
This item was submitted to [Loughborough's Research Repository](#) by the author.
Items in Figshare are protected by copyright, with all rights reserved, unless otherwise indicated.

Using a series of moving coils as a high redundancy actuator

PLEASE CITE THE PUBLISHED VERSION

PUBLISHER

© IEEE

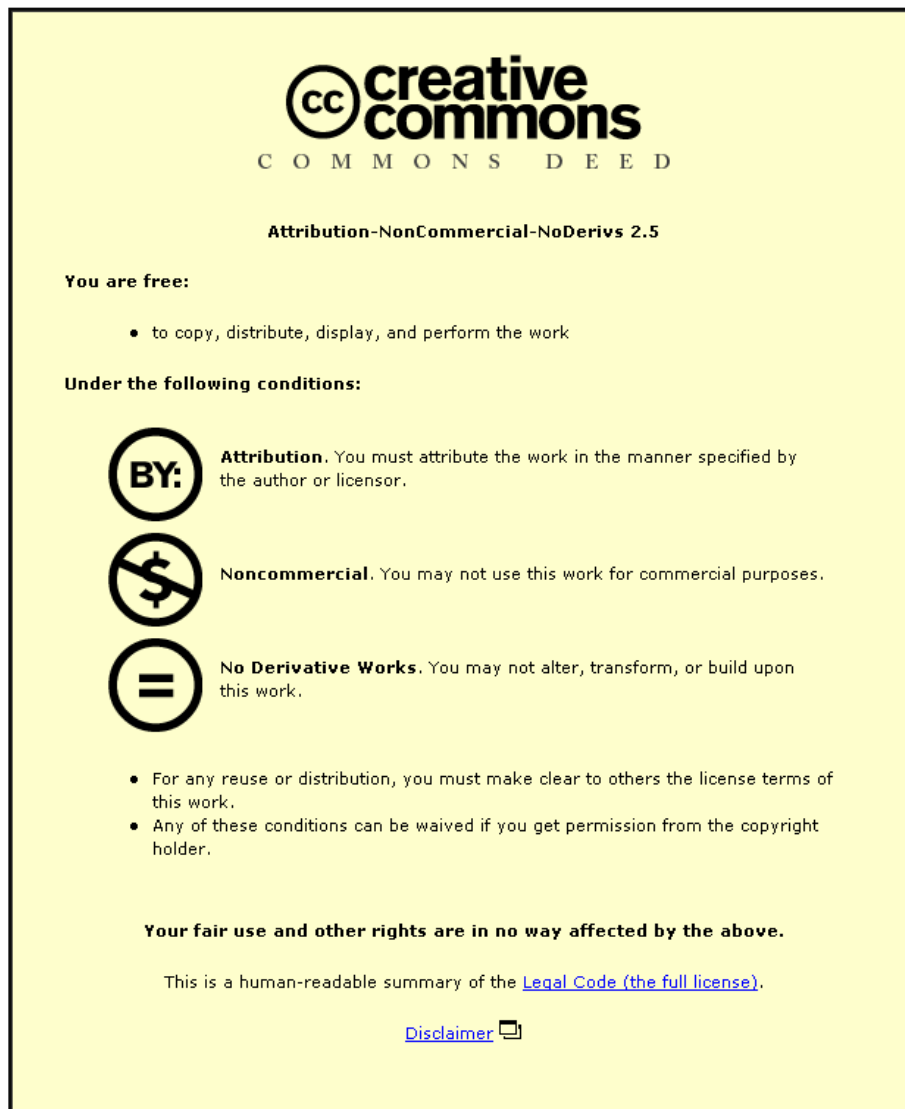
LICENCE

CC BY-NC-ND 4.0

REPOSITORY RECORD

Steffen, Thomas, Jessica Davies, Roger Dixon, Roger M. Goodall, and Argyrios C. Zolotas. 2019. "Using a Series of Moving Coils as a High Redundancy Actuator". figshare. <https://hdl.handle.net/2134/3014>.

This item was submitted to Loughborough's Institutional Repository by the author and is made available under the following Creative Commons Licence conditions.



