Aircraft Fuel Rig System Fault Diagnostics Using Digraphs

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Abstract

The issue of fault diagnostics is a dominant factor concerning current engineering systems. Information regarding possible failures is required in order to minimise disruption caused to functionality. A method proposed in this paper utilises digraphs to model the information flow within a system. Digraphs are comprised from a set of nodes representing system process variables or component failure modes. The nodes are connected by signed edges thus illustrating the influence, be it positive or negative, one node has on another.

Fault diagnostics is conducted through a procedure of back-tracing in the digraph from a known deviating variable. A computational method has been developed to conduct this process. Comparisons are made between retrieved transmitter readings and those expected whilst the system is in a known operating mode. Any noted deviations are assumed to indicate the presence of a failure.

This paper looks in detail at the application of the digraph diagnostic method to an industrially based test stand of an aircraft fuel system. Several operational phases of the system are investigated, with primary significance, with regards to system reliability, given to engine feed from the active supply tanks. This research includes transient system effects; with the rate of change of a parameter taken into consideration as a means of monitoring the system dynamically. The paper concludes with the evaluation and assessment of the validity of the results achieved.

Introduction

Fault diagnosis has become a fundamental facet of engineering applications. It is concerned with isolating the underlying causal faults leading to an observable effect in a monitored process. Effective detection of system faults aids in decreasing downtime and thus improves operational stability[1]. Methods employed to identify faults can be classified according to the detection of single or multiple system failures. Traditional approaches involved using testing algorithms to detect single failures and artificial intelligence techniques in the field of multiple fault diagnosis.

Novak et al.[2] focus on generating a sequential diagnosis tool (SDT). The SDT highlights a prospective fault through running a series of tests at a particular point in time. The tests are comprised from symptoms related to specific faults. This approach has been proven to be effective when determining single faults in a system with a known period of inactivity. However, difficulties arise when considering the complexity issue surrounding dependency in multiple fault combinations. Shakeri et al.[3] successfully extend the sequential testing technique through attempting to determine multiple fault causes for a given test. From the results further research is required to consider both unreliable tests and the combining of diagnostic results to form multiple failure options in fault tolerant systems (systems displaying redundancy).

Failure modes and effects analysis (FMEA) is an established system safety analysis technique. Attempts have been made to automate the process and thus increase its effectiveness through decreasing the time required to perform the analysis[4, 5]. Limitations have involved difficulties with the efficiency and scalability of the algorithms utilised. A different approach, proposed by Papadopoulos et al.[6], considers translating the information contained in a network of interconnected fault trees into FMEA style tables. Variability in performance of these methods is exhibited with increased system complexity.

Digraphs, also known as signed directed graphs[7, 8] can illustrate specific fault propagations through a system. The issue surrounding diagnosing single faults in systems is addressed by Rao[9]. Iverson and Pattersine-Hine extend this approach by considering the combination of two failures via an AND gate and identify the potential for real-time automated monitoring and diagnosis.

The characteristics associated with modern day systems require fault diagnosis to incorporate both adaptability and identification of multiple faults[10]. Modern systems are usually required to operate in more than one mode. An ideal diagnostic procedure would therefore incorporate an adaptable scope.

This paper applies the digraph method to a fuel rig which is representative of an aircraft fuel system. The issues surrounding multiple faults and dynamic analysis are addressed. A brief insight into digraphs by considering their representation of fault propagations through a system is provided. System fault diagnostics taking into account transient effects is discussed and the results yielded through automating the procedure are reviewed before presenting the conclusions of the research.

The Digraph Method

A digraph[11] is comprised from a set of nodes and edges, which are used to illustrate the ‘cause-effect’ relationships present within a system [12-14]; a related analogy being ‘input – output’.

The nodes represent system process variables or component failure modes and the edges connecting the nodes represent the interrelationships which are present. Digraph nodes contain an alphanumeric label which symbolises a specific process variable or component failure mode. With regards to process variable nodes, the numeric section of the label corresponds to a precise location in the application system. The precursor to the numeric section indicates the type of process variable the node represents. Examples of process variables include temperature, mass flow, pressure and signals from sensors. Following the same order, these would be represented in nodes by the precursors T, M, P and S. Process variable deviations[15, 16] are expressed as one of five discrete values: +10, +1, 0, -1 and-10 corresponding to large high, small high, normal, small low and large low deviations. These values are also used to describe the effect a disturbance (e.g. failure mode) has on a particular variable. Two further values (+5/-5) that are utilised when developing the fuel rig system digraph consider the presence of partial failures.

