detection to obtain target position and state vectors.

Quality of service parameters	Details	Performance characteristics
<i>Warning response time</i>	Time delay between a target infringement situation occurring at the input to the warning being generated at its output	<1s
<i>Probability of false infringement warning</i>	Probability that the service reports infringement when there may not be any	**No more than 3 per week of operations
<i>Probability of nuisance warning</i>	Probability that the service reports a short-living target infringement situation (duration is below pre-defined value)	

Table 9: Quality of Service Aspects [15]

Track uncertainty warning

The track uncertainty warning service provides warning to UAS operator about track quality below a pre-defined threshold.

Service Description

Definition: Provision of warnings to UAS operator for track quality below the pre-defined threshold level.

Operational range: The service shall be available in the entire surveillance area and

in uncontrolled airspace under all traffic densities.

Responsibilities: Significant change in responsibility of UAS operators as they have to react to warning.

Dependencies:

The service depends on the target detection to obtain target position and state vectors. Correlation of radar UA position report and UA position report from GCS required accessing the GPS data for UA communicated via telemetry link to GCS.

Quality of service parameters	Details	Performance characteristics
<i>Warning response time</i>	Time delay between a track quality uncertainty situation occurring at the input to the warning being generated at its output	<1s
<i>Probability of false infringement warning</i>	Probability that the service reports track uncertainty when there may not be any	No more than 3 per week of operations
<i>Probability of nuisance warning</i>	Probability that the service reports a short-living track uncertainty situation (duration is below pre-defined value)	

Table 10: Quality of Service Aspects [14], [15]

6.3.3 GBSAA system Analysis

Placing a UAV collision avoidance system on ground provides for many distinct advantages. The primary advantage of placement of equipment on the ground is that in the design of equipment, mass and power would no longer be considerations. Other benefit of a ground based sense and avoid system is, it provides a complete 360 degrees view of the approaching air traffic and a large detection range compared to airborne collision avoidance system which provide only the frontal view of the air targets within a short range. Finally, this system keeps the human in the loop for decision-making aspects involved with UAS operation.

As the sense and avoid system is for use primarily in uncontrolled airspace and replaces the human pilots eyes in the sky, only the non-cooperative technologies are being investigated. Non-cooperative technologies are those that do not rely on other aircrafts carrying a similar device to detect them in the shared airspace. Another

advantage of non-cooperative technology is the fact that it can be used to detect both airborne targets as well as ground-based obstacles. These non-cooperative technologies can be divided into two basic systems: active and passive. Active systems are those that transmit a particular kind of signal and wait for reflections from the surrounding environment to detect the presence of nearby obstacles. Some examples of which are radar, sonar and lidar. On the other hand, passive systems, listen to the signals transmitted or reflected from other obstacles in the vicinity for their detection. A few examples of this type of system are acoustic, passive radar, EO (Electro-optic) and IR (Infra-Red) systems.

Boat Radars

Boat radar is used for avoiding collisions with other ships or obstacles at sea and is extremely important under adverse weather conditions such as fog or heavy rain when the visible horizon is very low. The range of the radar is highly dependent on the frequency as well as the clutter environment that exists around the radar. Generally, the horizontal beam width of marine radars is much less compared to the vertical beam width to provide better accuracy and resolution between targets.

Range

From 20 nm to approximately 100 nm

(Dependant on operating wavelength & existing environmental conditions)

Antenna types

Radome

Approximate 20" in size

Range up to 40 nm

Price range – 2500 to 3000 (in dollars)

Planar Array

Approximately 4' in size

Range up to 100 nm

Price range – 5000 – 8000 (in dollars)

During navigation in turbulent weather a variation in the roll of between 10 to 15 degrees (without use of a radar levelling system) one side of radar can detect underwater vessels such as submarines whereas other side can detect aircrafts. This is due to the tilting of the radar antenna towards the side of the rolling of the boat.

This phenomenon may be useful to investigate further and look into whether boat radars can provide a low-cost solution for detecting low flying aircrafts in the coastal areas.

If a boat radar were fixed above a lighthouse structure in a tilted manner, such that it is able to detect low flying aircrafts, a disadvantage is that during half of the scan period radar coverage is towards the ground and during the other half the coverage is on the airspace above. Hence by using one of these a portion of the airspace can only be covered in a single scan period of the radar. Thereby many radar sensors have to employ to cover airspace if a complete circular region around single radar has to be covered. Although this could be done, a major limitation in the installation in the network of lighthouses is that each lighthouse is scattered at various locations. Thus the whole airspace would be difficult to cover by just installing the radars on top of each lighthouse in the lighthouse network. Hence it would not be appropriate to use commercially available boat radars in an arrangement to satisfy the system requirements.

Thales Coastal Radar family

The new coast watcher family of radars consists of a portfolio of three variations for providing a capability for any coastal surveillance application.

The coast watcher 10 is medium range coastal surveillance radar, covering distances of about 42 nm from the radar. The kinds of mission capabilities of this radar are site surveillance (ports, platforms etc.), anti- intrusion detection and territorial waters surveillance. Some of its features are that it can detect small targets (wooden boats, jet-skis etc.) under all weather conditions. The radar is well suited in terms of the range available but it does not provide any aerial surveillance capability for detecting low flying aircrafts.

The Coast Watcher 100 is long-range coastal surveillance radar that also provides a low altitude surveillance capability apart from the ability to detect surface targets. Surface targets up to range of 100 nm can be detected and aerially it can detect small aircrafts flying at about 1500 ft. Some of its mission capabilities are to provide site surveillance, territorial waters monitoring and coastal policing. Automatic detection of all targets under all weather conditions is possible with this radar. Although it serves the aerial surveillance capability, however it is limited in coverage and other disadvantage is that the antenna size is large compared to coast watcher 10. One other problem would be the higher cost associated with a bigger radar. The cost of the radar and its inability to satisfy the complete set of features required would be a major driver towards inability of choosing this product to provide a solution.

Finally, the third radar is Coast Watcher 200, which is a very long-range surveillance and early warning system operating at distances of over 200 nm. It uses over the horizon technology to detect targets at very long distances. Some of the missions performed by the coast watcher 200 are fisheries protection, territorial waters surveillance and coastal defence. One of the major drawbacks towards the implementation of this system is the cost as it would be expensive to install and maintain the radar during its period of operation. The cost of acquiring and running radar would be much more than cost of a UAV. Hence the cost factor would be a major hurdle towards the deployment of this system.

Thales Homeland Alerter 100

Homeland Alerter is a passive coherent location sensor, which uses the transmissions from FM radio broadcasts. The transmission signals could be extended to include analogue as well as digital TV. It has been developed to offer capabilities mainly for homeland security such as coastal surveillance, airport protection and sensitive site protection. The sensor provides all day surveillance with the ability to track real time air targets and having a detection range of nearly 100 km. It could be configurable for mobile platforms or fixed sites. A further set of specifications for the product is not

available at the moment. And also, an approximate estimate of the cost of the product is not available yet. The cost will be a major factor for use of this radar into the system. The cost of the product can be justified if the sensor could be used for dual purpose. That is if it could provide a capability for the detection of surface and aerial targets. Although this a potentially cheaper mean compared to a conventional radar. And they could be used as part of a network of sensors that when deployed can provide a detection capability throughout an area of uncontrolled airspace.

In the next stage, the technical specifications of the Homeland Alerter has to be looked into and an assessment of whether it is able to detect small targets such as UAVs as well as surface targets such as jet-skies or small wooden boats. It is very important that the radar sensor is able to detect these types of targets.

ThalesRaytheonSystems Improved Sentinel Radar Sense and Avoid Display System

The Improved Sentinel Sense and Avoid system utilises Sentinel Radar which is a highly mobile, three-dimensional phased array systems operating at X band frequency range. The Radar automatically detects, tracks and identifies other airborne objects including helicopters, UAVs, gliders, small aircrafts and balloons. The air surveillance coverage of the radar has an elevation angle of 55 degrees and azimuth coverage of 360 degrees with a search range of more than 75 Km.

The improved Sentinel Radar coupled with the SAVDS software from SAVDS Inc., provides a high level of safety for UAVs flying in global airspace. The software system fuses the UAV GPS position data with target data from the ground-based radar on to a display co-located with the UAV ground control station. Any air conflict data could be available for immediate viewing by the UAV pilot.

SAVDS Inc. and TRS are actively involved in a validation program, the aim of which is to systematically demonstrating and documenting the functionality of the SAVDS. Currently the validation testing is at phase 3 which involves the actual UAS flight with the live data form sentinel sense and avoid system for flight de-confliction with all

airborne obstacles compared to de-confliction recommendation from a chase aircraft. The next phase would involve compiling and analysing the results obtained from the previous phases and providing the necessary documentation of the validation testing as well as further demonstrations to the FAA achieve full system certification.

<i>Radar sensors</i>	<i>Detection range (nm)</i>	<i>3D air surveillance</i>	<i>Cost</i>	<i>Beamwidth</i>	<i>Multiple Targets</i>	<i>Maximum Altitude</i>
Boat radars	20 - 100	No	Very Low	Very narrow (1.5° azimuth & 22° vertical)	Yes	Low
Thales coastal radars	40 - 200	No	High	Narrow & broad	Yes	Low and High
Homeland Alerter	60	Yes	Low	-	Yes	Low & Medium (Up to 16000ft)
Sentinel radar S&A system	50	Yes	High	-	Yes	Low & Medium

Table 11: Comparison of radar sensors

Alternative Sensor Technologies

LIDAR

LIDAR technology is a new emerging technology and it is being used mostly in aerial platform for terrain mapping and other geological survey applications. The lower cost

of the technology and a day/night operation it offers several advantages compared to other sensor systems in use. The use of LIDAR is predominant in coastal zones and forest areas where it is more accurate as compared to other regions of surveillance. It is also fast emerging as a superior data collection tool as compared to photogrammetric tools. But for use in this project the need is to provide a superior surveillance capability as compared to a radar system or other sensor systems for that matter.

This technology has several disadvantages as well. Firstly, the lower cost of the technology is on the lifecycle of the technology use, but initially the cost of the acquisition of the equipment is very high which are more than for radars. Secondly, although LIDAR can be used for 24 hours a day but it does not perform well under harsh weather conditions such as rain, snowstorm, cloud cover, fog and other extreme weather. The technology relies upon the collection of large amounts of data for providing an accurate measure of the terrain maps. Additionally, high winds and turbulence can cause problems with the inertial system. However, this problem will not be present in a ground based LIDAR system because the scanner is in a static position all the time.

Hence in the coastal regions of UK, the requirements are such that the system has to perform accurately and efficiently under extreme weather conditions, which change very frequently. Hence a LIDAR system is ruled out from the list of sensors that could be used for the implementation in this system.

SONAR

Sonar technology is not the best suited for use as ground based UAV collision detection system. This technology was originally developed for use as underwater detection system. In an active sonar system, sound waves are transmitted underwater and the reflected waves are then used to create an image of the obstacles or other enemy targets. There are also passive sonar systems that only listen to the various sounds originating or reflected by the obstacles to provide the stealth capability.

However, the disadvantages of using Sonar as a UAV sense and avoid system is that sound waves travels slower in air than water. Also, the UAV has to be in close

proximity to the sonar for it to be detected. Another disadvantage is that the speed of sound changes greatly with temperature variations, and atmospheric temperature variation is much more than the variations in water.

Non-cooperative technologies	All weather operation	Day/Night	Detection range	3D aerial surveillance	Cost
Radar	Yes	Yes	High	Yes	High
Lidar	No	Yes	Low	No	Low
Sonar	No	No	Very Low	No	?
EO	No	No	Low	No	Low
IR	No	No	Low	No	Low

Table 12: Alternative Sensor Technologies

Potential Solution

Among the candidate technologies that were investigated, radar based systems seem to be the best suited form of technology for use as a ground based collision avoidance system. As mentioned above radars have an all-weather capability and can see through cloud at comparatively far off distances as compared to other sensor systems. And with the collision avoidance system based on the ground, one of the major disadvantages of radar being heavy, bulky and power consuming would not be of considerations.

Radar based sensors seem to provide many advantages for implementation as ground based UAV collision avoidance system. Among the ground based radar systems that were investigated, a set of criteria were used to assess the systems and select the radar system that could be best suited for use as a ground based sense and avoid system.

System Performance Model

In the basic GBSAA model the parameters, which are necessary for analysing the whole feasibility of the system is:

- Target Radar Cross Section (measure of how detectable the target is with a

radar)

- Time taken to detect target
- Time taken to return to safe state

Surveillance radius = 10 nmi (same as radar detection range) [18.52 km]

Threat radius = 8.63 nmi (As small aircraft threat must be detected 16 km away from landing site)

Operational radius = 5.39 nmi (As given in timeline model as 10 km operating radius)

Time required for UAS with an average speed of 80 knots and at a distance of 10 km and a height below 300ft to land to a safe point is = 4 min 40 sec

Hence the UAS should start moving to landing site when the target is at least 5 min away from landing point.

Commercial aircraft at 5 min 40 sec (at 250 knots) = 36 km from landing point

Small aircraft at 5 min 57 sec (at 120 knots) = 16 km away from landing point

Unmanned aircraft at 5 min 60 sec (at 80 knots) = 11 km from landing point

Approximate detection range for the targets using Thales Coast watcher 10:

*Keeping Power aperture product at 15915.5 for the unknown parameters in the datasheet.

Commercial aircraft (RCS = 3 m²): [13 nmi]

Detection range, R_D = 11.87 nmi (Calculated from model) [17.09 nmi]

Small aircraft (RCS = 2 m²):

Detection range, R_D = 9.5 nmi (from performance model) [12.46 nmi]

Unmanned aircraft (RCS = 1 m²):

Detection range, R_D = 8.752 nmi [11.43 nmi]

Aperture area = 3.67 m² [10.46 nmi]

Effective aperture area: - Calculated on the basis of a rectangular aperture with a width of 1.2 ft and antenna length approximately 10 ft.

Calculated based on the antenna height and target altitude taking into account spherical earth model

RCS = 1 m² : Radar antenna height = 1 m ASL ; Detection range = 16 nmi

RCS = 10 m² : Radar antenna height = 2 m ASL ; Detection range = 26 nmi

The Basic system performance model parameters are shown in Figure 6.10.

BASIC SYSTEM PERFORMANCE MODEL

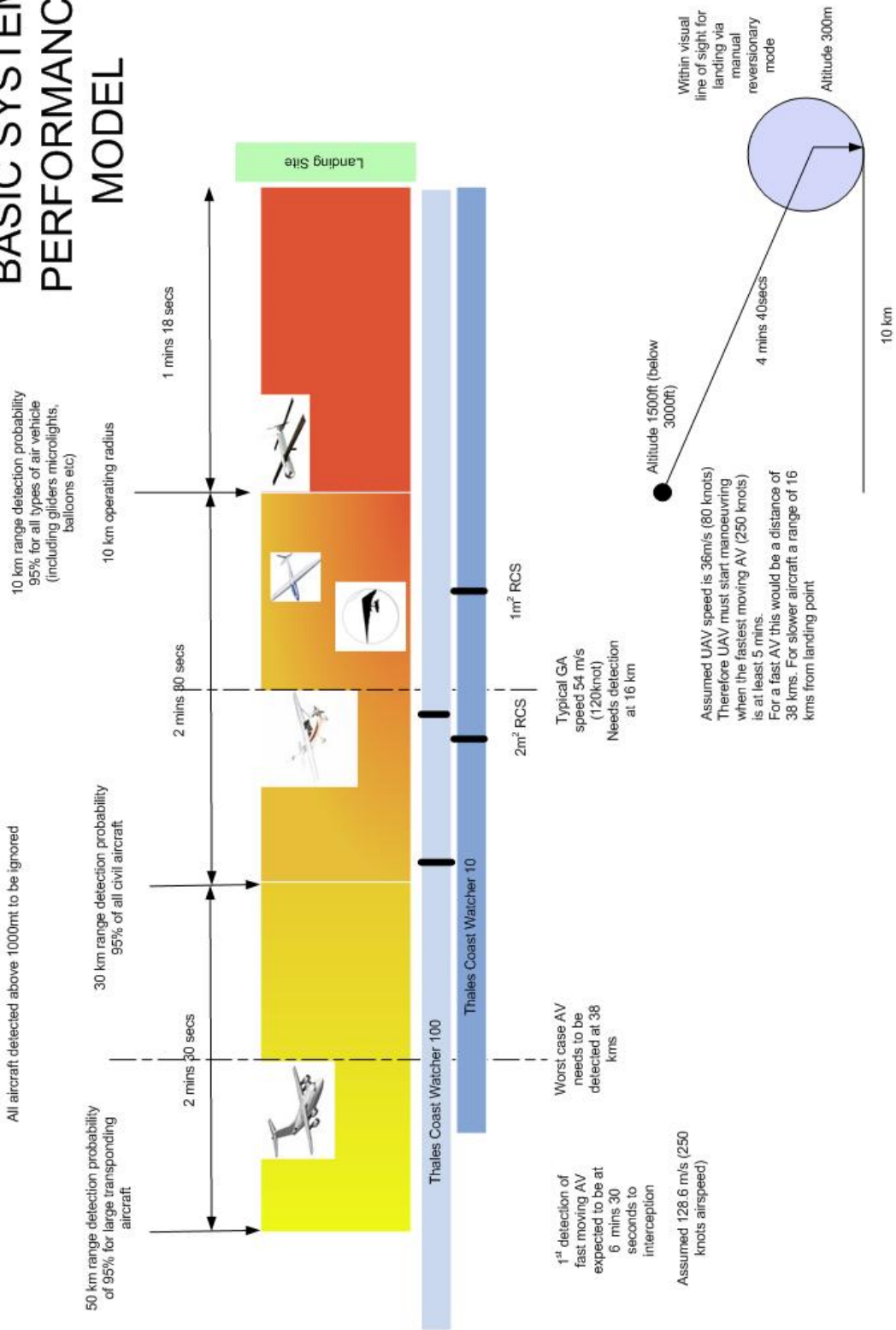


Figure 6.10 GBSAA System Performance Model

6.4 GBSAA: Proving the Safety Case

In order to develop a safety case for the GBSAA system for unmanned aircraft operations in unsegregated airspace, it is necessary to prove that the sense and avoid capability of the system for unmanned aircrafts is better than the current equivalent 'see and avoid' method used by the manned aircraft pilot's in the type of airspace under consideration [10]

According to the aviation authorities, the UAS operations in non-segregated should not in any way have a negative impact on the safety of the airspace [11]. This underlines the fact that, basic tenets for the deployment of UAS in non-segregated airspace must be based on UAS properties such as equivalence and transparency. This in turn means a UAS must behave like a manned aircraft [10]. In terms of collision avoidance procedure for UAS, this means that UAS must be able to a sense and avoid capability that is similar or better than a pilot of manned aircraft especially for detection and tracking of non-transponder equipped aircraft. The UAS collision avoidance performance measures are not clearly defined yet. The performance measures that are available at this stage are more qualitative in nature [10]. The system developer's currently having to work with the basic performance requirements that the UAS collision avoidance must be equivalent or more effective than collision avoidance function of manned aircrafts.