For the full text of this licence, please go to:
<http://creativecommons.org/licenses/by-nc-nd/2.5/>

Using a Series of Moving Coils as a High Redundancy Actuator

Thomas Steffen Jessica Davies Roger Dixon Roger Goodall Argyrios Zolotas
t.steffen@lboro.ac.uk j.davies@lboro.ac.uk r.dixon@lboro.ac.uk r.m.goodall@lboro.ac.uk a.c.zolotas@lboro.ac.uk

Control Systems Group, Department of Electronic and Electrical Engineering, Loughborough University, Loughborough, Leicestershire, LE11 3TU, UK, phone +44 1509 227 009, fax +44 1509 227 008, <http://www.lboro.ac.uk/departments/el/>

Abstract—This paper investigates the use of two electromagnetic actuation elements in series to produce a fault-tolerant actuator assembly. Faults in one or the other element are considered, and their influence on the behaviour of the whole system is analysed. By carefully choosing the mechanical parameters, it is possible to completely avoid any effect of these faults on the input/output behaviour. That means either of the two actuation elements can keep the system operational and restore the nominal behaviour without any changes to the system.

Index Terms—Fault-tolerant control, fault accommodation, model matching, robust control, electro-mechanical actuator.

I. INTRODUCTION

A. Fault Tolerant Control

This paper introduces a novel approach for dealing with actuator faults in mechanical systems. In general, fault tolerance can be achieved in three ways [2]:

- accommodation: a robust control strategy is able to maintain satisfactory performance in the presence of the parametric variations that characterise the fault [11], [5];
- adaptation: the controller structure is fixed but controller characteristics are varied in response to faults [3];
- reconfiguration: both the control structure and controller parameters are changed in response to the fault [10].

This paper uses the fault accommodation approach, which leads to a very simple control structure with a robust controller. This approach avoids problems inherent in the supervisory layer used for fault adaptation or fault reconfiguration.

B. Actuator Faults

Fault-tolerant operation in the presence of actuator faults requires some form of redundancy. This is due to the nature of actuators: they are necessary to keep the system in control (stable) and to bring it into the desired state. This requires a certain amount of power or force to be applied to the system. No approach can escape this basic requirement.

The common solution is to use some form of over-actuation in which the fault-free system has more control action than needed. For critical systems, the normal approach involves straightforward replication of the actuators, e.g. 3 or 4 actuators are used in parallel for aircraft flight control systems. Some form of 'consolidation' is needed to bring together the multiple control actions; this can be achieved in a variety of ways (mechanically, hydraulically, electrically etc). Analytical

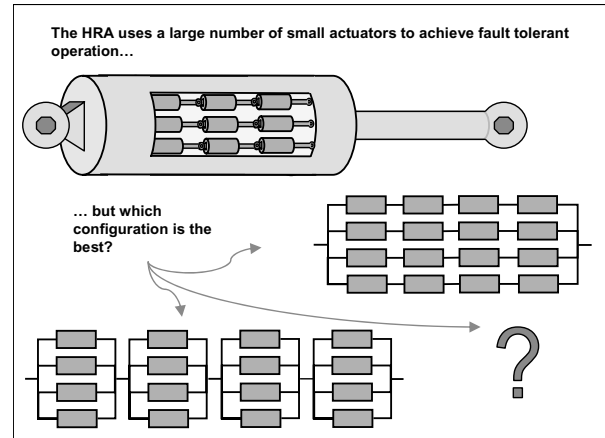


Figure 1. High Redundancy Actuator.

redundancy [7] can be used in addition to or even as a substitute for parallel elements, if the redundant elements have a strong enough influence on the relevant system state.

C. High Redundancy Actuator

The idea of the High Redundancy Actuator (HRA) is inspired by human musculature. A muscle is composed of many individual muscle cells, each of which provides only a minute contribution to the force and the travel of the muscle. These properties allow the muscle as a whole to be highly resilient to damage of individual cells.

The aim of this project is not to replicate muscles, but to use the same principle of cooperation with existing technology to provide intrinsic fault tolerance. To achieve this, a high number of small actuation elements are assembled in parallel and in series to form one actuator (see Figure 1). Faults within the actuator will affect the maximum capability, but through robust control, full performance can be maintained without either adaptation or reconfiguration. Some form of monitoring is necessary to provide warnings to the operator calling for maintenance. But this monitoring has no influence on the system itself, unlike in adaption or reconfiguration methods, which simplifies the design of the system significantly.