A simple digraph is illustrated in Figure 1. In the simple digraph illustration it can be noted that T1 and T2, the nodes, are connected by three edges. The alphanumeric code T1 represents temperature at location one. The edge with a gain of +1 is considered to be the normal edge since this represents the relationship which is normally true. The second and third edges in the illustration are termed conditional edges since their relationship is only true whenever the condition represented by ':' exists. It must be noted that only one edge is true at any one time.

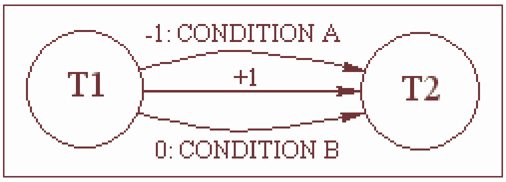

Figure 1 A Simple Digraph Representation

The example illustrated in Figure 2 demonstrates the use of some standard disturbances. Four component failure modes, labeled Fault One to Fault Four, are considered when developing the digraph for the example. Temperature at location one, under normal conditions, has a positive effect on temperature at location two.

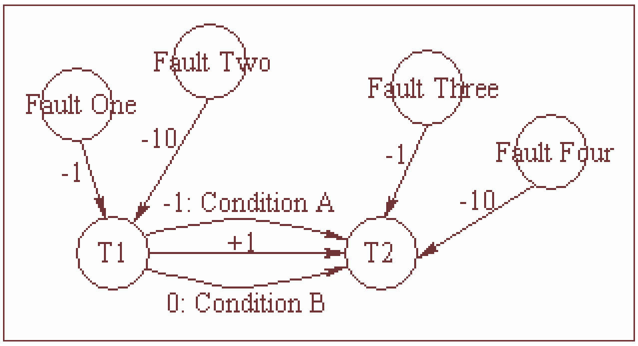

Figure 2 Digraph Example

The failure modes Fault One and Fault Three lead to a small negative disturbance in temperature at their respective locations, as illustrated by the '-1' signing of the edges connecting the failure mode and process variable nodes. The failure modes Fault Two and Fault Four lead to large negative disturbances in temperature as indicated by the '-10' signing of their respective edges.

Procedure

A generalized procedure outlining the main steps involved in developing a system digraph is provided:

Step One: System Analysis

Firstly the system under investigation is defined. A specific number is allocated to each component. In this manner, it is possible to create a straightforward location reference approach for process variables and component failure modes at a given point. All relevant component failures of the system are compiled. A failure mode code is then attached to each fault. The system is separated into sub-units and components. For example, one sub-unit could incorporate a valve and associated pipe-work. If control loops are present these are identified and classified accordingly into feed-back and feed-forward loops.

Step Two: Digraph Generation
The unit digraph models for the sub-units, previously noted in step one, are generated. All process variable deviations which could have an effect on the variables in the model are taken into consideration. The extent of the effect any disturbances may have on the system with regards to the assigning of discrete values is also noted. The system digraph is formed by connecting common variables from the sub-unit models.

The fault diagnostics process is conducted using the system digraph. System behaviour can be monitored through sensor data (e.g. via a level transmitter). In a given mode of operation the system would have a set of expected sensor readings. These are compared with the actual system readings during the diagnostics procedure (Steps 3 to 5) to identify if any deviations are present.

Step Three: Determination of System Deviations
The system sensor readings which are expected whilst the system is in a known operating mode, for example mode ON, are noted. The current sensor readings from the system are retrieved and then compared with those expected to determine if any deviations exist.

Step Four: Flagging of Non-Deviations
Non-deviating sensor nodes in the digraph are ‘flagged’. It is assumed that a non-deviating reading indicates the absence of a failure.

Step Five: Back-tracing Process
If a sensor registers a deviation then fault diagnosis involves back-tracing through the system digraph from the node which represents the location of the given deviation. The back-tracing process ceases once either (i) a flagged section is reached or (ii) no more back-tracing is possible. For multiple deviating sensors the diagnostic results obtained through back-tracing from each deviating node are ANDed together.

All potential fault causes are listed at the end of the fault diagnostics procedure.