The challenge arises due to several issues. Firstly, the human skills and ability vary from pilot to pilot. The visual perception and processing varies significantly and all the pilots do not have the same visual scanning pattern. The frequency of scanning also varies from pilot to pilot. Apart from this the pilot's see and avoid process is affected by physical and psychological issues [10]. The external environment especially the weather conditions have a considerable effect on the performance of the human visual range. The pilot's view is also affected by the size of the cockpit and the aircraft type. In order to factor in the degradation caused due to each of these factors and develop equivalent performance metrics for sense and avoid for UAS is a complex task.

There have been several working committees, which have been looking at the issue of collision avoidance. And the proposed solution so far has been based on

ASTM F-38 committee published standard, which most the system developers are following for developing sense and avoid system for UAS. The standard is based on the manned aircraft pilot maximum viewing angle of $\pm 15^\circ$ in elevation and $\pm 110^\circ$ in azimuth and also being able to respond to avoid a collision within 500 feet [2]. However, analysis of data available from mid-air collisions shows that they occur near an airfield where traffic volume is high and mainly at lower closing speeds. Most mid-air collisions occurring at low speed happen when two aircrafts are travelling roughly in the same direction when a faster aircraft is overtaking a slower aircraft. This situation may arise in case of UAS as cruising speed of many UAS are less compared to other manned aircrafts. Hence considering this limitation the standards based on limited field of view may not be enough. However, in UAS the backward-looking capability is achievable by placing sensors in such a way that full 360 degrees is possible [2].

The research on mid-air collisions also reveals that most of the collisions occur when visibility is normal during day and in uncontrolled airspace [2]. This also outlines the inherent limitation of the 'see and avoid' procedure and in the future with the increase in traffic of lighter aircrafts this might become a serious limitation. Hence to base the UAS collision avoidance performance on a standard that has many limitations may not guarantee certification of UAS sense and avoid systems.

Although the challenges do exist in terms of defining the performance measures for UAS sense and avoid, a set of agreed upon performance parameters and assessment methodologies is a key factor to understanding and moving towards a viable implementation strategy for SAA for UAS. The GBSAA initiative will provide a way to gather, test and verify data along with several modelling and simulation activities that will enable to define the system requirements and to support the development of a safety case.

In exploring the UAS SAA system requirements and performance measures, one of the key areas is to gain a thorough understanding of the manned aviation SAA regulatory framework and studying the performance of the human pilots in terms of the current SAA processes used. Hence this provides a basis for further understanding the system requirements for developing a safety case for a UAS SAA system (i.e. GBSAA).

This section examines the existing research in the effectiveness of visual performance of the human see and avoid. The many limitations of the pilot's see and avoid and why it is not the best means to SAA will also be mentioned. It also examines the pilot see and avoid encounter timeline that is the time required for the approaching aircraft to be detected and avoided successfully averting a collision and whether these parameters could be used as one of the performance measures to compare with the GBSAA system. This section also provides an overview of the various methods that could be used for validating the safety case. And finally, this section also mentions the contribution of the GBSAA demonstration platform that is proposed here towards the safety case development efforts for GBSAA system.

6.4.1 See and Avoid

See and avoid is a primary means for separation assurance in uncontrolled airspace and also it is the last resort for avoiding any near mid-air collisions in all types of airspace [16]. The fact that not all aircrafts are transponder equipped and also other small non-cooperative targets could be encountered in non-segregated airspace underlines the importance of See and Avoid. The effectiveness of see and avoid depends on various parameters that are based on characteristics such as target characteristics and the pilot performance level [17].

There has been research conducted in the past to determine the effectiveness of visual performance of the see and avoid compared to alerted search method. In this section, the visual acquisition model developed and validated by Massachusetts Institute of Technology (MIT) Lincoln Laboratory for human see and avoid will be stated and suggest that this model could be used for measuring probability of acquisition for small targets such as UA's and other small airspace users in different encounter scenarios [17].

6.4.2 Visual Acquisition Model

The visual acquisition mathematical model developed at MIT Lincoln Laboratory is based on modelling the visual acquisition rate as a continuous process and it is assumed a time-averaged acquisition effort is required to characterise performance.

The cumulative probability of acquisition distribution is estimated by evaluating acquisition rate at a given instant and following the process for every instant of time as the intruder aircraft approaches.

The cumulative probability of visual acquisition is given by [16]:

$$P(\text{acq by } t_2) = 1 - \exp \left\{ - \int_{-\infty}^{t_2} \tau(t) dt \right\}$$

Where, $\tau(t)$ is the visual acquisition per given instant.

Also from various trials performed by using numerous data collected it has been established that the visual acquisition rate is directly proportional to the angular size of the target [16].

$$\lambda = \beta \frac{A}{r^2} \exp \left\{ - 2.996 \frac{r}{R} \right\}$$

The cumulative probability of visual acquisition can be determined by inserting the value of lambda into the first equation. The resulting equation can then be evaluated using numerical integration. The expression can be simplified for a special case where the visual range is infinite (on a clear day) and the equation then is reduced to the following [16]:

$$P(\text{acq by } t_2) = 1 - \exp \left\{ \frac{-\beta A}{r^2 t_2} \right\}$$

In the above expression, the basic characteristics of the visual target such as closing rate, target cross section are or visual range can all be determined from a knowledge of the actual search conditions. However, the model parameter cannot be determined in this way but by evaluating the performance of the pilots in the flight trials. The test flights were conducted with an aim to determine optimal value of the model parameter that best outlines the performance of the pilot during unaltered search flights [16].

6.4.3 Visual Acquisition Performance

With the support of the FAA, the flight tests were performed with 24 general aviation pilots each flying the Beech Bonanza on triangular cross-country flight for a 45-minute duration. During their flight time, a Cessna 21 aircraft made three intercepts, flying both above and below the test route to provide the pilots with a visual acquisition target [16].

The data was collected for all the 64 encounters during the flight tests. The acquisition was achieved in only 36 of the encounters and the median acquisition range in those encounters was 0.99 NMI. From the plot of the visual acquisition probability as a function of Q (opportunity integral), the value of B that best fits the data was approximately 17,000 /steradian/sec [16, 17].

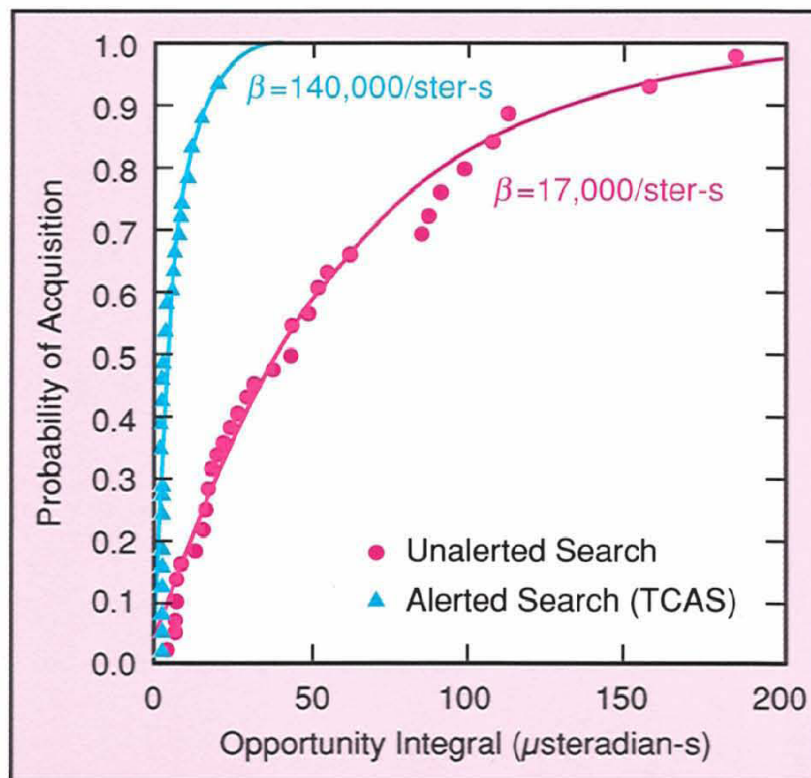


Figure 6.11 Observed acquisition probability and modelled visual acquisition probability for both unalerted and alerted search [16]

When the same estimation model was used for the alerted search scenario, in which the aircraft is equipped with a transponder that provides the pilot with the

necessary traffic details of the airspace. The model parameter value B was estimated to be approximately 14,0000 /steradian/sec. Hence the alerted search flight has a B value that is 8.2 times the unalerted search flight data. This means that the pilot in an alerted search mode requires one-eighth of the time required for a pilot to visually acquire the target in an unalerted search flight mode [16].

The visual acquisition model has been calibrated to reproduce the results of the flight so that using the model important insights into how the see and avoid will perform under real world conditions. The model can be used to extend its applications to other encounter scenarios as well as different type of flight and its characteristics. However, the model may not be applicable to evaluating visual performance of see and avoid under other modes of flight such as landing and take-off phases.

The acquisition model used for the un-alerted search pattern could also be extended to calculate the visual acquisition range for detecting small airspace users such as unmanned aircrafts. The Figure 6.12 shows the relative airspeed frequency distribution for different types of aircraft in airspace where there are no air traffic services. It is seen from the graph that the frequency of aircraft at lower speeds (less than 70 knots) is quite high compared to other having higher airspeeds [19]. Hence it is necessary to accurately predict the visual acquisition probability of such airspace, as it will enable in comparing the results with acquisition probability for alerted search (using a GBSAA system).

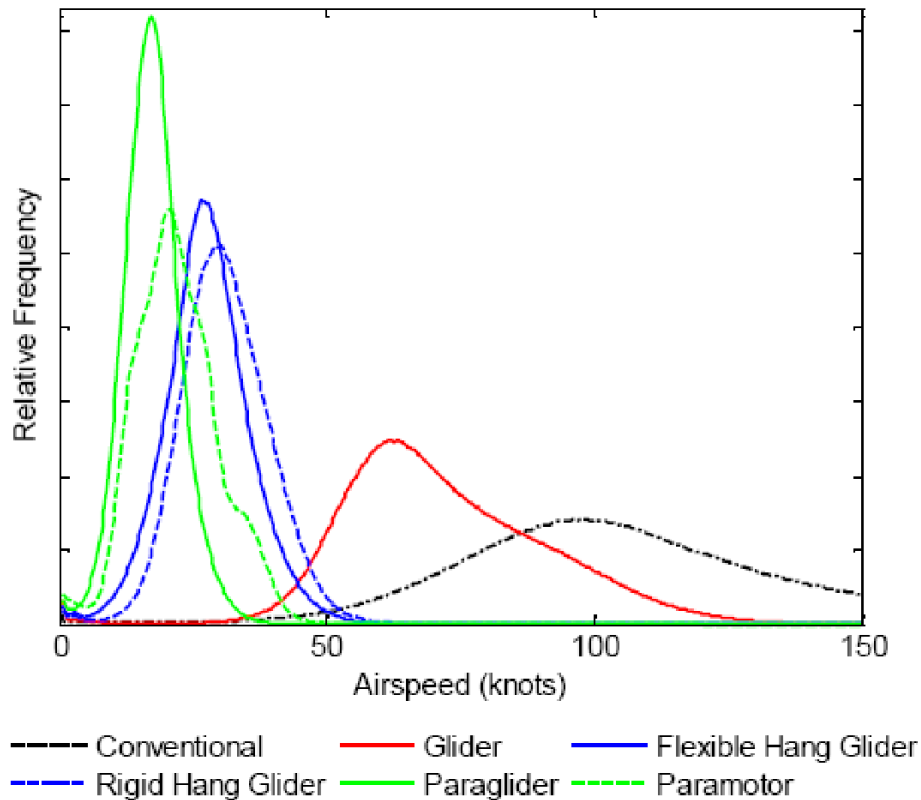


Figure 6.12 Relative airspeed frequency distribution of several types of aircraft in uncontrolled airspace [19]

6.4.4 Sense and Avoid Encounter Timeline

According to the FAA advisory (circular 90-48-C) which provides military derived data on the time required to see an approaching aircraft and execute a collision-averting manoeuvre, the pilot should be able to spot the aircraft at least 12.5 seconds to the time of impact [18]. The total reaction time involves, the sense and avoid processing time (includes time to see, recognise threat, decide on action), execute the manoeuvre and allow the aircraft to respond to the action [18].

Hence for GBSAA operation, the sense and avoid processing timeline would require the target to be detected at least 10.1 seconds to the time of impact, so that the UAS pilot is able to perform the necessary manoeuvre to keep a safe separation between the UA and the intruding aircraft. For GBSAA operation other aspect to keep in mind is that the pilot is executing the command from the ground and thus there will be a very small-time lag in the communication to the UA.

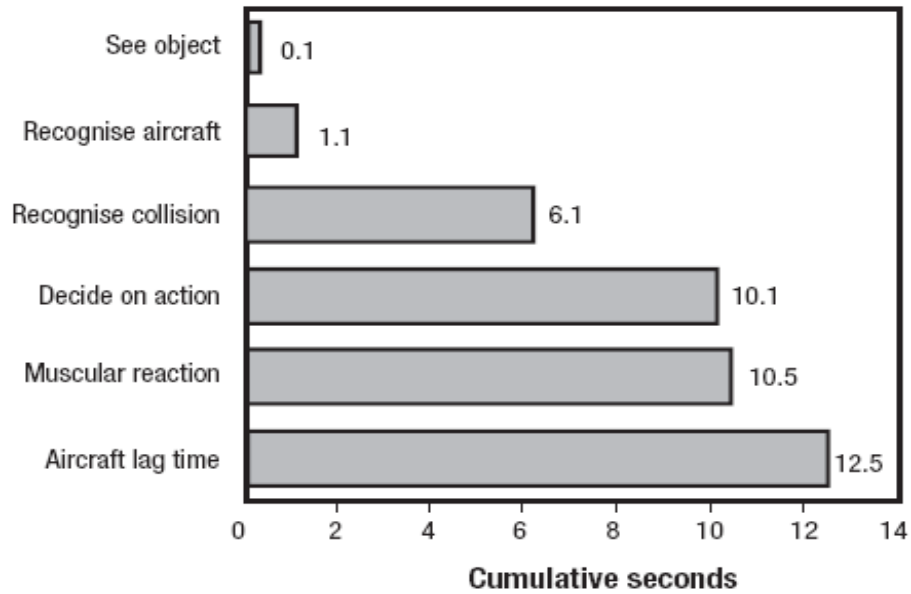


Figure 6.13 Time to react to collision threats [18]

6.5 Summary

This chapter provided a basis for the research into the GBSAA system. The system design concept and system operational description were described. This chapter also presented GBSAA system performance analysis performed. Further the safety case concept was detailed, and an approach towards presenting a safety case was outlined.

Chapter 7: Ground Based Sense and Avoid Experiment Design

7.1 Introduction

This chapter describes the methodology and approach taken in the research to address the research questions outlined in Section 1.3.2. Along with the need to address research objectives, the inputs from Chapter 7 regarding the technical, operational and safety case aspects of a UAS Ground Based Sense and Avoid (GBSAA) system were used to initially define the underlying concepts and issues for the experiment design. Following this a detailed description of the experiment design and the procedures used are provided. Finally, concluding with the tools and statistical techniques used to analyse the results.

7.2 Background

One of the most important challenges to be addressed for the routine operation of UAS in non-segregated airspace is the ability of the UAS to 'Sense and Avoid'. A key aspect of addressing that challenge is a mitigation strategy for the lack of on-board capability to 'see and avoid' in an UAS. Thus, UAS flight operations in non-segregated airspace will require maintaining safe separation distance from other air traffic which is challenging, as outlined in the UAS Sense and Avoid literature review, Chapter 6, especially when operating under Visual Flight Rules (VFR) conditions where most of the air traffic users may not be carrying transponders. In recent years, the aviation community is moving towards exploring concepts associated with Ground Based Sense and Avoid (GBSAA) as a short term to medium term strategy for effective self-separation and mitigating risk of potential conflict of UAS, so that they can be integrated safely and efficiently in the national airspace system. The previous chapter has focussed specifically on the technology, operational and safety case aspects involved with Ground Based Sense and Avoid (GBSAA) System and their effective implementation.