The HRA is an important new approach within the overall area of fault-tolerant control. When applicable, it can provide actuators that have graceful degradation, and that continue to

Table I
NOMENCLATURE

Symbol	Units	Meaning
B	T	Magnetic flux density
k_c	$\frac{N}{A}$	Coil constant
k_d	$\frac{N}{m/s}$	Damping constant
k_o	$\frac{N}{m/s}$	Back e.m.f. constant
k_s	$\frac{N}{m}$	Stiffness constant
l	m	Conductor length
L	H	Coil inductance
N	1	Number of turns
m	kg	Mass of moving part
R	Ω	Coil resistance
u	A	Control input (electrical current)
v	V	Applied voltage
x	m	State: position

operate at close to nominal performance even in the presence of multiple faults in the actuation elements. The early stages of the HRA research have focused on the use of electro-mechanical technology [4], and this paper describes the first analysis of an electro-magnetic HRA.

D. Actuators in Series

This paper concentrates upon analysing a set of electro-magnetic actuators in series. This configuration is rarely used so far, because the parallel arrangement is perceived to be more efficient.

However, there is one fault that is difficult to deal with in a parallel arrangement: the locking up of one actuation element. Because parallel actuation elements always have the same extension, one locked-up element can render the whole assembly useless. It is possible to mitigate this by guarding the elements against locking or by limiting the force exerted by a single element. But these measures reduce both the effectiveness of the system and introduce new points of failure.

The analysis of the serial configuration will show that it remains operational when one element is locked-up. This fact is important for the High Redundancy Actuator, as fault tolerance is required for different fault types. The goal of the HRA project is to use parallel and serial actuation elements to accommodate both the blocking and the inactivity (loss of force) of an element.

A second result of this paper is that the behaviour of the actuator with two serial elements is nearly unaffected by the locking of one element. This result is counter-intuitive, and it will be examined in detail. The understanding of the reasons for this result will be of great importance for the HRA project.

E. Overview

Section 2 deals with the modelling of the electro-magnetic actuator. NEWTON's 2nd law is used to produce a simple four state model of the two mass system. In Section 3, the effects of faults in either actuation element on the system model are analysed. This section contains the main result of the paper: given the right parameter constellation, the input/output behaviour is not affected by either fault. In Section 4, a robust

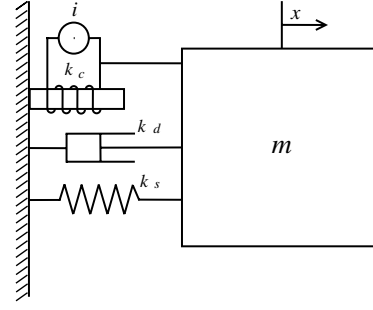


Figure 2. Moving coil actuator.

control is designed for a given set of parameters, and in Section 5 simulation results are presented to demonstrate the effectiveness of this approach.

II. MODELLING THE ELECTRO-MAGNETIC ACTUATOR

A. Single Element

In order to construct a multi-element actuation system, it is first necessary to model a single actuation element. This modelling will be addressed here. In this paper, electro-magnetic actuators with linear moving coils are used as the actuation elements in the HRA, while the basic approach should apply to any technology.

The actuator comprises a moving coil wound round the centre pole of a magnetic assembly that produces a uniform magnetic field perpendicular to the current conducted in the coil. On providing a voltage, a current flows in the coil generating an electromotive force (e.m.f.) which is parallel to the direction of travel. This force causes the coil, and the piston on which it is mounted, to move.

The force is proportional to the current in the coil, the number of turns, and the flux strength. It is reduced by the velocity of the coil, as a voltage (or counter-electromotive force) is induced, which opposes the movement.

A representation of the actuator is given in Figure 2. The mass m represents both the weight of the moving coil and its load, as it is assumed their connection is rigid. A number of other assumptions are made in the modelling of the actuator: the system is assumed to be linear; the magnetic flux density around the coil constant; and that a simple inductance in series with a resistance is a suitable representation of the coil. This last assumption allows the current flowing through the coil to be expressed as:

$$i(t) = \frac{v(t)}{R} - \frac{k_o \dot{x}(t)}{R} - L \frac{di}{dt} \quad (1)$$

The term $k_o \dot{x}$ represents the effects of the induced voltage on the coil current. However, the system can be significantly simplified if the actuator is driven with current instead of voltage, as the effects of the back e.m.f., resistance and inductance are handled within the current source. This also helps to decouple the different parts of the system.