The Fuel Rig

The purpose of a fuel system is to reliably provide an adequate amount of clean fuel at the right pressure to the engines during all phases of flight and manoeuvres. The fuel rig utilised is an aircraft simulation test stand that incorporates a stainless steel frame supporting three active supply tanks. The complete configuration of the fuel rig is representative of a modern aircraft fuel system; illustrating the flow of fuel from the main and auxiliary tanks to the engine. The rig recreates the function of a general aircraft fuel system through using water instead of kerosene. The general layout of the fuel rig is illustrated in Figure 3.

The three active supply tanks; Main, Wing and Collector, each have two associated pump trays. Each tray encompasses a peristaltic pump, pressure relief valve, powered and manual isolation valves and a pressure regulating valve.

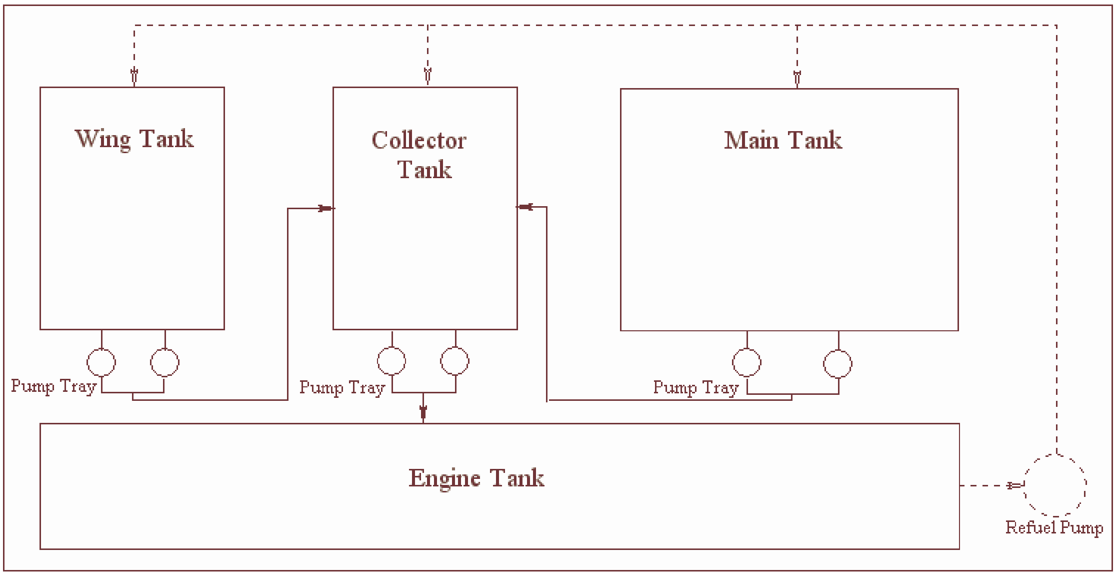

Figure 3. General Fuel Rig Layout

The main tank represents the core group of tanks on an aircraft. Two pumps, connected in parallel, pump water from the main tank to the collector tank. The auxiliary storage tanks of an aircraft fuel system are represented by the wing tank. In a similar manner to the main tank, two parallel pumps transfer water from the wing tank to the collector tank. A large single tank at the base of the fuel rig represents an aircraft engine. Fuel feeding to the engine (represented by the engine tank) is conducted via fluid transfer from the collector tank through a pair of parallel connected pumps. A final pump, the centrifugal refuel pump, transfers water back into the active supply tanks from the engine tank. Complete drainage of the fuel rig system is conducted through utilising the engine tank drain valve. Each of the three active supply tanks is also connected to the engine tank via a manually operated dump valve.

To monitor system behaviour and obtain the system status, data is retrieved from three types of sensors associated with the tanks. Level, flow and pressure transmitters are employed in the fuel rig system. The actual readings detected by the transmitters are classified into categories as follows:

- Level transmitter: High, low, within normal boundary, pump shut off or empty. There are two additional levels associated with the collector tank; thresholds one and two are of relevance when considering the ACTIVE operating mode, as described in the next section.
- Pressure transmitter: Pressure, no pressure or partial pressure.
- Flow transmitter: Flow, no flow or partial flow.

Modes of Operation

Three main modes of operation have been specified for the fuel rig:

1) 'ACTIVE': fluid is transferred from the collector tank to the 'engine' (engine tank). The tank pumps are switched on and powered isolation valves opened. As the collector tank level (CTL) decreases, transfer of water from the wing and main tanks to the collector tank commences in the following manner:
    - Phase One: CTL above threshold one: no transfer from main and wing tanks.