The aims of the research outlined in section 1.3.2, gaps in the academic

research and the industrial nature of this doctorate influenced the next stage of this research. As outlined in section 2.10.1, the industrial needs guided the research to the specific issue of UAS Sense and Avoid and further into Ground Based Sense and Avoid (GBSAA) system. The gaps in the academic literature that emerged from literature review of UAS Sense and Avoid (Chapter 6) and also the fact that another business line of the company (Thales) were working on the development of an Airborne Sense and Avoid (ABSAA) for UAS, led to pursuing further research and development in concepts related with Ground Based Sense and Avoid (GBSAA) for UAS. Apart from the literature review on UAS Sense and Avoid presented in Chapter 6 and detailed examination of all aspects related to Ground Based Sense and Avoid (GBSAA) presented in Chapter 7, the research also involved a detailed business case study of GBSAA concept and presented to project managers at the company (Thales) on the ways to further pursue the design and development of the concept into a commercial product. The study analysed the feasibility of using ground based sensors for providing separation assurance capability to UAS pilot/operator, both technically and economically. It also looked into various sensors that could be used for this purpose and specific application areas where the product could be used. Based on the study, a radar sensor ideally suited for the specific application of the product was finalised and further development of all the elements of the GBSAA concept was being undertaken with the objective of developing a fully integrated GBSAA system for performing field trials. The various elements involved the sensors, sensor data fusion and the information display system. However due to changes in the priority of the company, the further development of the GBSAA concept was not continued and thereby the resources available to develop the various elements of the GBSAA system were no longer available. This was one of the major challenges faced during the research. In view of this the research focus shifted to exploring one of the key aspects of the GBSAA system that also fulfilled the aims of the research.

One of the key elements of a GBSAA for UAS operations is the display system. The display provides situation awareness of the air traffic surrounding the vicinity of Unmanned Aircraft (UA) to the UAS pilot/observer. The literature review on GBSAA display system in the previous chapter revealed there is not a single standard concept

for the design of information display systems. There is no specific model to follow for the design of a traffic information display system for GBSAA. Hence the next stage of the research focussed on design of GBSAA display concept and evaluating the display system using a simulation environment. The research focus on GBSAA display system was necessarily due to three factors firstly that it fulfils the research objectives outlined in section 1.3.2, secondly the gaps in the academic literature and finally to leverage the existing display systems within the company (Thales) so that it could be part of integrated system for providing GBSAA capability in case the company decided to develop GBSAA system as a commercial product in the future.

7.2.1 GBSAA Overview

7.2.1.1 GBSAA Information Display

The GBSAA information display acts as an interface that provides the air traffic information to the UAS operator. The primary objective of the GBSAA display is to provide the UAS operator with an air situation picture, so that the operator has the situational awareness information to ensure safe UAS operations. To fulfil this objective, the GBSAA interface has to achieve the following goals: populate and update the tracks information on the display, determine if any danger of an impending or actual loss of separation by an intruding aircraft and finally generate an alert if there is loss of separation margin or any impending ones.

Several variations are possible based on where the GBSAA interface could be located in the operational architecture of the UAS operations using a GBSAA system. First scenario is when the GBSAA display is located in the GCS from where the UA is controlled by the UAS pilot. The flight crew of the UAS now become responsible for ensuring they sufficiently recognise and resolve the conflict by way of an extra instrument that is the GBSAA display. However, the GBSAA display information can also be provided to the UAS pilot by integrating the situation awareness information with the pilot Head-up display [23]. But there are several aspects to be addressed while employing this method such as the impact of pilot workload level on introducing this new functionality on HUD and whether it will be easier to achieve certification by not integrating the sense and avoid display functionality into the existing UAS pilot

display.

The second scenario involves the GBSAA display located at the GBSAA traffic operator/observer who may be at a different location to the GCS [23]. A dedicated GBSAA traffic operator observes the air traffic situation data and in case of a potential collision the observer effectively de-conflicts the situation by informing the co-ordinating between ATC and UAS pilot apart from providing information to UAS pilot to take an appropriate manoeuvre. This scenario is effective when surveillance coverage of a larger region is available through the deployment of a network of ground-based sensors, in which many UA's can operate simultaneously.

In the third scenario, the GBSAA display could be located in the ATC centre. The GBSAA traffic operator observes the separation alerts and co-ordinated with the UAS pilot to de-conflict a potential collision.

There are several key questions that need to be addressed with regards to the GBSAA display. Firstly, if the UAS pilot will be able to safely and accurately perform UAS operations using the situational awareness information to mitigate the risk of collision [20]. Secondly, how the air situation picture is presented to the UAS operator [23]. And finally, the decision support tools that will be required by the UAS pilot for performing UAS operations in the national airspace [20].

The information-received from the GBSAA sensor is to be presented to the UAS operator in order to improve the situational awareness. There are several ways in which this information can be presented to the UAS operator. A multi-perspective view of this information would be a better way to go about designing the user interface of the GBSAA display and from the UAS literature present it also suggests that implementation of multiple viewpoints with a smooth transition could be an asset [24, 20].

In this section one of the ways of differentiating the design of the display is presented by means of multiple viewpoints. The two viewpoints discussed are as given below:

Airspace view: The airspace view of the GBSAA display is similar to an Air Traffic Control (ATC) display used in the current ATM system. This kind of display provides

the operator with a view of the air traffic in the entire airspace. The radar tracks of the ownship aircraft along with the tracks of the other targets are presented to the UAS operator over a static electronic map of the area in and around the surveillance region of the radar.

The implementation of the airspace view will enable the UAS operator to view all the traffic in the surveillance region and also act in order to perform a manoeuvre when there is an infringement into the zero-conflict area or there is a loss in separation between the UA and the intruding aircraft.

Pilot's view: The pilot's view in the GBSAA display is similar to the TCAS display used by aircraft pilots in the current scenario. Although the normal TCAS display for manned aircraft is integrated into the head-up display of the pilot inside the cockpit. However, in the case of a GBSAA display, the implementation of the TCAS type display would be as a separate display to the GCS display and eventually the TCAS type display could be integrated into the GCS display of the UAS operator thereby providing a single display that can also providing the air traffic situation picture.

The implementation of the pilot's view as GBSAA display will enable the UAS pilot to able to receive alerts in the event of an infringement into the zero-conflict area or if a separation violation has occurred between the UA and the intruding aircraft.

7.2.1.2 Separation Strategy

The margin of separation is one of the criteria's, which will determine the effectiveness of the system. The optimum separation margin will ensure the balance between the numbers of nuisance alarms and number of missed detections. Currently, the separation measure used by the ATC for manned aircraft separation conflict alerting is based on a vertical separation of 1000 feet and a lateral separation of 1 nautical mile [11]. However, these are for manned aircraft operation as well as in regions where there is ATC control. Thus, these measures would not be suited for UAS and especially those operating in uncontrolled airspace. In order for UAS operations in uncontrolled airspace supported by USAS on the ground, there is need to understand and examine the margin of separation for various traffic situations.

The separation margin for USAS depends on various other interrelated system aspects. In the following section, some of the interrelated elements identified are discussed briefly.

Time to separation violation

Time is an important concept in the system effectiveness measure of the GBSAA. The time to loss of separation is an important parameter for separation assurance in a GBSAA system. Thus, ensuring an optimum time to separation will enable in reducing the number of false alarms thereby increasing the system effectiveness.

Target characteristics

The ability to detect the target depends largely on the target cross-section and for a smaller target the less likely it is to be detected at large distances. Hence the detection distance largely depends on the target characteristics. Depending on the ability of the sensor certain targets are detected more easily than the others based on the parameter of the sensor system.

Weather

Weather is one of the aspects that affect the effectiveness of the system. Especially, for the operation of the radar on the ground as it be adversely affected by the weather.

Manoeuvring capability

The velocity changes and the climb rate of the target are also necessary criteria upon which an effective separation manoeuvre of the UAS is based on.

Level of autonomy

With the GBSAA concept, the human-in- the-loop is a major underlying principle. At the lowest level of the system, the pilot can derive manoeuvring decisions based on the traffic awareness and conflict alerts. However, as the system matures and the complexities associated with automatic separation manoeuvre are well understood the, an automated separation manoeuvre selection and execution can be performed.

HMI presentation

The GBSAA system primarily provides an air traffic situation display, which improves the situational awareness of the UAS operator compared to the current level of situational awareness mechanism available to the UAS pilot. The GBSAA system will provide level 2 situational awareness to the UAS operator. It is envisaged in the short term; the UA will be remotely piloted by an operator i.e. operating at lower levels of autonomy. Hence the pilots need to be presented with the information in an efficient way so that they take evasive action when separation violation is predicted. The way the information has to be presented is important because at lower levels of autonomy, the UAS operator has a large amount of responsibility in operating the UA.

Number of intruding targets

The number of aircrafts within the surveillance region affects the margin of separation between the UA operating region and the traffic. An increased level of traffic in the region would mean an increased margin of separation thereby lower operating area for the UA.

7.2.2 GBSAA Display Concept

The in-depth analysis of the technical and operational aspects of GBSAA system in the previous chapter, outlined (section 7.4.3) the basic functions and requirements to consider for the design of GBSAA information display. The intent of the traffic information display is to provide an overall view of the airspace in order to assess the level of risk to the unmanned aircraft (UA) from other aircraft in the vicinity or in the operational area of the ground based sensor. The air traffic information system leverages the existing radar sensor technology to provide a wide surveillance area thereby providing the next step for UAS operation in non-segregated airspace to beyond line of sight of the UAS pilot/observer [93].

The GBSAA information display system should enable the UAS pilot/observer to have a greatly expanded field of view. It should also provide the UAS observer a top down two-dimension view of the airspace providing a clear view of the UA position

in relation to other aircrafts in the surrounding airspace. The position information of the UA from the ground based radar and the GPS information of the UA received from telemetry data provides greater level of position data integrity and also can be correlated to ensure that the ground based sensor is operating normally.

The design of an air traffic information display is not straightforward as there is no specified model to follow [93]. There is not a single standard concept for the design of traffic information display systems [93]. Many different types of air traffic information display systems exist though various facilities of the civil aviation authorities. The varied types of traffic displays are based on the different set of tasks each facility is expected to perform [93]. Even if a single design standard exists it has been the case that identical traffic information display systems have different interfaces depending on the system contractor who developed it. Previous works by Nielsen [94] and Alhstrom & Kudrick [95] have shown that a single design standard cannot specify a complete user interface and that the same design standard can be implemented in a variety of ways. There is no uniform traffic information display model that is present and the design of an information display system for the specific requirements of the display system must be based on the first principles using a spiral model (first described by Barry Boehm in 1986) [96]. The spiral model is primarily used as a standard user interface design model in software engineering, where the design process enables the display system designers to work directly with those designers developing the other aspects of the system and the users that would be the end users of the display system [97].

As there is no specified design standard for a GBSAA display system available, for providing situation awareness information to UAS pilot/observer in a UAS Ground Control Station (GCS), the research focussed further on exploring the use of existing air traffic display concepts as GBSAA information display system. The key aspects from this investigation are detailed in the next section below. Based on this, the research emphasis was on developing a GBSAA traffic information display concept and evaluating this using simulation exercises. Hence, the research work focussed on exploring the different display concepts and human factors aspects involved with their design. This work was used as a basis for outlining the key features and characteristics

of a USAS display and implementing these in on the prototype GBSAA information display system. However, the research work was not to define the requirements and standards for the design of UAS separation assurance display.

7.2.3 Existing Air Traffic Display Systems for use as GBSAA display

Cockpit Display

There has been a growing demand for the use of Traffic Alert and Collision Avoidance System (TCAS) on UAS. TCAS is an airborne system that functions independently of the ground-based Air Traffic Control (ATC) system and provides collision avoidance capability to a wide array of aircraft types [98]. The airborne system monitors the surrounding airspace for other transponder equipped aircraft that may present a threat of mid-air collision. The situational awareness information is then presented on a cockpit display for pilot to act to avoid a potential collision [99]. The cockpit awareness information acts as a last line of defence among a multi-layered defence against mid-air collisions.

The first-generation technology TCAS I, monitors the traffic situation around the aircraft and provide bearing and altitude details of nearby air traffic to pilot. It can generate warnings of an impending danger of collision known as “Traffic Advisory” (TA) to alert the pilot, but do not provide any collision avoidance manoeuvre procedure to avoid impending collision threat [99]. However, TCAS II provides specific instructions to pilot on how to avoid the conflict with the air traffic. These instructions are known as “Resolution Advisory” (RA) and the instructions to pilot may vary from climbing, descending or adjusting vertical speed [99]. TCAS II system also enables the transponders of two aircrafts with impending collision threat to communicate with each other to ensure the RA provided to each aircraft maximizes separation.

TCAS concept utilises the radio beacon transponders installed on aircraft to enable surveillance by ground-based ATC radars. TCAS is mandated on all large transport aircraft in all airspace regions worldwide [100]. In the European airspace, the current mandated rule suggests carrying TCAS II by all civil aeroplanes with Maximum Take-Off Mass (MTOM) exceeding 5700 kg or authorised to carry more than 19 passengers [101]. TCAS has been in operation for nearly two decades now and its

wide deployment as a decision support system has prevented several catastrophic accidents [100].

The advocates of the deployment of TCAS on UAS have proposed that the system will provide information to the UAS pilot to manoeuvre around potentially conflicting aircraft. The TCAS display was also envisaged to provide the generic situation awareness of the air traffic environment to the UAS pilot as the remote pilot lacks the ability to visually acquire and monitor aircraft in the vicinity of the UA. A recent FAA study was conducted for the use of TCAS on UAS and it concluded that the use of TCAS should not be allowed as it provides a compelling opportunity for the misuse of displayed information [102].

According to the study, TCAS display has several design limitations when used as a means for providing information for the pilot to estimate the current intruder state and also the pilot's projection of the intruder state in the near future [102]. The study also lists the information that is not provided on the display but is necessary to ascertain an accurate air traffic situation picture, but these are not limited to this set of information [102].

- No intruder speed information indicated on the display
- No intruder heading information present on the display
- All aircraft in the proximity of the display may not be depicted
- Aircraft location indicated on the display may not be true locations
- Displayed information may be a snapshot and may be delayed by a several seconds
- Intruder distance from ownship are not provided directly on the display
- Other aircraft may be responding to a TCAS RA
- Other aircraft may be manoeuvring based on visual acquisition
- Other aircraft may be manoeuvring in response to ATC clearances or instructions.
- TCAS data inaccuracies increase when in turns, climbs or descents.
- Potential drawbacks of a moving reference display

The several factors mentioned above render the use of TCAS display for providing

air traffic information to the UAS pilot not appropriate.

Air Traffic Control (ATC) Display

ATC display provides surveillance information on all aircrafts on the ground and through controlled airspace to air traffic controllers, to enable separation of aircrafts and maintain efficient flow of air traffic. The primary purpose of the air traffic controllers is to prevent aircraft collisions. The ATC display system provided for a continuously updated presentation of surveillance information, including aircraft track position indicators. The surveillance information provided to the controllers at the least includes position indicators, map information required to provide ATC surveillance services and, where available, information concerning the identity and aircraft level of the aircraft. The surveillance information may be obtained from single or multiple ground-based radars (primary or secondary) as well as other surveillance systems such as Automatic Dependent Surveillance Broadcast (ADSB).

Similar to the TCAS display, there are several design limitations of the ATC display for providing air traffic information to UA pilot. Some of the information that is not provided by an ATC display that is necessary to obtain an accurate situation awareness picture is as given below:

- ATC display does not provide a moving reference type display.
- UA track centric view of the airspace is not provided.
- Intruder distance from ownship is not provided directly on the display.
- Displayed information may be delayed by a several seconds.
- Other aircraft may be manoeuvring based on visual acquisition.
- Other aircraft may be manoeuvring in response to ATC clearances or instructions.
- Does not provide a decision support aid for making separation conflict avoidance manoeuvres.
- Current intruder state information is not displayed in a list.
- Aircraft location indicated on the display may not be true locations.

Thus, due to the factors mentioned above, the ATC display for providing

situation awareness information to the UA pilot is not the best suited interface. Hence a GBSAA information display system for UA operations in non-segregated airspace has to address these limitations in both TCAS and ATC display to provide a robust GBSAA display interface design.

The traffic information display system that is developed is a modification of ATM system for use as USAS/GBSAA display. The user interface concepts that will be evaluated in the human-in-the-loop (HITL) simulation can be categorised based on the viewpoints and orientations they provide to the user. Through the research carried out previously, it emerged that the existing displays such as TCAS or ATC are not suitable for use as GBSAA display.

These two concepts of traffic display design depict the two categories of displays that are used in terms of airborne and ground based operations in the current ATM system. The airborne cockpit display systems are the Cockpit Display of Traffic Information (CDTI) or TCAS display that provides traffic information to the pilot and also resolution manoeuvres. The ground-based interface is the ATC display which provides the controllers with air traffic picture over a vast coverage region.

The presumption that a TCAS or ATC display could be directly used as a separation assurance display for supporting self-separation operation of UAS is incorrect. The use of the two display types could cause a misinterpretation of information thereby leading to catastrophic accidents and thus they should not be used for GSBAA purposes. However, the research looks at the concepts of a generic GBSAA display and its characteristics, based on which it tries to incorporate these aspects by modifying the interface of an ATC display system

7.2.4 Separation Assurance

Area infringement alerting: - The initial step in GBSAA system deployment for UAS operations is an alerting system that alerts the UAS pilot/operator in the event of an intruding aircraft that infringes into the separation violation area of the UA operations. Once the alert is issued the UA pilot/operator can then decide to land the UA safely well before the intruding aircraft entering its operational area.

Safe state operations: - In the event of an aircraft entering the surveillance area, similar to the infringement alerting the GBSAA system alerts the UA of an impending separation violation. Based on the state of intruding aircraft and its heading, the UA pilot/operator would be able to manoeuvre the UA pilot/operator to a safe state. As the intruder aircraft moves through the operational volume, the operational area of the UA shrinks and there must be a safe state option available to the UA through its operation. The safe state could be a restricted area (similar to danger area) where operations are limited to UA only or to land the UA safely at the nearest landing site.

Safe separation: - When an intruder aircraft is predicted to lead to a separation conflict situation, the UA pilot/operator manoeuvres the UA in the air to a safe separation distance from the threat aircraft without the need to land the UA or to return the UA to a restricted area.

7.3 Experiment Method

After the initial study on the system concept and requirements, next stage of research looks at developing a pre-operational prototype of a GBSAA system to prove the application of concept. The developed prototype will enable to assess the inter-related system aspects such as separation strategy, procedures, display characteristics and UAS operator responsibilities. The research project proposes to prove the application of concept using a commercially available Air Traffic Management (ATM) system as the GBSAA display. The Thales TopSky ATM system would be used as the GBSAA display.