The force produced by the current is then expressed as:

$$F_c(t) = N B l i(t) = k_c i(t) \quad (2)$$

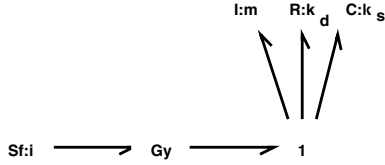


Figure 3. Simple bond graph of a single actuation element.

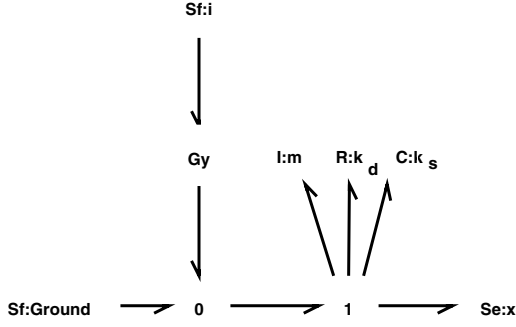


Figure 4. Expanded bond graph of single element actuator.

There is also a physical resistance to the motion of the coil due to eddy current damping in the metal bobbin on which the coil is wound, which is proportional to the velocity:

$$F_d(t) = k_d \dot{x}(t) \quad (3)$$

Any other damping effects may also be incorporated within this constant. Stiffness within the system may be represented by a spring, producing the force on the system:

$$F_s(t) = k_s x(t) \quad (4)$$

Using NEWTON's 2nd law, these forces can be combined to produce the expression:

$$\ddot{x}(t) = \frac{k_c}{m} i(t) - \frac{k_d}{m} \dot{x}(t) - \frac{k_s}{m} x(t) \quad (5)$$

Bond graphs describing the energy flow within the system are provided for reference in Figures 3 and 4. The state-space description of the system is

$$\dot{\mathbf{x}} = \begin{pmatrix} 0 & 1 \\ -\frac{k_s}{m} & -\frac{k_d}{m} \end{pmatrix} \mathbf{x} + \begin{pmatrix} 0 \\ \frac{k_c}{m} \end{pmatrix} u \quad (6)$$

with the state $\mathbf{x} = (x \ \dot{x})^T$ and the input $u = i$. The model is linear, because the mechanical limits of the system are ignored for the purpose of this paper.

B. Double Element

Having produced a model for a single actuation element, assemblies of these elements can be constructed. The structure considered within this paper is a simple serial structure of two actuation elements. A serial structure is chosen over parallel to highlight the potential of the HRA concept, as parallel configurations are common in physical redundancy

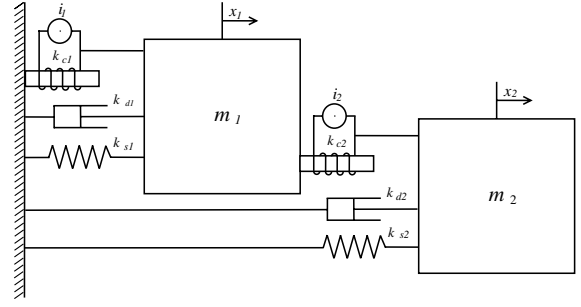


Figure 5. Series structure.

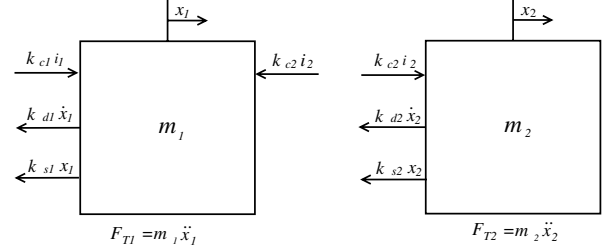


Figure 6. Free-body diagram of double element actuator.

schemes. The ultimate goal is to combine the advantages of both configurations.

Figure 5 illustrates how the actuators are connected. The first actuation element is fixed, and the force of its moving mass acts upon the casing of the second actuation element. The second actuation element is driven by a separate current and acts upon a load mass. The whole system may be modelled as two masses: the first mass, m_1 constitutes the moving mass of the first actuation element and the casing of the second; the second mass, m_2 constitutes the moving mass of the second actuator and the load mass.

Any damping between the actuators is neglected at this stage, as it may be considered a secondary effect. However, damping and stiffness is added between the load mass and a fixed surface so the movement of the load is constrained.