- Phase Two: CTL below threshold one and above threshold two: transfer from wing tank only. If wing tank at pump shut off level, transfer from main tank.
- Phase Three: CTL below threshold one and above pump shut off level: transfer from main tank if main tank level is above pump shut off level.

2) ‘DORMANT’: system is in standby mode, no transfer of water occurs between the active supply tanks and the engine. The tank pumps are switched off and powered isolation valves shut.
3) ‘DRAIN’: system is drained of fluid. Fluid is transferred from the main, wing and collector tanks to the engine tank via their specific drain valves.

Component Failure Modes

Table 1 contains the component failure modes considered to affect the functionality of the fuel rig system. In total, there are forty-three types taken into account. The usage of ‘***’ in the component failure mode codes allows for the insertion of the individual component identification numbers.

Code	Component Failure	Code	Component Failure
TK***L	Tank leakage	TK***R	Tank rupture
P***L	Pipe leakage	P***B	Pipe blocked
P***R	Pipe ruptured	P***PB	Pipe partially blocked
PP***O	Peristaltic pump failed on	PP***L	Pipe in peristaltic pump leaks
PP***S	Peristaltic pump failed off	PP***M	Mechanical failure of peristaltic pump
CP***O	Centrifugal pump failed on	CP***L	Centrifugal pump leaks
CP***S	Centrifugal pump failed off	PSV***S	Pressure relief valve stuck (intermed.)
PSV***C	Pressure relief valve closed at incorrect pressure	PSV***O	Pressure relief valve opened at incorrect pressure
PSV***PB	Pressure relief valve partially blocked	PSV***B	Pressure relief valve blocked
PSV***L	Pressure relief valve leaks	IVP***S	Powered isolation valve stuck (intermed.)
IVP***B	Powered isolation valve blocked	IVP***O	Powered isolation valve failed open
IVP***PB	Powered isolation valve partially blocked	IVP***C	Powered isolation valve failed closed
CK***B	Check valve blocked	CK***PB	Check valve partially blocked
CK***L	Check valve leaks	BP***L	Pressure regulating valve leaks
BP***B	Pressure regulating valve blocked	BP***PB	Pressure regulating valve partially blocked
BBV***B	Block bleed valve blocked	BBV***O	Block bleed valve failed open
BBV***L	Block bleed valve leaks	BBV***C	Block bleed valve failed closed
TVT***B	Reconfiguration valve blocked	TVT***PB	Reconfiguration valve partially blocked
TVT***L	Reconfiguration valve leaks	TVT***P	Reconfiguration valve set in position
IV***O	Drain valve failed open	IV***C	Drain valve failed closed
IV***L	Drain valve leaks	IV***B	Drain valve blocked
IV***PB	Drain valve partially blocked		

Table 1. Component Failure Modes

Fuel Rig Digraph Development

Steps one and two from the previously described digraph procedure are used to develop the fuel rig system digraph[17]. The system is split into four sub-units consisting of the main, wing, collector and engine tank sections. The respective sub-unit digraphs are joined at common process variables in order to form the overall system digraph. In total, the system digraph is constructed from 842 nodes; of which there are 151 process variable nodes and 691 component failure mode nodes.

As a means of illustrating the development of the fuel rig digraph, Figure 4 shows a detailed section of both main tank pump trays incorporating powered isolation valves (IVP0110/IVP0120), back pressure valves (BP0110/BP0120), flow transmitter FT0110 and interconnecting pipe work. A section of the respective main tank digraph is presented in Figure 5. Mass flow along the top pump tray is represented through the process flow structure exhibited in the upper branch (nodes M106 to M108). The relationship between M106 and M107 represents the powered isolation valve IVP0110. If the valve is closed by the operator then the relationship (0: IVP110C) between the two mass flow nodes is nullified. Similarly, the back pressure valve BP0110 is represented by the '+1' edge joining M107 with M108. All mass flow nodes have at least four associated failure modes related to four possible pipe faults: partial or complete blockages, ruptures or leakages. Any additional failure modes depend on the presence of other components, such as valves. In Figure 5 nodes M108 and M116 are connected through an 'AND' gate (represented by solid vertical line) since a failure would have had to occur in both main tank feed lines if no mass flow were to pass to the collector tank through the pipe at location 117.