The benefits of proving the concept using commercial off-the shelf software are many folds. Firstly, once concept is proved on a fully certified system, then the implementation from an operational prototype to a fully operational system can be much faster and easier. Secondly, the usage of TopSky for a new application would be useful in showing its flexible operational capabilities. Thirdly, if TopSky is eventually used for GBSAA display in the operational system it could open up new market and future possible applications in that area. Especially if the military could use the system

for training UAS in civil airspace, the GBSAA system could be a possible solution in the near term.

7.3.1 Display Concepts

Airspace Centric

The Airspace centric display has similar characteristics to an ATC display in that it covers the whole surveillance region and it's a North-up type of display. And the Unmanned Aircraft (UA) is not centred on the display and the absolute heading of the tracks is presented.

Aircraft Centric

The Aircraft centric view has a few similar attributes to a TCAS display in that it is UA is centred on the display and it's a track-up display. All the headings and other track parameters are presented as relative measure from the UA track measures.

The null hypothesis for the experiment is the assumption that the two display concepts have similar effect on the performance of the participant.

7.3.2 Design and Selection of Scenarios

The choice of the scenarios must be based on an assessment of the main aim and fulfilling the various objectives of the USAS/GBSAA experiment. As the key goal of the experiment is not to evaluate the separation resolution algorithm or to compare various separations alerting system, the need is to test for all possible scenarios is not required. Hence keeping with the goal of the experiment, which is to assess the decision-making aspects of UA observer/operator when in a separation conflict situation with other aircrafts, a set of scenarios can be selected which will provide a range of conflict scenarios that may occur in class G or class F airspace.

The scenarios have been selected based on following criteria's.:

Firstly, the separation conflict situation that enhances the human factors issues of the ATC and TCAS displays in terms of providing situation awareness information

to the UA pilot. Hence some of the encounter scenarios have been selected through the research done on previous studies about the human factor issues involved with the different types of displays.

Secondly, the encounter situations have been chosen from the data on aircraft encounters in uncontrolled airspace. A standard set of scenarios are provided in the general rules of air that give guidance to the pilot on the type of manoeuvre to be taken in order to resolve a potential collision conflict situation. Hence these scenarios were included in the experiment to assess how the participants interpreted the rules of the air when encountered with a separation conflict situation while operating as a remote pilot without using the visual eyesight for intruder aircraft detection.

7.3.3 Participants

The participants in the experiment are envisaged to be largely novices to the information display system and who are not aviation knowledgeable. However, there are a few participants who would be aviation knowledgeable and also are involved in the field of UAS. One of the main reasons for choosing such an array of participants as the experiment is aimed at evaluating and understanding the decision-making aspects of the human (UAS observer/pilot), hence the involvement of novices to such a system may be beneficial due to the lack of their past learning and experience that might affect the outcomes in case of aviation or UAS experts. Thus, in this way the bias introduced by experience is eliminated from the experiment.

Although the removal of learning bias is beneficial, there are other downsides that may arise due to it. One of them may be the lack of testing or assessment by controllers or UAS operators who will be the primary users of the system. The main aims of the experiment are two folds: Firstly, to examine the intuitiveness of the display and secondly to assess the impact of the decision support tools on the decision-making aspects of the UA observer/operator.

7.3.4 Experiment Set-up

As this is a proof of concept demonstration system, a system was developed to simulate the expected environment so that a related fully functional sense and avoid

system can be developed as part of future work to validate and certify a GBSAA system for UAS operations. The experiment set-up consists of several simulations that were developed as shown in Figure 7.1 and also has been described below.

7.3.4.1 UAS simulation Environment

The UAS simulation should be able to model the flight characteristics of the UA and generate an environment similar to a UAS Ground Control Station (GCS). The existing UAS simulation environment located at the Systems Laboratory at Loughborough University was used so as to generate the UA flight characteristics as well as various tasks performed by the UA operator/pilot during the experiment. The simulator was developed in conjunction with other colleagues (My. L.Le-Ngoc, Mr.C. Wright and Mr.G. Bedford) based in Advanced VR Research Centre (AVRRC) at Loughborough University. This included the hardware and software set ups for undertaking the flight simulator development task. The simulation package that was used in UAS simulation environment to generate UAS flights was X-plane. The simulation package provides a cost-effective way to simulate the UA flights. The simulation environment also included a VFR flight planning tool in the form of Plan G which is a standard flight planner used with X-plane. Apart from the UA flight simulations, the surveillance tasks oriented towards engaging the UA pilot/operator to look at the UAS pilot display rather than the Traffic information display, which is envisaged to be used in the event of a separation violation situation to resolve the separation conflict.

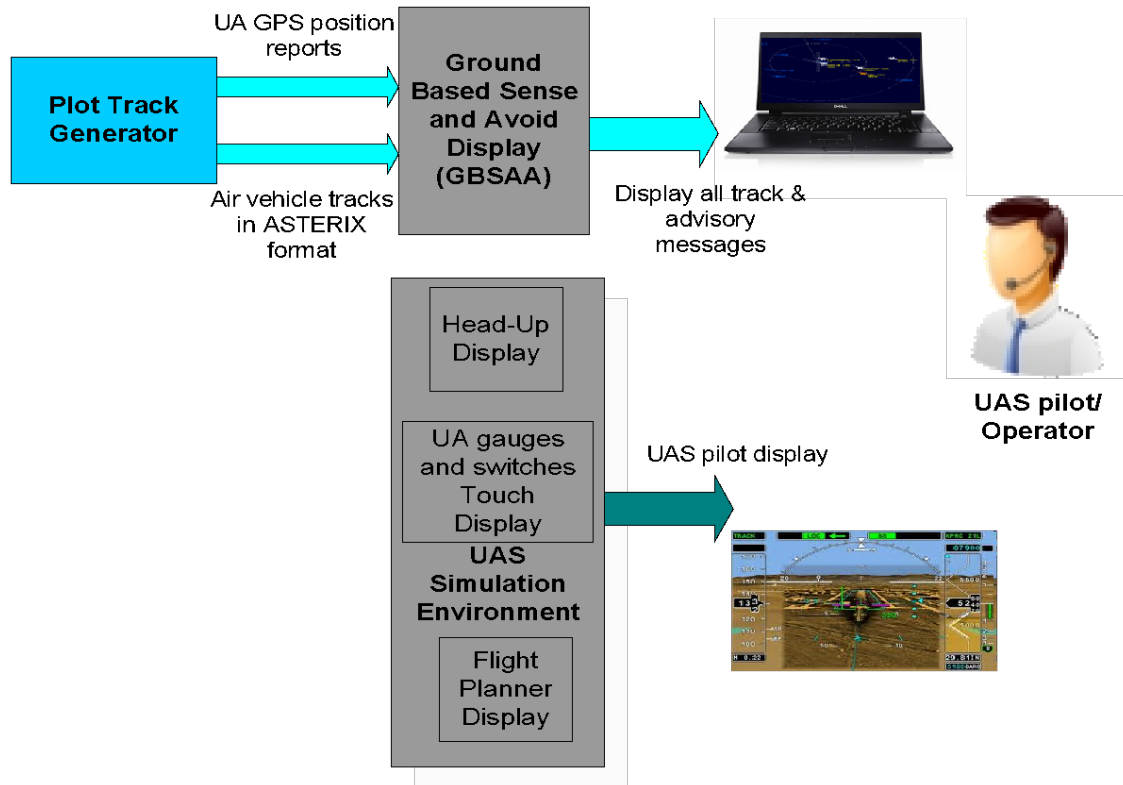


Figure 7.1 GBSAA Simulation Architecture



Figure 7.2 GBSAA System Experiment Set-Up

7.3.4.2 Airspace Simulation

The airspace simulation consists of the intruder aircraft and other aircrafts in the surrounding airspace present in the scenarios conducted during the experiment. The aircrafts tracks in the various scenarios are simulated and recorded on a plot track generator (PTG) software simulation located at Thales ATM. The PTG machine is used to simulate radar system tracks for testing and validation of the ATC Display software.

All the aircrafts in airspace simulation are generated as radar tracks and recorded into a file which is then replayed on the GBSAA display during the running of experiment scenarios. The surrounding aircraft tracks information in the airspace is sent every five seconds unlike the UA information which is sent every second (as it is the GPS derived data made available at the GCS in a fully operational GBSAA system).

7.3.4.3 Prototype GBSAA Display

One of the key aspects to certify the system is to ensure enhanced level of system reliability. As the display is a safety critical part of the USAS/GBSAA system the system must adhere to high level of safety standards in terms of the software and hardware components. Hence instead of developing an information display system for USAS from scratch, the approach of using a commercially available air traffic information system was explored. The air traffic display was modified as there are several functions and settings that are not required for application to a USAS/GBSAA display system. Also, the display of air traffic information to the air traffic controllers is slightly different human factors consideration compared to that of UAS operator. However, the separation function provided by the UA pilot for GBSAA system provision could have some similarities to the separation of aircrafts performed by the air traffic controllers in ATC controlled airspace. Thus, the air traffic display was changed or reduced in terms of its display functions and also a few other functions added to form a basic USAS/GBSAA display for use in UA operations.



Figure 7.3 Prototype GBSAA display

The traffic information display system that was developed is a modification of ATM system for use as USAS/GBSAA display. Through the research carried out previously, it emerged that the existing displays such as TCAS or ATC are not suitable for use as GBSAA display.

The TopSky display has been modified to develop an air traffic information display for the proof of concept GBSAA display system. The features of the ATC display have been modified so as the 2D information from the GBSAA radar is presented on the information display taking into consideration the need to develop intuitive and robust display. During the experiment, the GBSAA display is to be used by the UAS operator/pilot in a separation violation situation to assess the surrounding air traffic and decide on a separation manoeuvre to be undertaken at a certain time instant. The UA pilot/observer performs the task or mission similar to a remotely piloted aircraft pilot. The UA pilot navigates the UA through a pre-determined path for a set of several mission scenarios and when an intruding aircraft comes within the surveillance range of the radar the traffic information display alerts the UA pilot of an intruder. The UA pilot then has to assess the situation of the UA from the information

available on the GBSAA display and decide on whether to perform a manoeuvre or not. If a manoeuvre has to be performed the UA pilot has to specify which type of manoeuvre would be best suited according to him/her.

System Modifications

There are a few key differences in the system requirements of the USAS as compared to the current usage of TopSky; therefore a few modifications would be required before using the TopSky system for USAS implementation. These modifications are necessary to develop a system that is similar to the GBSAA system concept and would enable in accurately determining the performance measures as envisaged in the concept stage.

The TopSky system uses a distributed computing architecture that is capable of integrating geographically spread air traffic control centres within a flight information region into a single system for airspace control and management. TopSKy has a large variety of functions required for smooth operation air traffic control. ATC is a safety critical system and software design The software itself was originally developed using Ada and C programming language.

The modifications that were made in the Eurocat-C software package:

Separation criteria – The USAS provides separation assurance based on algorithms that use only two-dimensional position of the aircrafts. At this stage it is assumed that the ground-based sensor provides primary radar tracks that do not have any target altitude information. Hence an alert would be raised when an intruder aircraft penetrates the separation area. However in the Eurocat-C, the separation alerts and infringement warnings are raised based on the geometries, speed and the altitude of the two conflicting aircrafts. And the separation criteria are based on the current ATM standards.

Two warning messages that are to be used for the purpose of USAS concept are the AIW (Airspace Infringement Warning) and STCA (Short-Term Conflict Alert). In the current Eurocat-C ATM system, both aircraft lateral position and height are necessary pre-requisites to perform the STCA processing. Hence for implementing

USAS, the STCA process has to be modified to operate on lateral position of aircrafts alone without the height information. Conversely, the AIW process can be used as it is without making any changes in the Eurocat-C software, as the changes are easily configurable from the AIW settings.

HMI presentation – The presentation of track information and alert messages will be investigated for a USAS display. This would involve varying the colour format of certain tracks and also generated alerts being displayed. Investigate the best way to present information from a UA pilot/observer perspective, based on previous studies conducted on human factors design of cockpit displays and also leveraging some existing research in the field of ground based sense and avoid display system.

Display design characteristics

Track Information Display – The traffic label for the USAS display requires an additional data to be displayed as compared to a normal ATC display. Track label of USAS display has to present separation distance field information for each aircraft track that is not the UA track. The separation distance field is the distance in nautical miles of the aircraft track relative to the UA track data.

Separation conflict Alerting - STCA function is a safety net in the Eurocat-C system, which alerts the controllers of short-term conflicts. The STCA is normally defined over an area and an altitude level within which it applies and for the entire region where STCA is enabled all aircraft pairs inside it are checked for conflicts. STCA processing essentially requires both the lateral position and a valid height as pre-requisites.

The principle of operation of separation conflict alerting will be similar to the STCA function. However, the difference is that the STCA process must determine conflict based on the lateral position of targets without having valid altitude information. Also, the STCA function must operate on track pairs between the UA and other intruding targets.

7.4 Experiment Design

A repeated measures study will be used to conduct the study of UAS pilot/operator performance and situation awareness while flying two kinds of mission scenarios; costal patrol and a land surveillance missions. The repeated task scenario tasks were used to compare two traffic display concepts against varying traffic densities and intruder encounter conditions.

Traffic Display: - The two traffic display concepts were used to run the same set of scenarios with each participant. The two display concepts present the air traffic information to the UAS pilot with varying characteristics in terms of their orientation, viewpoint and perspectives. The UAS pilot were able to set an autopilot navigation option after taking-off and also adjust the viewing angle of the sensor payload to assist them in performing the patrol mission scenarios. While flying the missions, if any other aircraft in the vicinity of the UA violates a safe separation lateral distance a separation alert is displayed on the GBSAA display. The display also provided several aircraft parameters of all the air traffic data in the surveillance coverage area of the GBSAA radar.

Traffic Density: - The levels of traffic densities were varied for each of the scenarios. The high traffic density condition in the mission scenarios consists of a maximum number of seven aircrafts. As the operational airspace is the uncontrolled regions of the airspace where ATC separation services do not exist, the traffic density condition experienced in VFR regions away from aerodromes is generally low. Hence the highest traffic density condition in the mission scenarios only consists of 7 aircrafts.

Mission Scenarios: - A training session and six scenarios have been developed for this experiment. The training session was approximately 20 – 30 minutes long and provided familiarity with the two display concepts as well as the UAS flight simulator. As during the mission scenarios the majority of the time the UA is flying in the autopilot mode, the skill and training on the use of UAS flight simulator will not be important criteria affecting the outcome of the experiment scenarios. Experiment scenarios are each approximately 4-5 minutes long and included autopilot UA flight with UAS pilot

performing surveillance tasks and also importantly deciding on a separation manoeuvre in the event of a separation violation situation.

Mission Objectives: - The participants were instructed to fly a mission scenario with two mission objectives: 1) to perform surveillance tasks such as surveying the coast for any vehicle traffic or spotting land vehicles nears an airport/place of interest; and 2) to assess and decide on a loss of separation avoidance manoeuvre in response to a separation violation situation when alerted by the GBSAA display system. The first objective requires the participants to fly the UA in a pre-programmed flight path using the autopilot option while monitoring or surveying a target of interest (ships, cars, people) in a coastal patrol or land surveillance. Upon spotting the target of interest, the UAS pilot then surveys the object closely to monitor it. The second objective will require the UAS pilot to respond to a loss of separation situation by assessing the air traffic information on the GBSAA display and decide on a separation manoeuvre that would resolve the violation condition.

7.5 Experiment Procedure

7.5.1 Training

The pre-experiment briefing text is provided to the participant's prior to start of the experiment in order to give detailed explanation of the experiment and the role of the participant in the experiment. A set of rules and advisories that need to be followed during the experiment will also be clarified to the participant through the briefing text. Each participant will initially be given approximately 20 – 30 minutes of individual instruction and training prior to start of the evaluation. Training will consist of a tutorial session where the participant was given explanation on the UAS pilot interface, GBSAA display, rules of air and airspace operations. They will also be briefed on the manoeuvres they can select and where they could be selected from during the experiment. The participants will view static screen shots from the UAS pilot display and GBSAA display scenarios and several videos of the same. This is done to familiarise them with the interfaces they will be using in the experiment. The tutorial

session will be preceded by providing the participant with a briefing text material, which gives a brief explanation of the experimental set-up and the role of the participant in the experiment.

During the training session, the participants can request explanation and clarification from the researcher when necessary. Towards the end of the training session, the participant is given a brief test run in order to ensure that they understood the displays and their role to be performed during the scenarios. If the participants are clear of their task and they are comfortable with the display, they are now ready to proceed to the evaluation phase.

7.5.2 Experiment Scenarios

The experiment will involve twelve scenarios, which would be carried out in two different display concepts. (The order of running of scenarios will be a random selection and a reversed order will be used for the two displays). The duration of each of the scenarios will be approximately four-five minutes and the entire duration of the experiment would be approximately 75 minutes.

The experimental sessions will be conducted in a phased manner with first phase consisting of running all the six scenarios on Airspace centric display concept and second phase with the Aircraft centric display present. In-between the two phases the participants will be provided with questionnaire for evaluating situation awareness measures as well as the display functionalities. And finally at the end of the experiment participants completed a post-simulation questionnaire. Also between the two phases of experiment, a distraction task (i.e. mathematical task) will be given to the participant.

Scenario 1 (Head-on approach):

The scenario is designed so as to test the ability of the operator to assess the air traffic situation and take the right manoeuvre decision. In the scenario envisaged there are three aircrafts in the surveillance area including the Unmanned Aircraft (UA).

The UA and another track are approaching on a flight path course that is head-on. The other aircraft in the scenario is diagonally heading on a near crossing path to the UA.

The approaching head-on intruder aircraft to the UA initially causes an impending separation violation alert. The flight path of the other intruding aircraft is designed in such a way that if the UA takes a right manoeuvre immediately after impending separation loss is issued, the UA movement will cause a loss of separation violation with the other intruding aircraft that is on a crossing path with UA. However if the operator makes a decision to manoeuvre the UA after several seconds, there is a possibility of separation alert not taking place due to the speed and flight path of the other intruding aircraft in a near diagonal flight path with the UA. The scenario is assessing the ability of the operator to assess the complete air picture thoroughly and remain vigilant about another intruding aircraft in a crossing path before performing any manoeuvre.