For reference purposes, a bond graph describing this serial structure is provided in Figure 7. However, comprehension of the bond graph is not necessary to achieve an understanding of the system. A free body diagram of the two actuation elements is shown in Figure 6. The free-body diagram shows that the forces acting upon m_2 are the same as in the single actuator case. The situation for m_1 is similar, except that it is also subject to the reaction force from the second actuator. From the free-body diagram, the following state-space expression is derived:

$$\dot{\mathbf{x}} = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -\frac{k_{s1}}{m_1} & 0 & -\frac{k_{d1}}{m_1} & 0 \\ 0 & -\frac{k_{s2}}{m_2} & 0 & -\frac{k_{d2}}{m_2} \end{pmatrix} \mathbf{x} + \begin{pmatrix} 0 & 0 \\ 0 & 0 \\ \frac{k_{c1}}{m_1} & -\frac{k_{c2}}{m_1} \\ 0 & \frac{k_{c2}}{m_2} \end{pmatrix} \mathbf{u} \quad (7)$$

where $\mathbf{x} = (x_1 \ x_2 \ \dot{x}_1 \ \dot{x}_2)^T$ is the state vector and $\mathbf{u} = (i_1 \ i_2)^T$ the input.

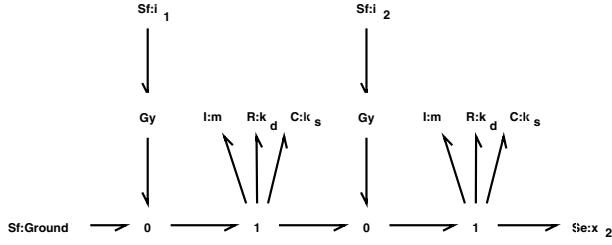


Figure 7. Bond graph of the double element actuator.

III. ANALYSIS OF THE BEHAVIOUR BY FAULT CASE

In this section, the input/output behaviour of the actuator is analysed for different fault cases. The input of the system is the driving current, and the output is the position of m_2 . Therefore, it is a single-input single-output system (SISO).

There are different ways in which an actuation element can fail, but this paper is only concerned with a locking up of one coil element. This can happen if the coil overheats, expands and touches the magnet. The effect of this fault depends on which actuation element is locked-up, so there are two fault cases to analyse. Together with the faultless case, this leads to the three different models.

A. Faultless Case (F0)

The model of the faultless case is given above in Equation (7). To get a single-input single-output system, both actuators are provided with the same current. This leads to the state-space model

$$\dot{\mathbf{x}} = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -\frac{k_{s1}}{m_1} & 0 & -\frac{k_{d1}}{m_1} & 0 \\ 0 & -\frac{k_{s2}}{m_2} & 0 & -\frac{k_{d2}}{m_2} \end{pmatrix} \mathbf{x} + \begin{pmatrix} 0 \\ 0 \\ \frac{k_{c1}-k_{c2}}{m_1} \\ \frac{k_{c2}}{m_2} \end{pmatrix} u \quad (8)$$

$$y = (0 \ 1 \ 0 \ 0) \mathbf{x} \quad (9)$$

with $\mathbf{x} = (x_1 \ x_2 \ \dot{x}_1 \ \dot{x}_2)^T$. Analysing the state space using the geometric approach [1] or structural methods [6] reveals an interesting result. While the second and fourth states are controllable and observable, both the first and the third are unobservable. This can easily be verified by the fact that x_1 and \dot{x}_1 have no influence on x_2 , \dot{x}_2 or y .¹ Depending on the relation between k_{c1} and k_{c2} , x_1 and \dot{x}_1 may also be uncontrollable. In any case, they are not relevant for the input/output behaviour, and can be removed from the model. This leads to a new model

$$\dot{\mathbf{x}}' = \begin{pmatrix} 0 & 1 \\ -\frac{k_{s2}}{m_2} & -\frac{k_{d2}}{m_2} \end{pmatrix} \mathbf{x}' + \begin{pmatrix} 0 \\ \frac{k_{c2}}{m_2} \end{pmatrix} u \quad (10)$$

$$y = (1 \ 0) \mathbf{x}' \quad (11)$$

with $\mathbf{x}' = (x_2 \ \dot{x}_2)^T$. The transfer function of this model is

$$G_{F0}(s) = \frac{k_{c2}}{m_2 s^2 + k_{d2} s + k_{s2}} \quad (12)$$

¹Using a current source for the coils is the reason for this independence. Any energy transfer from m_1 to m_2 is absorbed in the current source of i_2 .

where the subscript F0 is used to denote the faultless case.