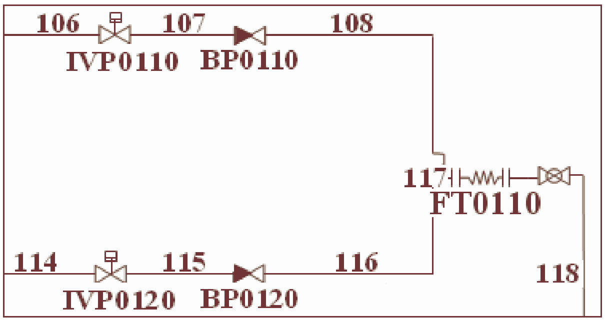

Figure 4. Main Tank Section

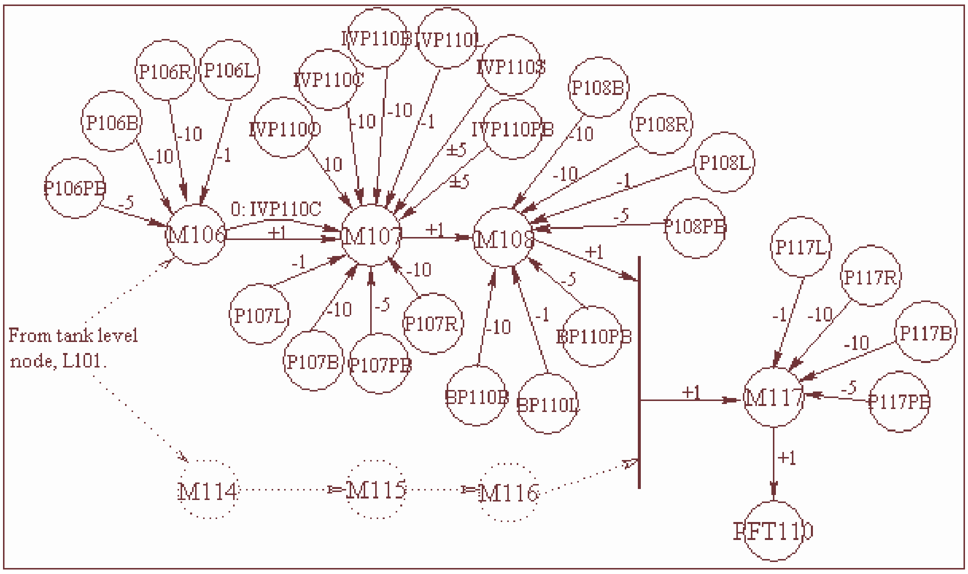

Figure 5. Section of Main Tank Digraph

System Fault Diagnostics Using Digraphs

The method derived for using digraphs in fault diagnostics is based on comparing system sensor readings with those which would be expected whilst the system is in a known operating mode. Should any sensor register a deviation, this would be indicative of a fault having occurred within the system. Diagnosis therefore involves back-tracing through the system digraph from specific nodes which represent the location of any given deviations. Back-tracing refers to the manner in which an analyst moves from a deviating node through the digraph until all possible failure modes, which could have contributed to the deviation, are noted.

During the diagnostics procedure, data from the transmitters is used in order to 'flag' nodes, and sometimes whole digraph sections, representing process variables which are known to not be deviating from the system operating mode. 'Flagged' sections therefore indicate the absence of an associated section failure. Back-tracing from any known deviating node ceases either (i) once the analyst has reached a flagged section or (ii) if there are no further nodes to back-trace to.

The following assumptions were employed during the diagnostics procedure:
(a) All transmitters provide reliable readings.
(b) For full flow and no flow registered deviations at the flow transmitters FT0110 (main tank), FT0210 (wing tank) or FT0310 (collector tank) a fault must have occurred in both tank feed lines. The transmitters are located at the flow exit point from each tank section.
(c) For partial flow deviations, of gains ±5 or -1, a failure must have occurred in at least one of the tank lines. '-1' is termed a partial failure in this analysis since it is used to describe the disturbance caused by a leakage fault.

Diagnostic Program Incorporating Transient Effects

To enable a more complete system analysis, consideration of dynamic effects is required. The main area of focus when considering system dynamics relates to abrupt fault analysis[18]. Abrupt faults represent dramatic changes in a system and can therefore result in a significant visible deviation, known as a transient, from the normal system operating mode. In time, the system can be said to have moved into a new 'steady state' due to the deviation. This is synonymous with the fuel rig system changing scenario when assumed to be in one of the operating modes. The term scenario in the fuel rig analysis relates to an altered system status based on the retrieved transmitter readings.