Scenario parameters

Number of aircrafts: - **3 (including Unmanned Aircraft (UA))**

Surveillance area: **20 nautical miles**

GBSAA radar position: -

Based at centre having geographic position of **50 30 46 North 02 27 24 West**

Aircraft type	Starting position	Speed (knots)	Heading
UA	X = 2.0 ; Y = 10.0	80	297.49
	Lat: 50 40 58 N Long: 02 26 52 W		
Aircraft 1 <i>Intruding aircraft (head-on)</i>	X = -8.64 ; Y = 15.53	150	117.49
	Lat: 50 48 31 N Long: 02 28 35 W		
Aircraft 2	X = 8.86 ; Y = 18.61	190	262.49
	Lat: 50 51 22 N Long: 02 26 07 W		

Table 13: Aircraft Flight Information
(On the two-dimensional system grid 1 unit = 1 Nautical Mile for both X and Y axis)

Simulation time: Approximately 3 - 4 minutes

Note: Callsign of UA must be sent in the CAT 48 messages (Callsign: 'UAV')

Scenario 2 (converging intruder aircraft right-angled approach):

This scenario is designed to highlight the misinterpretations of information, which may arise due to a moving reference display. Two significant instances where this situation is likely to arise are when two aircrafts are converging at 90 degrees and also when an aircraft is catching up with a slower aircraft flying in the same direction.

Scenario 3 (Overtaking Aircraft):

This scenario is designed to highlight the misinterpretations of information, which may arise due to a moving reference display. Two significant instances where this situation is likely to arise are when two aircrafts are converging at 90 degrees and also when an aircraft is catching up with a slower aircraft flying in the same direction. In this scenario, the situation where the UA is catching up with a slower aircraft flying in the same direction is generated.

Scenario 4 (Converging Aircraft):

This scenario is designed to assess the situational awareness of the UAS operator and his ability to make a correct manoeuvre decision so as to avoid a loss of separation event with other aircrafts in the vicinity. In this scenario five aircrafts are approaching or flying away from each other, the operator must assess the situation and follow the rules of the air, which says the aircraft that has the intruding aircraft on its right must give way.

In this scenario five aircrafts are approaching or flying away from each other, the operator must assess the situation and follow the rules of the air, which says that the aircraft that has the intruding aircraft on its right must give way.

Scenario 5 (Converging Aircraft with UAS having right-of-way):

This scenario is a combination of the two instances of a near loss of separation that were used separately in the earlier scenarios. The reason for including two such

peculiar situations is to assess increase the level of difficulty in the task by having aircrafts close together and also those may cause a loss of separation in the future.

Scenario 6 (Overtaking Aircraft dual conflict):

This scenario is a combination of the two instances of a near loss of separation that were used separately in the earlier scenarios. The two-close separation loss situation that are considered here are an UA overtaking a slower aircraft and another aircraft approaching UA on a head-on direction simultaneously. The use of two such encounters, which may both seem that they may led to an impending loss of separation is to increase the uncertainty in turn the difficulty level on the decision to be made by the UA operator for a performing a manoeuvre.

Chapter 8: Ground Based Sense and Avoid Experiment Results and Discussion

8.1 Introduction

This chapter presents the results of the experiments carried out with the GBSAA simulation environment developed, after performing the statistical analysis methods. The results obtained provide insight into the benefits obtained with modified Air Traffic Control (ATC) display that incorporates some of the advantages of Traffic Collision Avoidance System (TCAS) displays, as compared to a standard ATC display for use as traffic information display by UAS pilot. Further the results obtained are discussed within the context of answering the experiment objectives.

8.2 Results

Eighteen participants both male and female were recruited to participate in this experiment. There were 16 males and 2 female participants between the ages of 20 to 32. All the participants recruited were current engineering students or research staff with no prior experience of aviation domain. A few of the participants were gamers (categorised as playing once a fortnight) but the rest were non-gamers or had not been gaming for years. There were three participants who had seen an Air Traffic Control (ATC) or Traffic Collision Avoidance System (TCAS) display but not used them. The rest of the participants had not seen/used either ATC/TCAS display before. All the participants were given similar time duration of 30 minutes for training on the simulation environment for them to familiarise with the flight simulator and GBSAA information display system. One of the benefits of participants not having prior experience of using these types of displays is learning or experience bias is removed from the evaluation of the information display system. However a drawback is that the display system is not evaluated by primary users of the system. The participants rated a high level of motivation to participate in the experiment. On a rating scale from 1 to 10, with 1 being low and 10 high level of motivation, the mean motivation level was 8.4 with a standard deviation of 1.3. The level of tiredness among the participants

indicated a medium to high level of fatigue before starting the experiment. A rating scale of 1 to 10, with 1 being low and 10 high fatigue levels, the mean tiredness level was 5.7 with a standard deviation of 2.5.

With a single group of participants and two independent variables (Display configuration and scenario levels), a two-way repeated measures ANOVA was utilized for statistical analysis of decision time (time taken to decide on manoeuvre by participant where the assumptions of normality and homogeneity of variance was met. Each participant participated in two display configurations (Airspace view, Aircraft view) and across six scenarios. The participants generated a total of $(9 \times 12 =)$ 108 measurement runs. Normality of the dependent variables was tested using the Shapiro-Wilks (S-W) test rather than the Kilmolgorov-Smirnoff test, as the S-W is a better method to assess whether data are well-described by a normal distribution for small data sets (less than 100 samples). If the p-value is less than 0.05 then the data does not show normal distribution, the skewness in the data is corrected through transformation to comply with the normal distribution. However for some dependent variables normally distributed and homogeneity of variance had been violated and it was not possible to transform the data in order to validate the parametric assumptions, therefore non-parametric tests was applied for their analysis.

8.2.1 Technical Performance Measures

Decision Processing Timeline

Further a two way repeated measures ANOVA was conducted with display configuration and scenario levels as the two factors, to investigate the interaction effect of these two on the time taken to decide manoeuvre within subjects. The results showed there were no significant effects of the display configuration used on the decision processing time, $F(1, 17) = 0.007$, $p = 0.936$. On the contrary there was significant effect of the scenario level on the total decision processing time, $F(5, 85) = 5.730$, $p = 0.001$. This implies that the total decision processing time for different scenario levels was varied. There was also a significant interaction between the display configuration used and the scenario level encountered, on the total decision-making timeline of the participant, $F(5, 85) = 8.062$, $p = 0.001$. This implies that the

total decision processing time for different scenario levels was different for Airspace and Aircraft view display configurations. The overall repeated measures ANOVA result is displayed in Table 14. The near equivalence in the means of the two display configurations, Airspace view (Mean = 9.256, SD = 3.84) and Aircraft view (Mean = 9.379, SD = 3.80) is shown in Figure 8.1

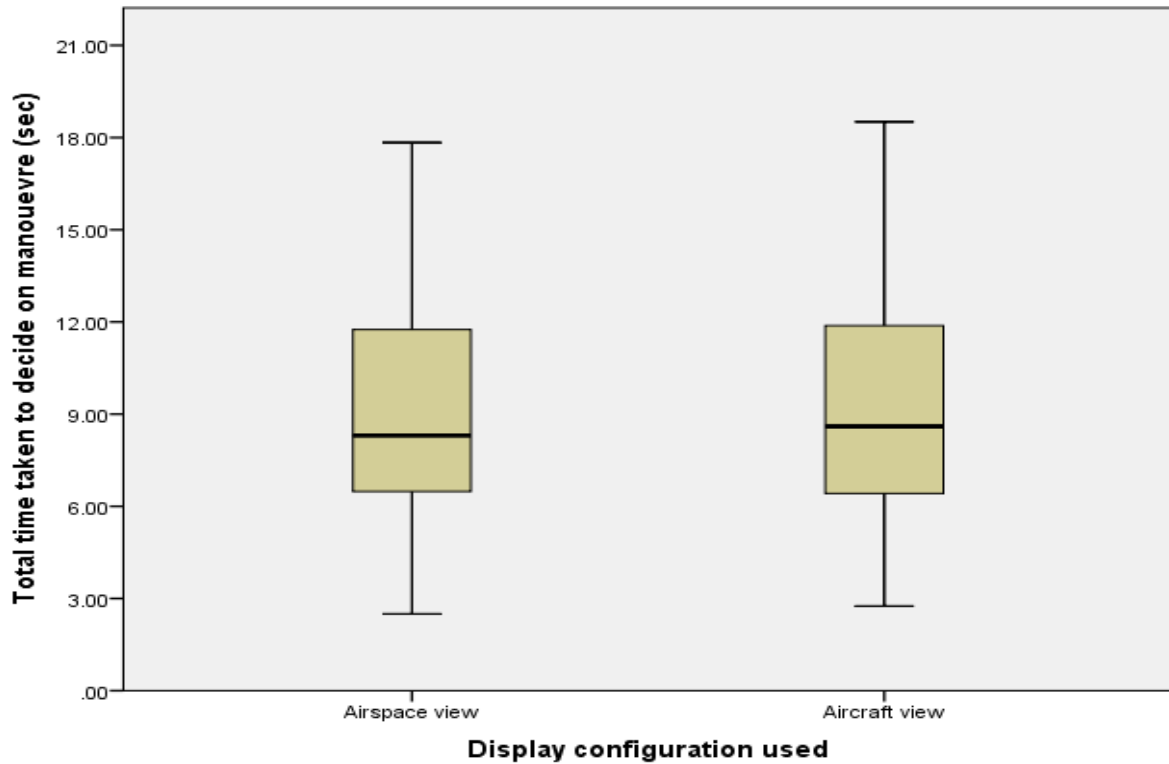


Figure 8.1 Boxplot of total decision processing time for the display configuration used

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Display	Sphericity Assumed	1	.042	.007	.936	.000
	Greenhouse-Geisser	1.000	.042	.007	.936	.000
	Huynh-Feldt	1.000	.042	.007	.936	.000
	Lower-bound	1.000	.042	.007	.936	.000
Error(Display)	Sphericity Assumed	17	6.174			
	Greenhouse-Geisser	17.000	6.174			
	Huynh-Feldt	17.000	6.174			
	Lower-bound	17.000	6.174			
Scenario	Sphericity Assumed	5	52.461	5.730	.000	.252
	Greenhouse-Geisser	3.222	81.406	5.730	.001	.252
	Huynh-Feldt	4.065	64.536	5.730	.000	.252
	Lower-bound	1.000	262.307	5.730	.028	.252
Error(Scenario)	Sphericity Assumed	85	9.156			
	Greenhouse-Geisser	54.778	14.207			
	Huynh-Feldt	69.097	11.263			
	Lower-bound	17.000	45.778			
Display * Scenario	Sphericity Assumed	5	69.344	8.062	.000	.322
	Greenhouse-Geisser	3.521	98.475	8.062	.000	.322
	Huynh-Feldt	4.553	76.145	8.062	.000	.322
	Lower-bound	1.000	346.718	8.062	.011	.322
Error(Display*Scenario)	Sphericity Assumed	85	8.602			
	Greenhouse-Geisser	59.855	12.215			
	Huynh-Feldt	77.407	9.445			
	Lower-bound	17.000	43.009			

Table 14: Overall repeated measures ANOVA result

Accuracy of Manoeuvre

This is a measure that relates to accuracy of the manoeuvre performed by the participant in each measurement run. As this is a categorical dependent variable a Chi-Square distribution test was used to test whether there is any association with each of the independent variables. If there was any significant association between the two categorical variables the Phi and Cramer's V test was used to further test the strengths of association.

The Chi-Square distribution results indicated that there is no statistically significant association between display configuration used and the accuracy of manoeuvre performed, $\chi(1) = 0.487$, $p = .485$. The assumptions of the Chi-Square were not violated. The near equivalence in the frequency of correct and incorrect manoeuvres performed for the two-display configuration is shown in Figure 8.2 and further substantiates the insignificant association between the two categorical variables.

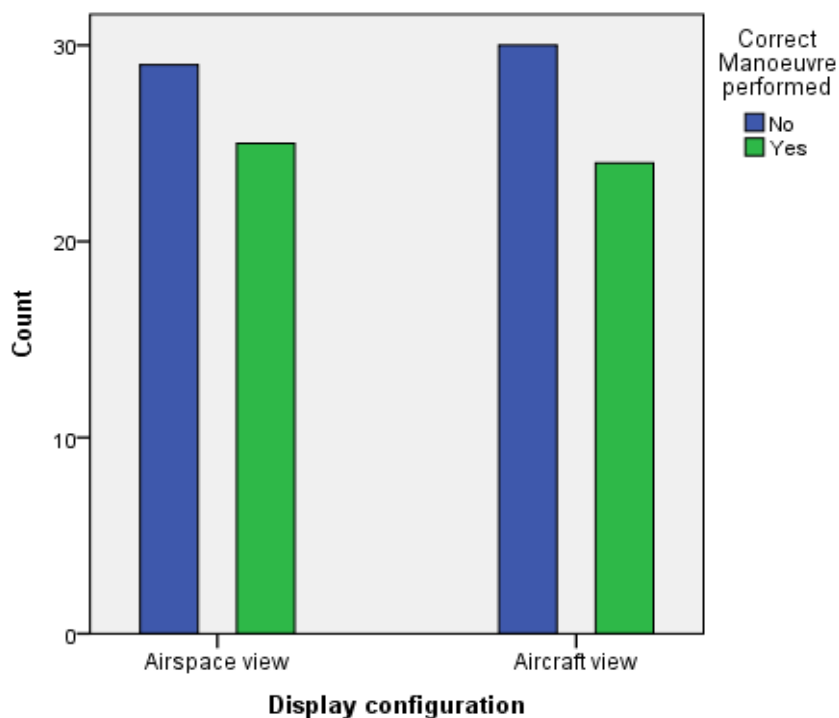


Figure 8.2 Clustered bar chart of number of correct manoeuvres performed against the display configuration used

A further investigation into all scenarios and their association with accuracy of manoeuvres was looked at. There was significant association indicated when the Chi-Square test was performed between the scenario level and the accuracy of manoeuvre, $\chi(5) = 26.636, p < 0.01$. The size of the effect was determined by the Phi and Cramer's V test which showed a strong correlation between the scenario level and the accuracy of manoeuvre selected, $\text{Phi} = 0.497, p < 0.01$.

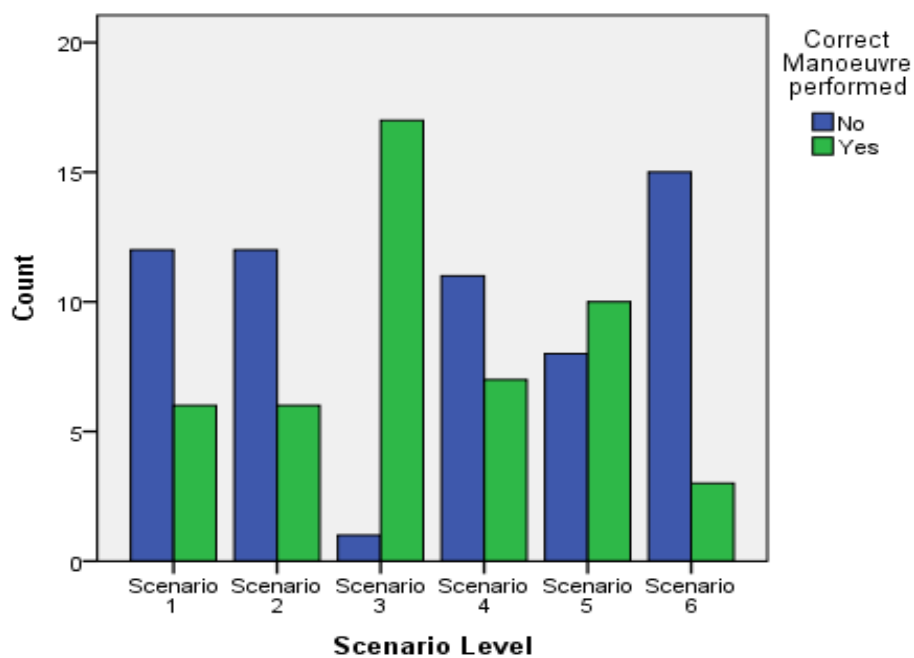


Figure 8.3 Clustered bar chart of frequency of correct manoeuvres performed against the scenario level

8.2.2 Workload Measurement Results

NASA-TLX Score

NASA-TLX score was not testable through ANOVA due to non-normality and it was not possible to transform the data in order to validate the parametric assumptions, hence a non-parametric test namely Kruskal-Wallis test was used to perform the analysis of NASA-TLX workload scores. Multiple Kruskal-Wallis tests were then applied for the individual workload scales.

There was no significant difference found between the two display

configurations for the NASA-TLX scores, $\chi^2 (1) = 0.093, p = .761$. Multiple Kruskal-Wallis for the individual workload scores also revealed that mental demand ($\chi^2 (1) = 0.129, p = .719$), physical demand ($\chi^2 (1) = 0.629, p = .428$), temporal demand ($\chi^2 (1) = 0.030, p = .863$), performance ($\chi^2 (1) = 0.218, p = .640$), effort ($\chi^2 (1) = 0.035, p = .851$) and frustration ($\chi^2 (1) = 0.673, p = .412$) are all not significantly different.