B. Behaviour with 1st Coil Locked-Up (F1)

If the coil of the first actuation element is deformed, it will touch the magnet. This fixes the mass m_1 with respect to the reference point, and consequently the position x_1 is constant and the speed \dot{x}_1 is zero. Removing these variables from the state space leads to

$$\dot{\mathbf{x}}' = \begin{pmatrix} 0 & 1 \\ -\frac{k_{s2}}{m_2} & -\frac{k_{d2}}{m_2} \end{pmatrix} \mathbf{x}' + \begin{pmatrix} 0 \\ \frac{k_{c2}}{m_2} \end{pmatrix} u \quad (13)$$

$$y = (1 \ 0) \mathbf{x}' \quad (14)$$

This system model is identical to the reduced model in the faultless case. The trajectories for x_1 and \dot{x}_1 may be different, but since these two states are unobservable, they have no effect on the output y . Therefore, the transfer function is identical to the previous case:

$$G_{F1}(s) = G_{F0}(s) \quad (15)$$

C. Behaviour with 2nd Coil Locked-Up (F2)

If the same fault happens in the second actuation element, the distance between m_1 and m_2 becomes fixed. This means that x_1 and x_2 are identical (a possible offset is ignored for clarity), leading to the restrictions $x_1 = x_2$ and $\dot{x}_1 = \dot{x}_2$.

While it is possible to satisfy these restrictions by a state reduction, it is easier to start from the model of the single element actuator (6). Now the two springs $k_{s1} + k_{s2}$ and the two dampers $k_{d1} + k_{d2}$ both work on the combined mass $m_1 + m_2$. This leads to the state space model:

$$\dot{\mathbf{x}} = \begin{pmatrix} 0 & 1 \\ -\frac{k_{s1}+k_{s2}}{m_1+m_2} & -\frac{k_{d1}+k_{d2}}{m_1+m_2} \end{pmatrix} \mathbf{x} + \begin{pmatrix} 0 \\ \frac{k_{c1}}{m_1+m_2} \end{pmatrix} u \quad (16)$$

$$y = (1 \ 0) \mathbf{x} \quad (17)$$

with $\mathbf{x} = (x_1 \ \dot{x}_1)^T = (x_2 \ \dot{x}_2)^T$. The transfer function of this system is

$$G_{F2}(s) = \frac{k_{c1}}{(m_1+m_2)s^2 + (k_{d1}+k_{d2})s + k_{s1}+k_{s2}} \quad (18)$$

The basic structure is identical to the reduced models (10) and (13) from the previous two fault cases, but the parameters are different. By comparing the coefficients of the rational polynomial, it is possible to determine when the transfer functions are identical. This is the case if and only if

$$\frac{k_{c1}}{k_{c2}} = \frac{k_{d1}+k_{d2}}{k_{d2}} = \frac{k_{s1}+k_{s2}}{k_{s2}} = \frac{m_1+m_2}{m_2} \quad (19)$$

D. Matching the Behaviour

The analysis of the system in the different fault cases shows that it is possible for the input/output behaviour to be identical across all faults. A special choice of parameters according to equation (19) is necessary for this. Satisfying this condition should be feasible if the actuation elements can be designed according to this requirement. From a conceptual point of view this approach is similar to model matching [9], with the

Table II
SYSTEM PARAMETERS

Symbol	Value	Meaning
m_1	1 kg	Connecting Mass
m_2	2 kg	Load Mass
k_{c1}	25 $\frac{N}{A}$	Coil Constant of Element 1
k_{c2}	20 $\frac{N}{A}$	Coil Constant of Element 2
k_{d1}	0.5 $\frac{N}{m/s}$	Damping Constant of Element 1
k_{d2}	2 $\frac{N}{m/s}$	Damping Constant of Element 2
k_{s1}	5 $\frac{N}{m}$	Stiffness Constant of Element 1
k_{s2}	20 $\frac{N}{m}$	Stiffness Constant of Element 2

Table III
REQUIREMENTS

	Value
Overshoot	< 1 %
Settling time	< 0.5 s
Deviation	< 2 %
Frequency range	> -3 dB at up to 2 Hz

difference that the parameters of the system itself are tuned, and not the feed-back matrix.

When using off-the-shelf actuation elements, it is unlikely that the condition is met even approximately. And even if custom elements are designed specifically for this requirement, there are always going to be tolerances, so the system will never exactly meet the condition.