A necessary strategy is to analyze system behaviour at frequent intervals in order to perform diagnostics and identify if the system has shifted from its normal operating mode. This strategy involves monitoring the fuel rig system and determining if the system is in an abnormal scenario. This does not, however, include scenarios that would be expected during fault rectification. Data is retrieved according to a set sampling rate. The dynamic effects of faults are investigated through the monitoring of tank levels, in particular the rate of change in levels.

The diagnostic program, coded in Matlab, can be sub-divided into four main sections. Namely; input, comparison, fault diagnostics and output. During the 'input' stage the individual fuel rig transmitter readings and assumed operating mode of the fuel rig are ‘read into’ the program by way of a text file. The transmitter readings are then separated and allocated to an associated computer variable for use during the ‘comparison’ phase. The readings are separated for ease of future functions conducted in later phases of the program.

The expected fuel rig operating mode state is determined in the ‘comparison’ section through considering the individual tank levels. Should the fuel rig be in the ACTIVE mode then the collector tank level is used in order to determine which ACTIVE phase, as detailed in the ‘Modes of Operation’ section. Specific rules are employed in the program for all of the operational modes as a means of providing consistency. These rules relate to the tank levels and in turn the flow readings which would be permissible for a given situation. The expected readings for a known operating mode may therefore be altered depending on the level information:

- If any tank level is at or below Pump Shut Off level, expect readings of no flow and no pressure at the respective flow and pressure transmitters in the tank section.
- If the collector tank level is high, expect no flow out of the main and wing tanks.
- If there is flow out of a tank (via pipes) and the level is below PSO, all failures are assumed to be due to the flow out, not an actual tank failure (e.g. fracture).

A deviation matrix [D] is formed at the end of the ‘comparison’ phase by comparing the retrieved transmitter data with those readings which would be expected under the assumed fuel rig system operating mode. If the readings are identical then an element in the deviation matrix corresponding to a relevant transmitter is allocated the value ‘0’. This indicates the presence of a non-deviating sensor and so it is assumed no failures are present in the corresponding specific section of the fuel rig. Should a reading deviate then the respective element in [D] is assigned a value which is consistent with the deviation (e.g. +10).

On generating the deviation matrix the next phase in the process revolves around determining transmitter flags for non-deviating readings. This has been split into two steps. Firstly, whole tank section flags are allocated to specific tanks that indicate no deviations in [D]. If deviations are outlined in [D] for a specific tank then its corresponding tank flag is assigned the value ‘1’. The second step involves allocating values to individual transmitter flags from tank sections with registered deviations.

The procedure of back-tracing is re-enacted through using matrices which contain the individual component failure mode results for a given transmitter deviation. The number of flags signed ‘1’, representing system deviations, for given tank sections and transmitters dictates which back-tracing results should be ANDed. The signing of a flag with ‘1’ indicates the presence of system deviations.

The tank level data is used to calculate the rate of change in the fuel rig tank levels. These calculations are performed after data has been retrieved from the second sampling interval. The rate of change in tank heights is used during the ‘fault diagnostics’ section. For specific cases where no flow is registered in the tank feed lines then the rate of change in tank level is utilised to determine whether there has been a pipe blockage (or valve closure / pump shut down) or pipe rupture. A rupture, unlike a blockage, would lead to a decreasing tank level.

The diagnostic results are displayed whilst the program runs. Initial display features involve outputting the expected operating mode readings, retrieved transmitter data and the deviation matrix. Information regarding the presence or absence of failures in individual tank sections is also displayed along with the rate of change in tank levels. If the complete tank flags are signed ‘0’ then a statement is output noting the absence of any deviations in a specific tank section.

Each fuel rig tank section is linked to specific text files which contain the diagnostic results for the given transmitter deviations. From engineering knowledge, it is assumed more probable for fault combinations of the lowest order to be the cause for a noted set of deviations.

Results Obtained for a Given Dynamic Scenario

The transmitter data presented in Table 2 contains a sample of readings retrieved over two time periods of 30 seconds. The fuel rig is assumed to be set in the ACTIVE mode. Given the height of the collector tank level is less than threshold one but greater than threshold two, fluid transfer would be expected to flow from the wing tank to the collector tank during this ACTIVE mode phase. The expected readings are illustrated above the retrieved interval data. The retrieved data exhibits both single and multiple deviations (highlighted in bold in Table 2) in the individual tank sections. The codes contained within Table 2 are explained in a table key.