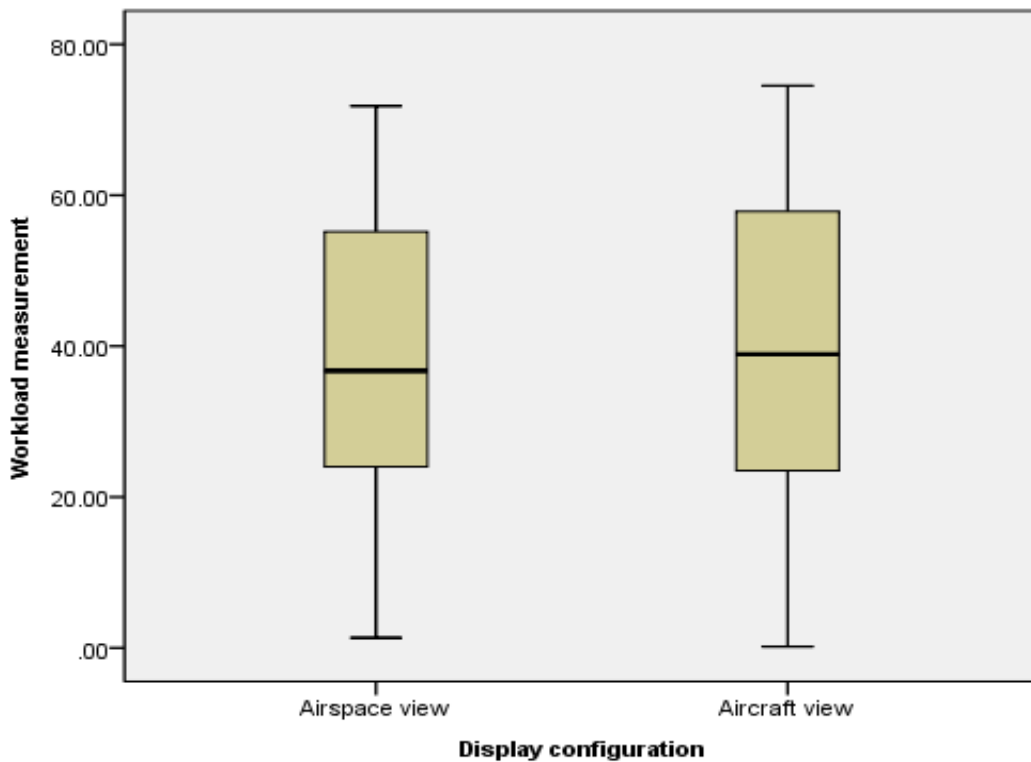


Figure 8.4 Boxplot of NASA-TLX workload rating

Spotting Task

The object spotting scores were not normally distributed due to which parametric Mann-Whitney test was used. The test results showed that there was no significant difference in the spotting scores across the two-display configuration used, $p = 0.442$. This was expected as this was a secondary task performed on the flight simulator.

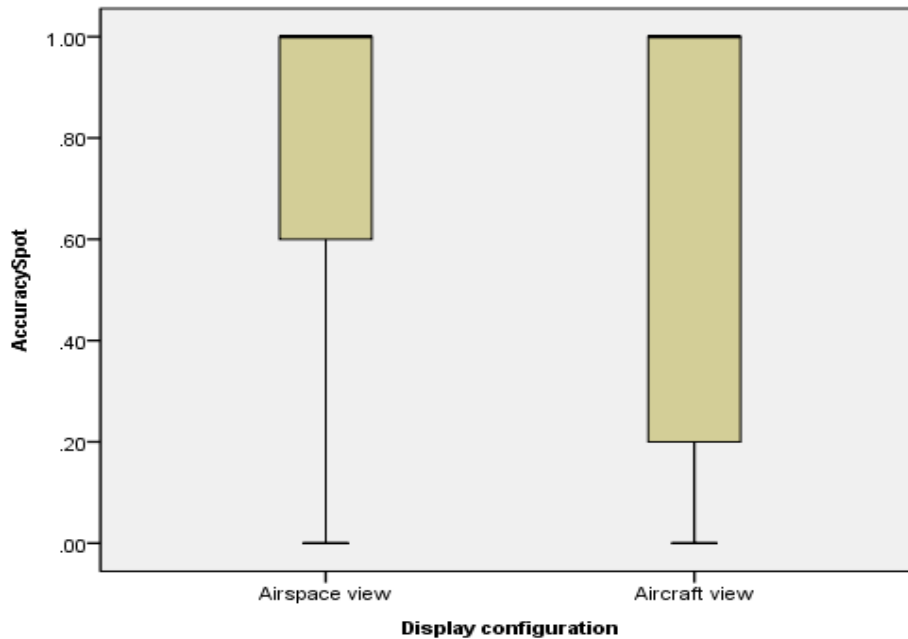


Figure 8.5 Box plot of Spotting scores

8.2.3 Scenario Specific Results

A further investigation of the individual scenarios was conducted to examine any inferences that can be drawn from the evaluation of performance measures across the display configurations for individual scenarios. The results of the decision processing time and the accuracy of the manoeuvre across the two display configurations for individual scenarios are provided here.

The plot for the average time taken by the subject to decide on manoeuvre versus the display type for the individual scenarios is provided in Figure 8.6. The figure shows that there is no inference to be drawn on the preference for a particular display configuration in which the subjects performed better in terms of decision processing time across all the scenarios. There were only three scenarios (scenario 2, scenario 3 and scenario 6), where there was predominant variation in the average time taken to manoeuvre across the two display configurations. The decision time for scenario 3 (overtake situation) on Airspace view (Mean = 12.714, SD = 4.28) and Aircraft view (Mean = 9.831. SD= 9.831) were predominantly different. Similarly for scenario 6 (Overtake situation dual conflict) the decision time on Airspace view (Mean = 11.311, SD = 3.561) and Aircraft view (Mean = 8.768. SD= 3.89) were also predominantly

different. There is a strong indication that the subjects performed better in terms of the average time taken to decide on manoeuvre on the aircraft view than the airspace view display configuration across two specific scenarios having the same conflict situations (overtaking aircraft). The variation in the mean decision time for scenario 3 and scenario 6 across two display configurations is indicated also in box plot for the individual scenarios in Figures 8.7 and 8.8.

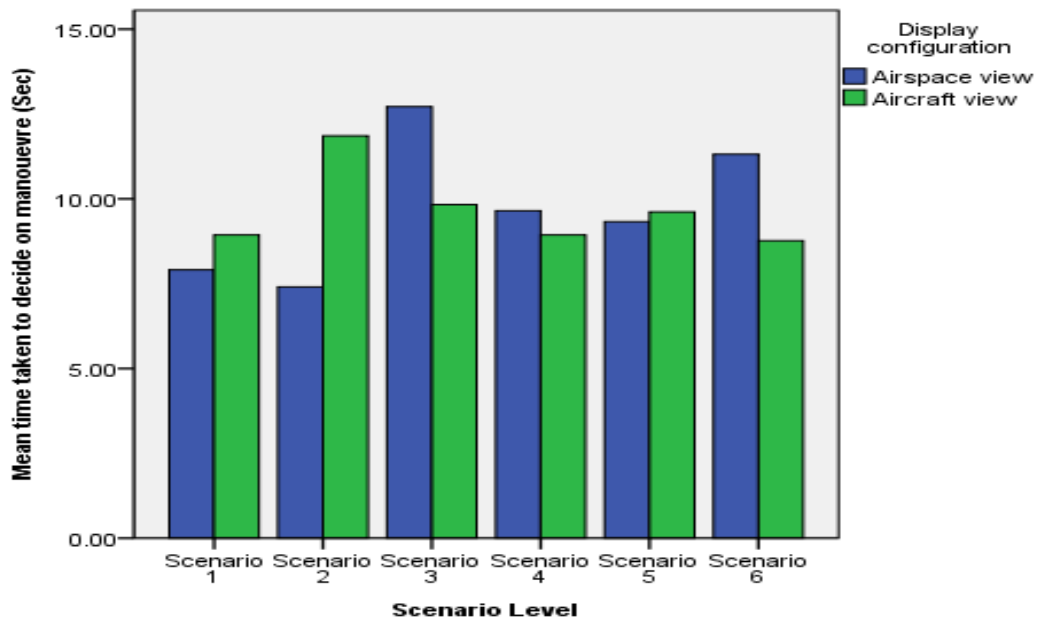


Figure 8.6 Bar chart of average time taken to decide manoeuvre

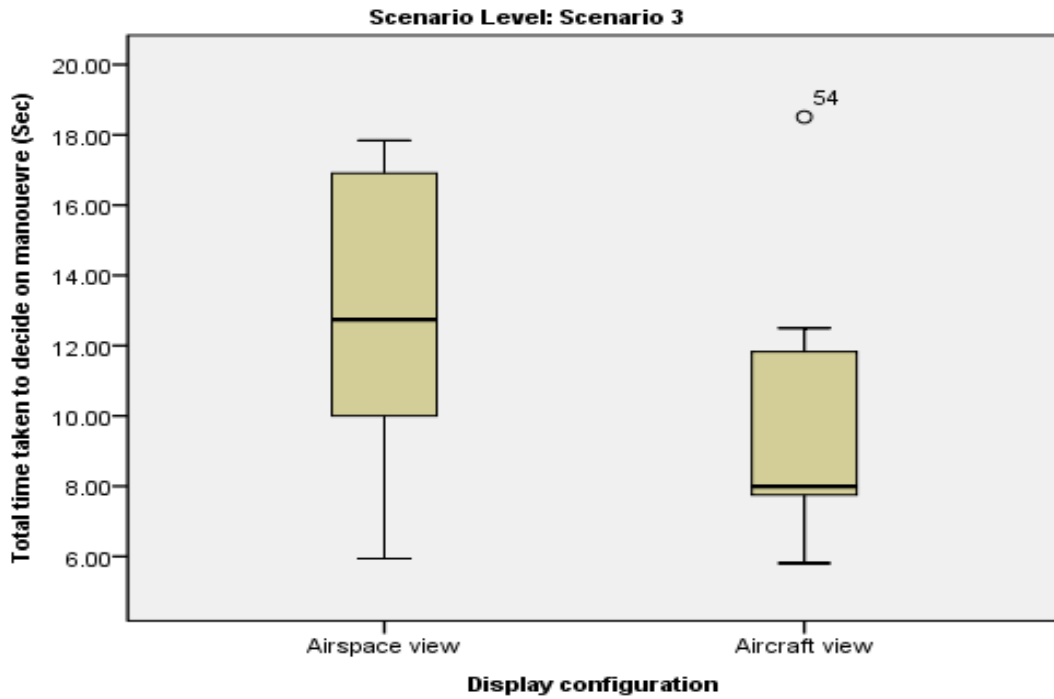


Figure 8.7 Box plot of total time taken to decide manoeuvre (Scenario 3)

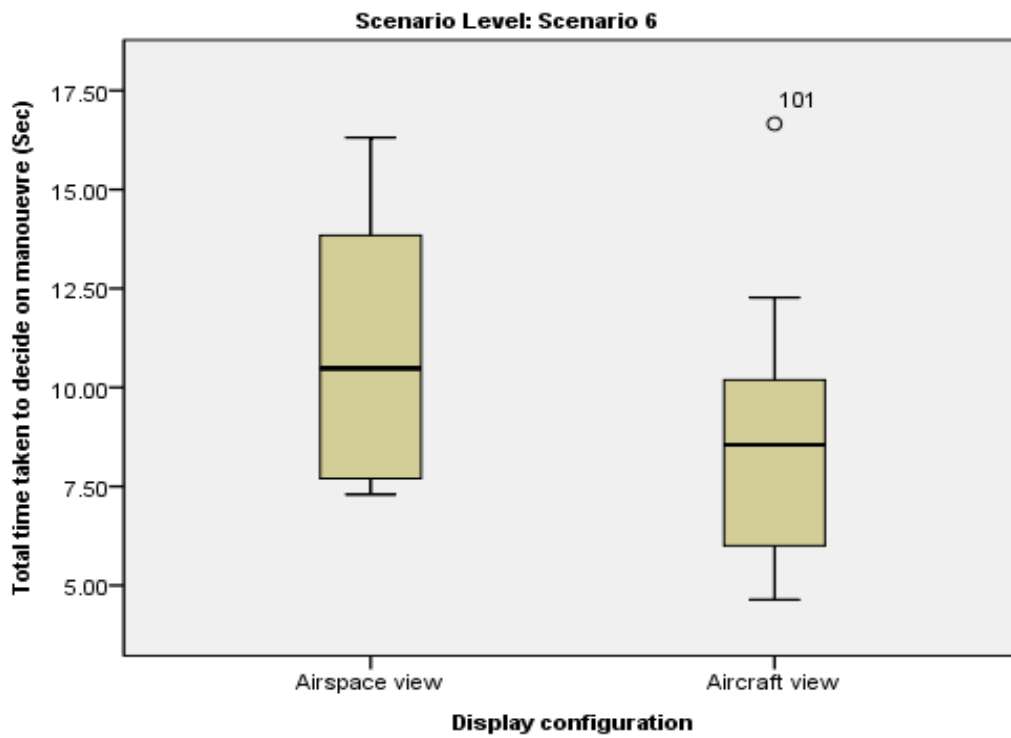


Figure 8.8 Box plot of total time taken to decide manoeuvre (Scenario 6)

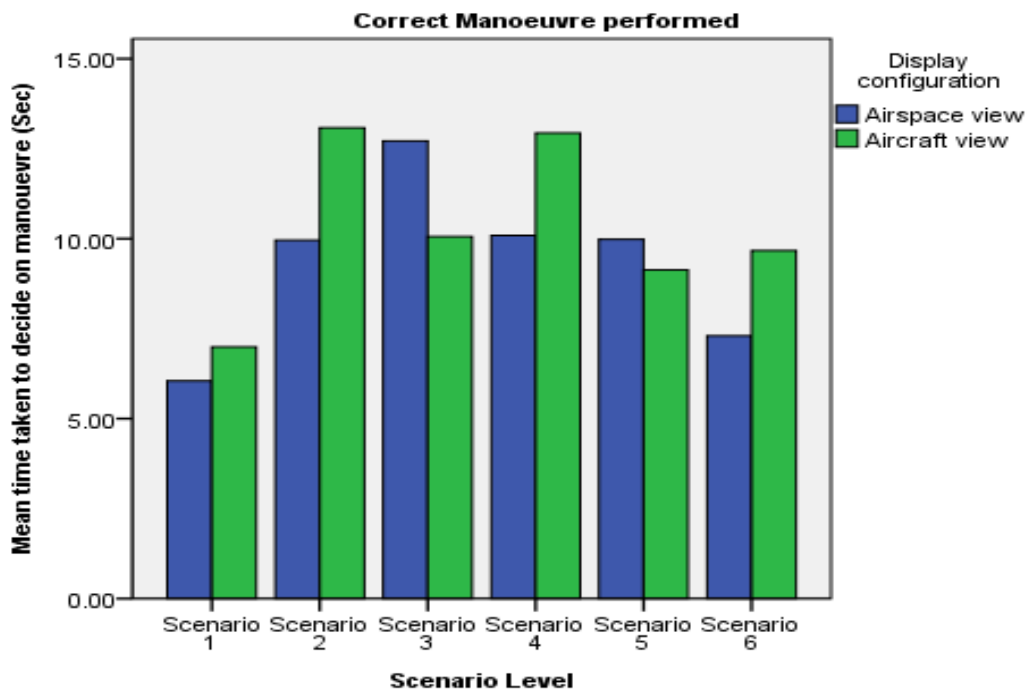


Figure 8.9 Bar chart of Average time taken to decide manoeuvre for correct manoeuvre selected

The plot for the average time taken to decide on manoeuvre and the accuracy of the manoeuvre (correct manoeuvre performed) versus the display type for the individual scenarios is provided in Figure 8.9. The figure shows that the average decision time across the individual scenarios (except scenario 3 and scenario 5) performed slightly better (took less time to decide on manoeuvre) on Airspace view compared to the Aircraft view display configuration. However, the performance differential is not large enough to infer a strong preference towards one display configuration or the other across the entire population.

8.2.4 Final Questionnaire Results

Subjective display ratings were scored by the participants by a comparison questionnaire generally used in Analytic Hierarchy Process. The participant display preference question used a five-level format which were 'same' or 'slightly better' or 'better' or 'much better' or absolutely better'. The overall ratings for participant display

preference are provided in Figure 8.10. It shows that the participants greatly preferred the Aircraft view display configuration compared to the Airspace view. Four participants had a very strong preference for the Aircraft view display configuration (approx. 22%). Only one participant had a preference for Airspace view display configuration.

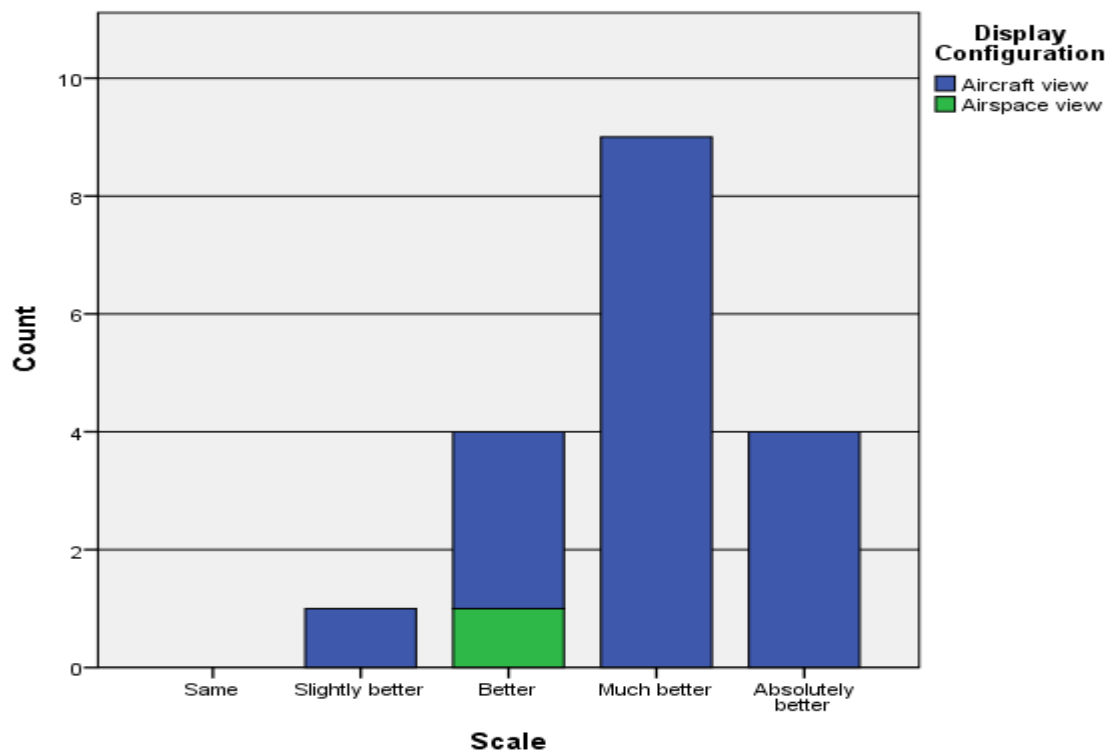


Figure 8.10 Participant Display preference

In addition to rating the displays, the participants were also asked to indicate the value of information that was used by them to resolve the conflict situation. The information varied from intent information to visual cues on the display. The 'highlight of UAV track' to differentiate from other aircrafts in the display, was found to be very valuable by 10 out of 18 participants (approx. 56 %), as shown in Figure 8.11. The 'prediction vectors' which provided intent information relating to heading of the aircraft tracks was also rated very valuable by the participants, with 15 out of 18 participants rating it very useful (approx. 83%), as shown in Figure 8.12. The 'highlight of intruder

track' information which highlighted the conflicting aircraft when there was a conflict alert with the UAV track, also was valuable to the participants. Around half of the participants (9 out of 18) rated it as being very valuable, as shown in Figure 8.13. The usefulness of the colour format for aircraft tracks surrounding the UAV track was also rated by the participants. They found it useful but not as much as the others. Most of the participants (8 out of 18) rated it as being somewhat valuable, two participants found it very valuable and only one participant gave a somewhat detrimental score, as shown in Figure 8.14. Finally, the usefulness of track list window that provided sensor obtained values of heading, altitude and separation distance from UAV track was assessed. All the participants indicated that they did not use them during the experiment and had a neutral rating, as shown in Figure 8.15.