But even if the equation (19) is not exactly satisfied, the behaviour under faults $F0$ and $F1$ is always identical, and the transfer function for $F2$ is going to be reasonably similar. Designing a robust controller that can handle either transfer function is reasonably straight forward.

IV. CONTROLLER DESIGN

A. System Parameters

The system parameters, shown in table II, are based on the LAL90-50 series SMAC moving coil actuators [8]. Differing values are used for each actuation element in order to demonstrate the ability to control the second fault case in the presence of dissimilarities in coil constants, damping and stiffness.

The requirements for the control design are shown in table III.

B. Root Locus Design

For the purpose of illustrating the results from Section 3, a very simple controller is used. For practical applications, a more powerful design is recommended.

Since the system gets very close to a phase of -180° , a phase lead compensator is added to the system with the transfer function $\frac{s+10}{s+200}$. Then the controller gain is determined using the root locus method. The lowest amplification with all real poles is 35. The resulting controller is given by

$$G(s) = 35 \frac{\frac{s}{10} + 1}{\frac{s}{200} + 1} \quad (20)$$

The root locus diagram and the BODE diagram are reproduced in Figure 8.

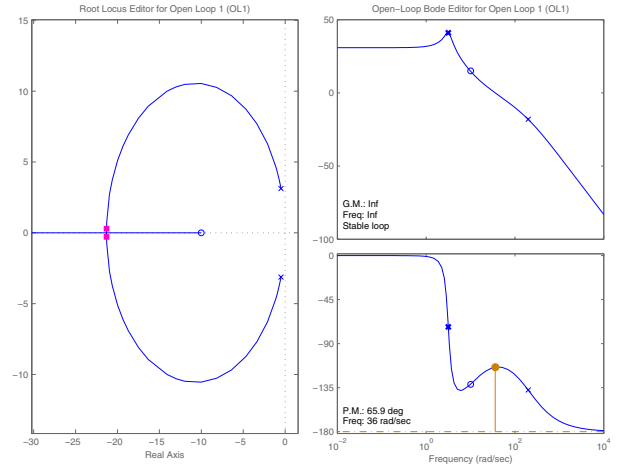


Figure 8. Root locus diagram.

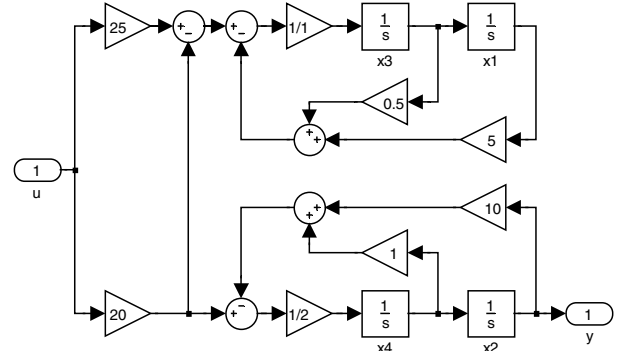


Figure 9. Block diagram of the actuator model.

V. SIMULATION RESULTS

A model of the actuator and of the control has been created in MATLAB/Simulink, to verify the results from Section 3 in a closed loop simulation. The block diagrams of the Simulink models are shown in Figure 9 and Figure 10. The model of the actuator under the different fault cases is not shown for space reasons, but it is based on the model in the faultless case.

To compare the behaviour, a step of the reference value from 0 to 0.1 m is simulated. The results are shown in Figure 11. The thick solid line shows the faultless simulation, while the dotted line and the thin line belong to fault cases $F1$ and $F2$ respectively. The top graph shows the input current u , the centre graph shows the inner state x_1 , and the bottom graph

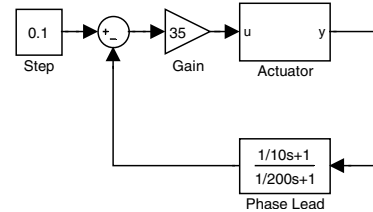


Figure 10. Block diagram of the control system.