Assumed ACTIVE Mode	**Main Tank**				**Wing Tank**				**Collector Tank**			
	LT0110	FT0100	FT0110	PT0110 / PT0120	LT0210	FT0200	FT0210	PT0210 / PT0220	LT0310	FT0300	FT0310	PT0310 / PT0320
ACTIVE	RL	NF	NF	NP	< RL & > PSO	NF	F	P	< T1 & > T2	NF	F	P
Interval 1	80 (RL)	NF	NF	NP	72 (<RL &> PSO)	NF	F	P	50 (<T1 &> T2)	NF	**PF(-5)**	**NP** / P
Interval 2	80 (RL)	NF	NF	NP	53 (<RL &> PSO)	NF	**NF**	P	47 (<T1 &> T2)	NF	**PF(-5)**	**NP** / P

Table 2. Fuel Rig Transmitter Data

<u>Table Key</u>

NF : no flow	NP : no pressure	T1 : threshold one
F : flow	P : Pressure	T2 : threshold two
PF : partial flow	RL : required level	PSO : pump shut off

When reading the retrieved operational data from the fuel rig into the program, results are output for each interval. For interval one it is stated that no deviations exist in the main and wing tank sections, however deviations are noted in the collector tank. The flow transmitter FT0310 and pressure transmitter PT0310 both register deviations of partial flow and no pressure respectively. The pressure transmitter PT0320 notes the expected status. From the given deviations, the program assumes faults are present in feed line one only. The results are output in two text files; one contains all possible multiple failures by ANDing the results achieved through back-tracing from the nodes representing FT0310 and PT0310 in the digraph and the second simply contains a list of the single failures which may have led to both of the deviations. There are nine first order and 351 second order failure causes. It is assumed that the registered deviations are more likely to have been caused by a single fault.

The output for the second interval firstly notes a change in status between intervals one and two. Deviations are registered in the wing and collector tanks but not in the main tank. The diagnostic results for the given deviations are produced in four text files. The results obtained for the collector tank are identical to those produced for interval one since the same collector tank deviations remain. With regards to the two text files generated for the wing tank; one outlines the results when back-tracing through both feed lines, and the second highlights the failure causes located after both feed lines join to form a single pipe. In total, 83 failure causes are noted for the wing tank section deviations; two first order and 81 second order. The results for the wing and collector tanks are output separately since the registered deviations occur independently of one another.

Conclusion

Digraphs provide a clear representation of the relationships between system variables since they closely reflect the physical structure of the system under investigation. The discrete values used to describe the relationships between nodes have proved to be sufficient with the addition of +/- 5 enabling the introduction of partial failures.

The incorporation of 'flagging' into the diagnostics process eradicates potential inconsistent failure mode results and anomalies. 'Flagging' therefore acts as a form of consistency check and removes the possibility of conflicting results existing between non-deviating transmitter nodes and failure modes yielded through back-tracing from specific deviating nodes. This process is adapted when considering the dynamics of a system. For scenarios whereby a tank level is noted to be within an abnormal boundary in consecutive intervals, if the rate of change in height of the tank level is not negative it is assumed that the tank failure has been rectified and therefore the deviation is masked. For example, consider a low wing tank level with a decreasing rate of change in the first interval. If the tank failure is rectified a low level will still be retrieved in the second interval, however the low level should not be considered a deviation.

The rate of change in height of a particular tank level can be utilised to distinguish between and 'hone in' on failures which may be the cause for a given deviation. This has proved successful in cases where there are registered deviations of no flow and no pressure. If a negative rate of change is noted then this pinpoints pipe rupture faults whereas a positive or zero rate of change indicates faults incorporating blockages or closures.

It is proposed that future research consider the inclusion of unreliable transmitters and thus the identification of such transmitters. A mechanism to further identify the most likely causes of a registered deviation is required. Focus is to be based on the weighting of failure modes through using previous data or on the importance of the type and location of transmitters providing relevant system information.

The results from the application of the automated diagnostics process, based on the digraph method, to the fuel rig system have been proven to be credible. Injecting faults into the fuel rig has allowed various scenarios to be tested using the diagnostic method. Valid failure mode results are obtained when considering single or multiple faults in either individual tank sections of the fuel rig or across the whole system.

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