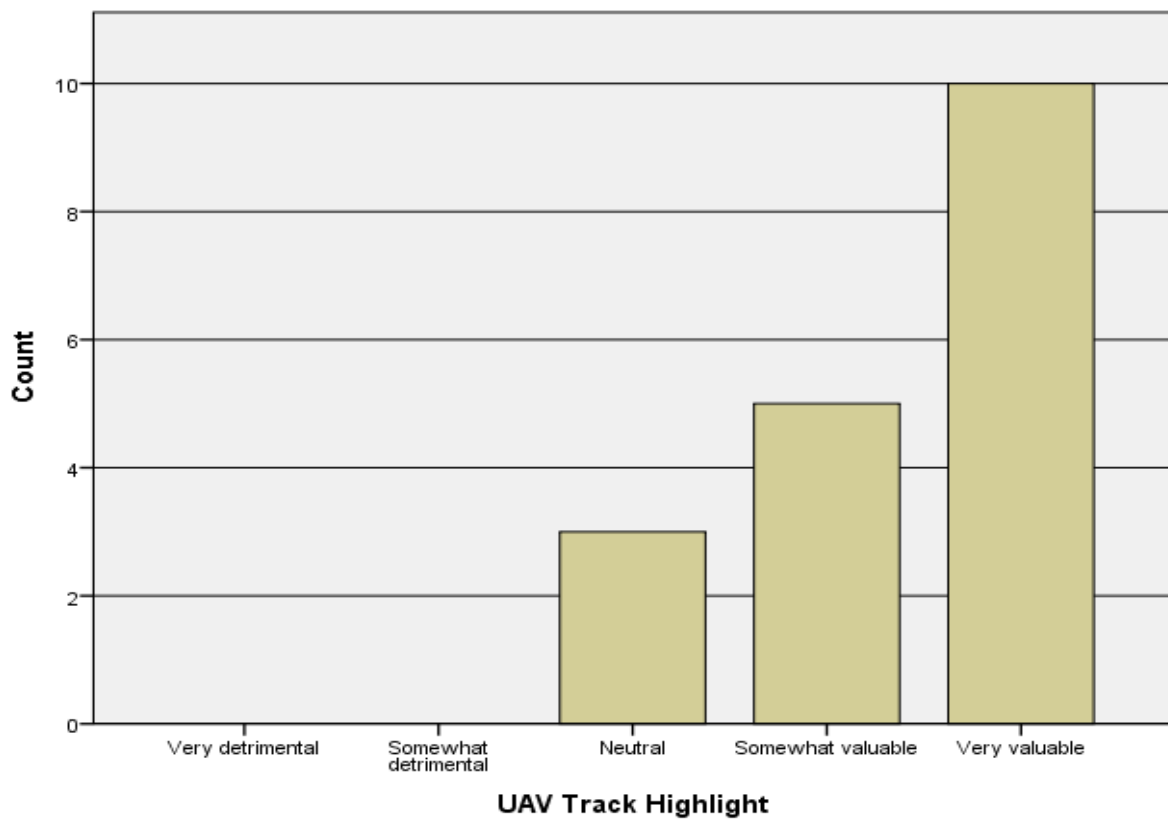


Figure 8.11 Value of 'highlight of UAV track' information

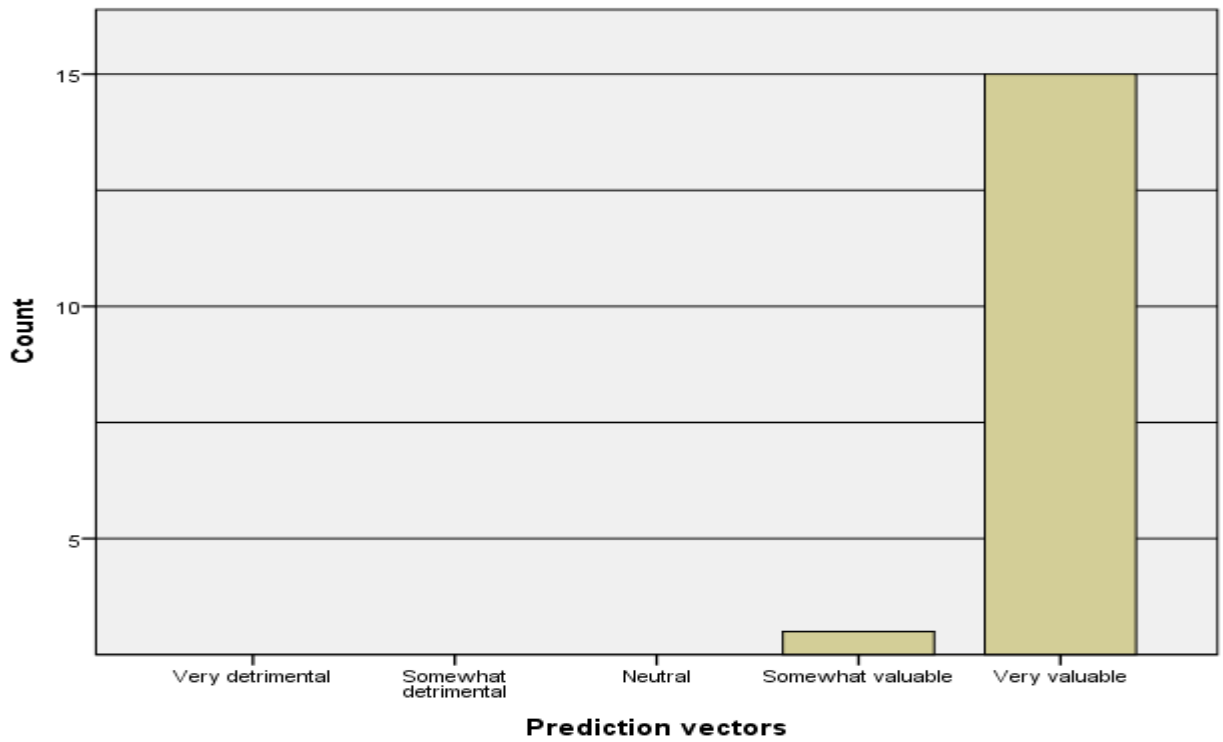


Figure 8.12 Value of 'prediction vectors' information

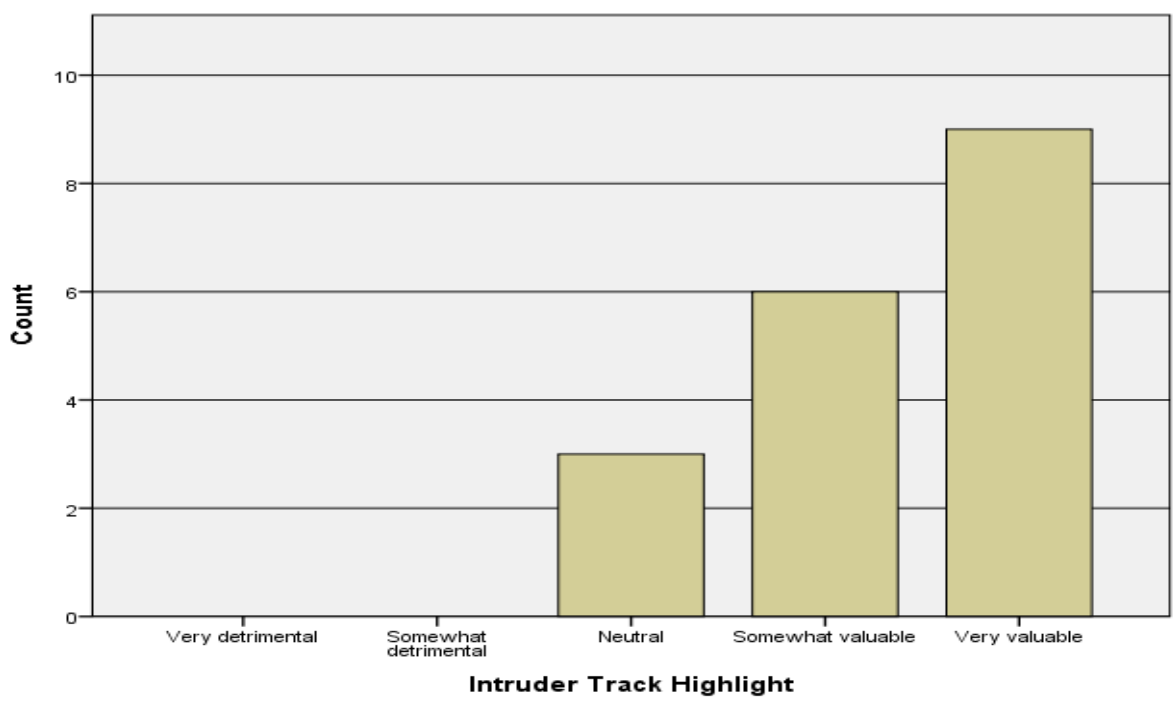


Figure 8.13 Value of 'Highlight of intruder track' information

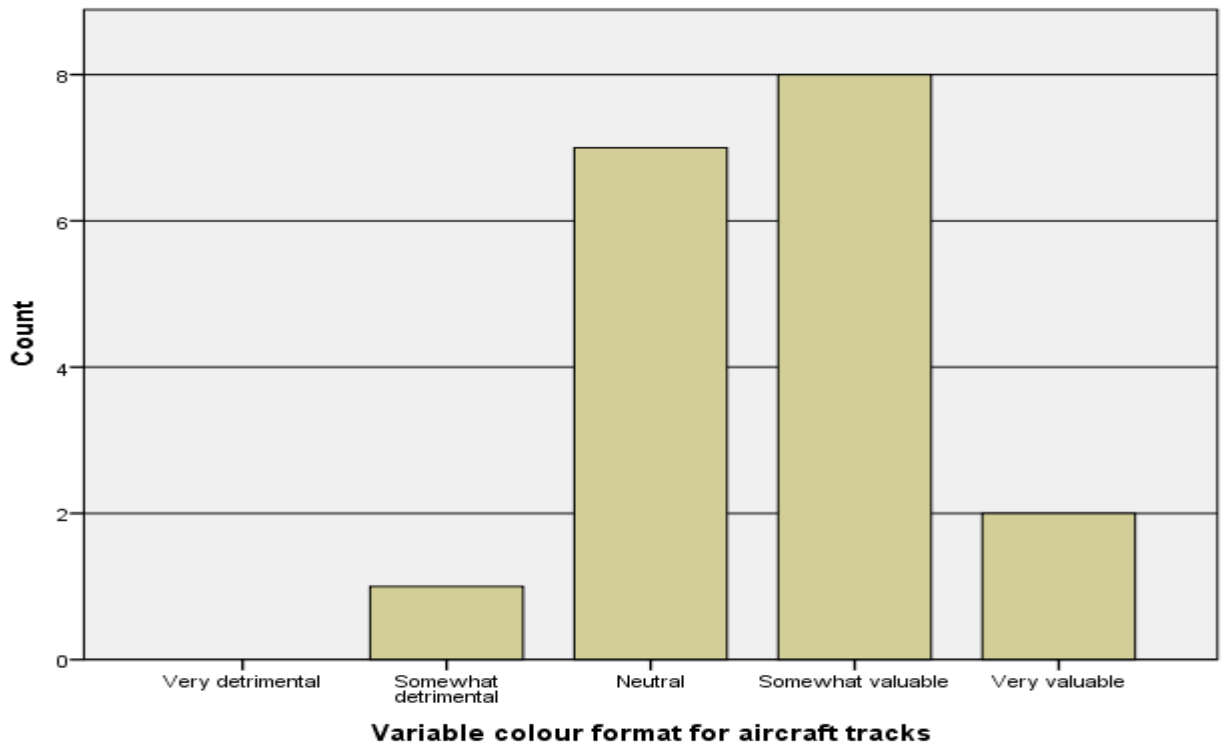


Figure 8.14 Value of 'Surrounding aircrafts colour format' information

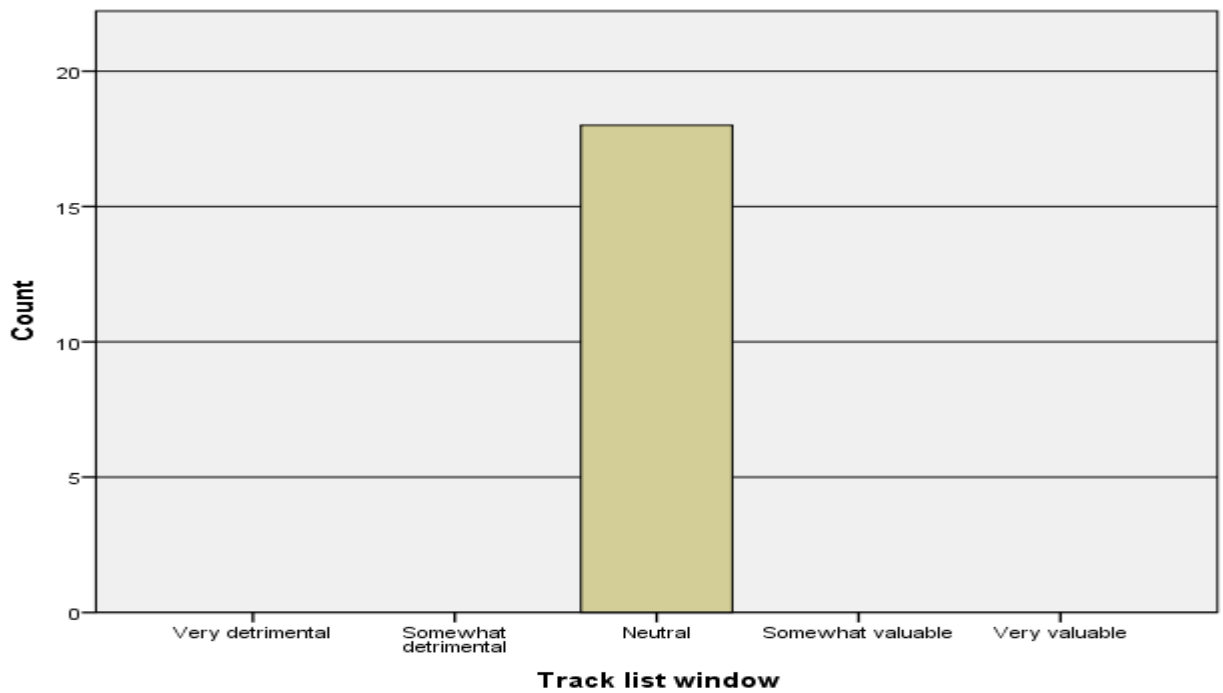


Figure 8.15 Value of 'Track list window' information

8.3 Discussion

The key objective of the GBSAA system simulation experiment was to assess the effects of two display configurations (airspace and aircraft view) on the situation awareness and decision-making ability of participants to resolve aircraft separation violation situations. Airspace view uses a standard ATC display (with few track symbol and colour changes) which presented a north-up top-down view of the UA and surrounding aircraft tracks. Whereas the Aircraft view uses a modified ATC display (incorporating the benefits of TCAS and ATC displays) which presented UA heading up view on a moving map display with UA always centred on the display. The experiment was made possible by performing human-in-the-loop simulator trials with these two display configurations across several traffic situations (six scenarios).

One of the key performance measures for proving the safety case for any sense and avoid system for UAS is the processing timeline. The total reaction time involves, the sense and avoid processing time (includes time to see, recognise threat, decide on action), execute the manoeuvre and allow the aircraft to respond to the action. According to FAA, any sense and avoid processing time would require the target to be detected at least 10.1 seconds to the time of impact, so that the UAS pilot is able to perform the necessary manoeuvre to keep a safe separation between the UA and the intruding aircraft. The decision processing time (time taken to decide on manoeuvre) results from the experiment indicate that across both the display configurations (Airspace view: Mean = 9.718, Aircraft view (Mean = 9.656) were below the 10.1 seconds level. This is significant as this will be an important measure to present to the aviation authorities when the safety case for a GBSAA system is presented. As this result has been obtained in a human-in-the-loop simulation context, this would need to be further tested by integrating the radar sensor to the GBSAA system and performing field trials. In the real-world conditions there are external factors such as weather and intruder aircraft types which may cause variation in detection ability of the ground based sensor and thereby affect the decision processing timeline. However once the aerial object has been detected by the ground based sensor, the performance of the GBSAA system in terms of processing sensor data and displaying the aircraft location information would not differ much between simulation environment

and real-time operation of fully integrated GBSAA system.

The results indicated there was no significant effect of display configurations on the time taken to decide on manoeuvre. Similarly there was no significant effect of scenario levels (different aircraft encounter situation) on the decision processing time. However the results indicated there was a significant interaction between the display configuration used and the scenario level encountered, on the total time taken to decide on manoeuvre. A further investigation of the significance effects scenario specific results showed that the mean decision time for scenario 3 (overtaking) and scenario 6 (overtaking with dual conflict) were predominantly different. In both the scenarios the mean decision time for Aircraft view was lower compared to the Airspace view display configuration. This could be explained due to the head-up and UA centred view presented to the participant, made it easier evaluate the encounter situation as the intruder aircraft was directly ahead of the UA. The scenario specific results also indicated predominant difference in the means of the decision processing time of scenario 2 (converging intruder aircraft, right-angled approach) for the two display configurations. The time to decide on manoeuvre was significantly lower in this scenario for Airspace view as compared to Aircraft view.

The results also indicated that there was no significance of accuracy of manoeuvre across display configurations. The percentage of accuracy of manoeuvre of participant was quite similar across the two display configurations. The workload measure results also indicated there was no significant effect across the two display configurations. Similarly, the results for the object spotting task also indicated no significant effects across the display configurations. This was expected as the spotting task performed on the flight simulator, the participant ability to control the aircraft flight on the simulator was responsible for the performance of the spotting task. Similarly, the workload performance measures were impacted by the flight simulator task which had a similar level of difficulty across all the display conditions except the variation in location of objects to be spotted by the participant.

The subjective results of the experiment are more conclusive and show a preference for particular display configuration. Nearly all participants preferred the aircraft view (modified ATC display) over the airspace view (standard ATC display).

The results for the overall ratings of the track symbol and colour format used for highlighting the UA in relation to other surrounding aircrafts also showed that they were very valuable for the participants to identify the UAS aircraft and the intruder aircraft (separation conflict) from other aircrafts in the airspace in order to decide on the manoeuvre to execute based on the rules of the air. Hence these features which were developed in an existing ATC display were useful aids for improving situation awareness and also improve the decision-making ability of the users of the GBSAA information display system.

Part IV: Conclusions

Chapter 9: Conclusions

The main aim of this research is to examine the issues associated with guaranteeing that information on which decisions are made is valid and of very high integrity in an Air Traffic environment where UAS is an integral part. This leads to the derivation of the three key aspects that are addressed in the research.

The first aspect that the research focussed on was to examine the current architecture of the Air Traffic Management (ATM), which is a System-of-System (SoS) in itself, and its evolution to enable the integration of UAS into the national airspace system. This research used a systems approach to understand the problem of UAS integration in non-segregated airspace more holistically. The underlying framework for this approach was based on a high-level architecture analysis using architecture patterns. This research shows that the method of using architecture patterns to represent an inherently complex SoS such as the current ATM can provide a significant step in the understanding of the SoS operation. This approach is especially useful when integrating new airspace users, such as UAS, which are completely different to current airspace users, into an already complex SoS. The architecture patterns to represent future ATM architectures is also presented which provides a basis for understanding the trade-offs between different architecture solutions where the UAS is integrated in a phased manner into the ATM architecture. The next generation ATM architecture is envisaged to be designed in such a way that more and more decisions will be made by the system rather than humans; hence it is imperative to understand the evolution of ATM architecture to enable safe and efficient operation of UAS in the national airspace system.

The second aspect of this research involved looking into the specific issue of UAS sense and avoid. The research evaluated several system architecture solutions for UAS Sense and Avoid with regards to decision making processing i.e. whether remotely or on the ground. The various approaches to the problem had varying technology readiness, commercial viability, development risks and timescale for operational implementation. The industrial nature of the project meant the solution was looked at not only in a technical nature but also from a commercial viability. Further

research then focussed on Ground Based Sense and Avoid (GBSAA) system which is seen as a short-to-medium term solution to achieve separation assurance capability for UAS in non-segregated airspace. This research provided an analysis of the technical, operational and technical aspects of a UAS GBSAA system.

The third aspect of this research was to develop a GBSAA simulation environment in order to investigate the effects of different display configurations of GBSAA information display system on the decision-making capability of the human operator. The experiment was made possible by performing human-in-the-loop simulator trials with these two display configurations: Airspace view that used a standard ATC display (with few track symbol and colour changes) which presented a north-up top-down view of the UA and surrounding aircraft tracks. Whereas the Aircraft view used a modified ATC display (incorporating the benefits of TCAS and ATC displays) which presented UA head up view on a moving map display with UA always centred on the display. The results show that a key performance measure the decision processing time (total time taken to decide on manoeuvre) for both display configurations (Airspace view: Mean = 9.256 sec, Aircraft view: Mean = 9.379 sec) were below the decision processing timeline (10.1 sec based on human see and avoid capability) that would be required for a sense and avoid system for proving the safety case. The objective measures did not show any significant difference in the decision processing time across the two display configurations. However, the subjective results were more conclusive and showed a preference for aircraft view display configuration, most of the participants preferred the aircraft view (modified ATC display) over the airspace view (standard ATC display).

The outcomes of this research are briefly outlined in the form the recommendations that would provide more knowledge to the field of integration of UAS into national airspace. First and foremost is a change in mind-set and behaviour is required among main stakeholders (Aviation authorities, other airspace users, public pressure groups, UAV operators etc.) to provide a solution such a complex SoS problem. The wide viewpoint of major stakeholders on the problem to the solution has meant that there has not been much progress until even with huge resources (money, time and effort) spent for integration of UAS in national airspace system. A key area

where the change in mind-set is required is in the perception of UAS operational risk by aviation authorities.

The other recommendation of this research is based on the research study on UAS Sense and Avoid and outcome of the GBSAA prototype system evaluation. The process of UAS integration in non-segregated airspace should occur in a phased manner which will enable only restricted access initially which would lead to more learning and information on operational performance of UAS. GBSAA is one of the approach which will enable restricted access to national airspace for some UAS operators (government and military agencies) at the initial phase. The safety case for GBSAA based on the current view of the aviation authorities is presented in this research.

9.1 Thesis Contributions

The contributions to the research area based on the method and techniques adopted in this thesis can be listed as follows:

- The problem of integration of UAS in non-segregated airspace was looked at holistically using an underlying systems engineering framework. The research uses the method of architecture patterns to represent SoS and applies this to the current ATM architecture to understand its operation in a better way and also examine the possible architecture solutions for integration of UAS into ATM architecture in the future. Although there has been a lot of research into the field of UAS integration in national airspace the routine operation of UAS in national airspace is still not yet been possible. The challenges are well beyond the technical and regulatory aspects. This research used wicked problem (often used in Social Science to describe a social or cultural problem that is difficult or impossible to solve) as an analysis method to examines the key issues associated with the integration of UAS in non-segregated airspace. Therefore an interdisciplinary approach was applied to the research problem.
- The development of a GBSAA simulation environment to prove the application of the concept. This involved several software changes to an existing ATC display system in order to automate some of the features for it is used as a

Ground Based Sense and Avoid (GBSAA) information display system. The use of an existing ATC display greatly reduces the rigorous software certification process for proving the safety case which would lead to easier certification route for a commercially feasible product. This provides a high level of integrity to the proposed GBSAA information display concept. The integration of the flight simulator with the prototype GBSAA information display system that would provide as a demonstration platform for the concept and also enable further research in order to perform field trial with a fully integrated GBSAA system.

- The GBSAA information display system simulation experiment showed that the concept of using a modified ATC display as an information display system could be viable. The experiment set out to assess the effects a standard ATC display and a modified ATC display (for use as a GBSAA information display system) on the situation awareness and decision-making ability of participants to resolve aircraft separation violation situations. The objective measures of the experiment were not conclusive in terms of the preference of display, however the subjective results showed that the participants rated the modified ATC display (includes features such a moving map display and UAS aircraft as display centre) much better and preferred that display over a standard ATC display. The experiment also proved that a modified ATC display could be used to provide situation awareness and intent information to the human operator on the ground that will enable them to resolve separation conflict situation with surrounding aircrafts. This could be seen as an extension to the current operation of UAS in national airspace which involves a ground observer always being within visual line-of-sight of UAS to avoid separation conflict situations and stay well clear of other surrounding aircrafts.

9.2 Further Research

Future research should focus on mining more high-level architecture patterns of the current ATM system and alternative architecture solution for integration of UAS into ATM system. The architectural patterns could be specified in an architecture modelling framework so that different architecture solutions can be evaluated through modelling

and simulation approaches. This will enable in analysing the impact of different architecture solutions on the performance of the overall SoS.

With the experimental constraints and sample size limitation in this research, further work is required in terms of understanding the effects of prototype GBSAA information display system (modified ATC display) on the situation awareness and decision-making ability of UAS operator/observer. The key challenge faced in this research which is common to aerospace studies was the recruitment of primary users of the system for the experiment. If primary users of the system were recruited, the scope of the experiment could expand further with having a UAS pilot and a UAS observer together in a UAS GCS performing the experiment. The communication between the UAS pilot and observer can also be assessed as this would be important to ensure safe separation of UAS from other aircrafts.

The future work could be expanded to developing a fully integrated GBSAA system which will include the ground based sensor element along with the information display system. The field trails of the fully operational GBSAA system would enable is further validating the proof of concept and also help generate performance data in order to support the development of a safety case.

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Appendices

Appendix 1: Consent Form



Effect of Increasing Workload on Potential Remotely Piloted System Operators

INFORMED CONSENT FORM

(to be completed after Participant Information Sheet has been read)

The purpose and details of this study have been explained to me. I understand that this study is designed to further scientific knowledge and that all procedures have been approved by the Loughborough University Ethical Approvals (Human Participants) Sub-Committee.

I have read and understood the information sheet and this consent form.

I have had an opportunity to ask questions about my participation.

I understand that I am under no obligation to take part in the study.

I understand that I have the right to withdraw from this study at any stage for any reason, and that I will not be required to explain my reasons for withdrawing.

I understand that all the information I provide will be treated in strict confidence and will be kept anonymous and confidential to the researchers unless (under the statutory obligations of the agencies which the researchers are working with), it is judged that confidentiality will have to be breached for the safety of the participant or others.

I agree to participate in this study.

Your name

Your signature

Signature of investigator

Appendix 2: Participant Pre-briefing material

Introduction to the experiment

The purpose of this research is to evaluate the various interface display concepts for Ground Based Sense and Avoid (GBSAA) system implementation to support UAS operations in non-segregated airspace. The experiment is based on various scenarios, which are designed so as to analyse the evaluation of separation violation potential, prioritizing of impending loss of separation threats and determining a manoeuvre to avoid the impending loss of separation. This includes the functions of operator that are noticing the alert situation, assessing the air traffic picture in the vicinity of UA and then determining a manoeuvre to be performed to avoid the impending loss of separation between UA and intruding aircraft. The performance of the participant based on the kind of manoeuvre they make and the effects of their manoeuvre will be used as one of the many outputs measured from the experiment. The aim is to always ensure that the separation with other aircrafts is maintained at always to ensure safety of the airspace. Hence causing a loss of separation event would be the undesirable at all time during the scenarios.

General Rules of Air (International Civil Aviation Organisation)

Note. — It is important that vigilance for the purpose of detecting potential collisions be not relaxed on board an aircraft in flight, regardless of the type of flight or the class of *airspace in which the aircraft is operating, and while operating on the movement area of an aerodrome.*

3.2.1 Proximity

An aircraft shall not be operated in such proximity to other aircraft as to create a collision hazard.

3.2.2 Right-of-way

The aircraft that has the right-of-way shall maintain its heading and speed, but nothing in these rules shall relieve the pilot-in-command of an aircraft from the responsibility of taking such action, including collision avoidance maneuvers based on resolution advisories provided by ACAS equipment, as will best avert collision.

3.2.2.1 An aircraft that is obliged by the following rules to keep out of the way of another shall avoid passing over, under or in front of the other, unless it passes well clear and takes into account the effect of aircraft wake turbulence.

3.2.2.2 *Approaching head-on.* When two aircraft are approaching head-on or approximately

so and there is danger of collision, each shall alter its heading to the right.

3.2.2.3 *Converging*. When two aircraft are converging at approximately the same level, the aircraft that has the other on its right shall give way, except as follows:

- a) Power-driven heavier-than-air aircraft shall give way to airships, gliders and balloons;
- b) Airships shall give way to gliders and balloons;
- c) Gliders shall give way to balloons;
- d) power-driven aircraft shall give way to aircraft, which are seen to be towing other aircraft or objects.

3.2.2.4 *Overtaking*. An overtaking aircraft is an aircraft that approaches another from the rear on a line forming an angle of less than 70 degrees with the plane of symmetry of the latter, i.e. is in such a position with reference to the other aircraft that at night it should be unable to see either of the aircraft's left (port) or right (starboard) navigation lights. An aircraft that is being overtaken has the right-of-way and the overtaking aircraft, whether climbing, descending or in horizontal flight, shall keep out of the way of the other aircraft by altering its heading to the right, and no subsequent change in the relative positions of the two aircraft shall absolve the overtaking aircraft from this obligation until it is entirely past and clear.

Appendix 3: Pre-experiment Questionnaire

This questionnaire will be used only to obtain information about your background and experience of using several interfaces in day-to-day life. Researchers will only use this information to describe the participants in this study as a group. Your identity will be kept anonymous.

1. Have you seen/used Air Traffic Controller (ATC) displays before?
Never, Seen, Used
2. Have you seen/used Traffic Collision Avoidance System (TCAS) displays before?
Never, Seen, Used
3. Rate your level of motivation to participate in this study? (1-10 scale)
4. Do you wear glasses for eyesight correction?
5. Rate your level of fatigue or tiredness at this time of day? (1 – 10)

Appendix 4: Post-Experiment Questionnaire Form

1. Which is better display?

Airspace Centric

Aircraft Centric

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Absolutely better much better better slightly better same slightly better better much better Absolutely better

2. What was your overall strategy for avoiding conflicts and did it change with the display?

3. Rate each information for its use in resolving separation violation situations?

- UA track highlight
- Prediction vectors
- Highlight of intruder track
- Surrounding aircrafts variable colour format
- Track list window

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Very detrimental Somewhat Detrimental neutral somewhat valuable Very valuable


4. What information should be added to the display?

5. What information was unnecessary on the display?


6. Any further comments or suggestions on the display?

Appendix 5: NASA-TLX


Mental Demand: How mentally demanding was the task?




Physical Demand: How physically demanding was the task?




Temporal Demand: How hurried or rushed was the pace of the task?




Performance: How successful were you in accomplishing what you were asked to do?



Effort: How hard did you have to work to accomplish your level of performance?



Frustration: How insecure, discouraged, irritated, stressed, and annoyed were you?



INSTRUCTIONS:

Please rate all six workload measures on the left by clicking a point on the scale that best represents your experience with the task you just completed.

Consider each scale individually and select your responses carefully. Mouse over the scale definitions for additional information.

Your ratings will play an important role in the evaluation being conducted. Your active participation is essential to the success of this experiment, and is greatly appreciated.

Click the Submit button when you have completed all six ratings.

Please note that the Performance scale goes from **Poor** on the left to **Good** on the right.

SUBMIT

Test

Appendix 6: Surveillance Data Exchange Category 048

FRN	Data Item	Data Item Description	Length in Octets
1	I048/010	Data Source Identifier	2
2	I048/140	Time-of-Day	3
3	I048/020	Target Report Descriptor	1+
4	I048/040	Measured Position in Slant Polar Coordinates	4
5	I048/070	Mode-3/A Code in Octal Representation	2
6	I048/090	Flight Level in Binary Representation	2
7	I048/130	Radar Plot Characteristics	1+1+
FX	n.a.	Field Extension Indicator	n.a.
8	I048/220	Aircraft Address	3
9	I048/240	Aircraft Identification	6
10	I048/250	Mode S MB Data	1+8*n
11	I048/161	Track Number	2
12	I048/042	Calculated Position in Cartesian Coordinates	4
13	I048/200	Calculated Track Velocity in Polar Representation	4
14	I048/170	Track Status	1+
FX	n.a.	Field Extension Indicator	n.a.
15	I048/210	Track Quality	4
16	I048/030	Warning/Error Conditions	1+
17	I048/080	Mode-3/A Code Confidence Indicator	2
18	I048/100	Mode-C Code and Confidence Indicator	4
19	I048/110	Height Measured by 3D Radar	2
20	I048/120	Radial Doppler Speed	1+
21	I048/230	Communications / ACAS Capability and Flight Status	2
FX	n.a.	Field Extension Indicator	n.a.
22	I048/260	ACAS Resolution Advisory Report	7
23	I048/055	Mode-1 Code in Octal Representation	1
24	I048/050	Mode-2 Code in Octal Representation	2
25	I048/065	Mode-1 Code Confidence Indicator	1
26	I048/060	Mode-2 Code Confidence Indicator	2
27	SP-Data Item	Special Purpose Field	1+1+
28	RE-Data Item	Reserved Expansion Field	1+1+
FX	n.a.	Field Extension Indicator	n.a.

Appendix 7: Surveillance Data Exchange Category 034

FRN	Data Item	Data Item Description	Length in Octets
1	I034/010	Data Source Identifier	2
2	I034/000	Message Type	1
3	I034/030	Time-of-Day	3
4	I034/020	Sector Number	1
5	I034/041	Antenna Rotation Period	2
6	I034/050	System Configuration and Status	1+
7	I034/060	System Processing Mode	1+
FX	N/A.	Field Extension Indicator	N/A.
8	I034/070	Message Count Values	(1+2*N)
9	I034/100	Generic Polar Window	8
10	I034/110	Data Filter	1
11	I034/120	3D-Position of Data Source	8
12	I034/090	Collimation Error	2
13	RE-Data Item	Reserved Expansion Field	1+1+
14	SP-Data Item	Special Purpose Field	1+1+
FX	N/A.	Field Extension Indicator	n.a.