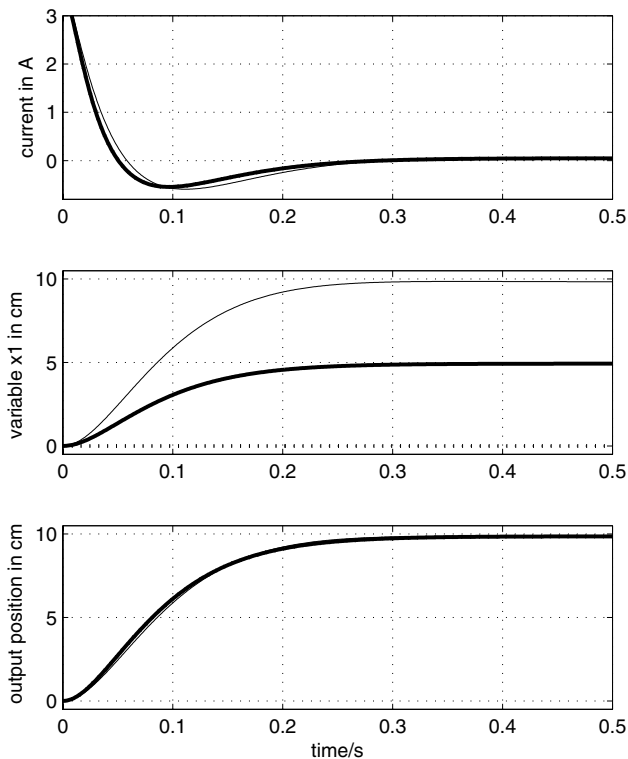


Figure 11. Step response of the faultless system (thick solid line) and fault case F1 (thin solid line) and F2 (dotted line).

shows the position x_2 , which is also the output.

According to the results in Section 3, the open-loop behaviour should be identical in all three cases under condition (19). The system parameters do not satisfy this condition exactly, so small differences in behaviour are to be expected. The controller from Section 4 is designed to be robust, so it should be able to deal with these differences.

Comparing the three simulations shows that the controller is successful in every case. The requirements from Section 4.1 are met in all simulations. Furthermore, the differences between the step responses are very minor in both u and x_2 .

As expected, the graphs for x_1 show a very different picture. In the faultless case, this state was unobservable. It is therefore following the natural dynamics of the system (see Figure 11). In the two fault cases, x_1 is not a free variable, and it is determined by the locked-up actuator.

So the simulation results confirm the analysis in Section 3 and the controller design in Section 4.

VI. CONCLUSIONS

The fault tolerant behaviour of two electro-magnetic actuation elements in a serial configuration has been analysed. This assembly is found to be fault tolerant to the locking of either actuation element, because the other element can provide the necessary force and travel.

More surprising, it has been shown that the input/output behaviour of the configuration is unaffected by the locking under certain conditions. This is explained by the interaction

between the mechanical and the electrical side of the system. Using this conclusion, it is possible to build a controller that can keep the system operational despite the locking of one of the actuation elements.

Further studies will be directed into several directions. From a system theoretic point of view, it would be interesting to determine conditions under which the input/output behaviour remains unchanged in several fault cases. The behaviour of the unobservable state should be crucial here, and ways of controlling it should be investigated. The results will be useful for transferring this approach to other technologies and applications.

In terms of the HRA project, the results need to be extended to more complex parallel and serial configuration, and they need to be verified experimentally. A first step in this direction can be found in [4], and further steps are planned.

VII. ACKNOWLEDGEMENTS

This project is a cooperation of the Control Systems group at Loughborough University, the Systems Engineering and Innovation Centre (SEIC), and the actuator supplier SMAC Europe limited. The project is funded by the UK's Engineering and Physical Sciences Research Council (EPSRC) under reference EP/D078350/1.

REFERENCES

- [1] G. Basile and G. Marro: "Controlled and Conditioned Invariants in Linear System Theory", URL http://www.deis.unibo.it/Staff/FullProf/GiovanniMarro/gm_books.htm, Prentice Hall, 1992.
- [2] M. Blanke, M. Kinnaert, J. Lunze, M. Staroswiecki, J. Schröder: "Diagnosis and Fault-Tolerant Control", ISBN 978-3540356523, Springer, New York, 2006.
- [3] S. Chen, G. Tao, and S. M. Joshi: "On matching conditions for adaptive state tracking control of systems with actuator failures", in *IEEE Transactions on Automatic Control*, vol. 47, no. 3, pp. 473–478, 2002.
- [4] X. Du, R. Dixon, R.M. Goodall, and A.C. Zolotas: "LQG Control for a High Redundancy Actuator", submitted to *IEEE Conference for Advanced Intelligent Mechatronics (AIM)*, Zurich, 2007.
- [5] M. Karpenko and N. Sepehri: "Robust position control of an electrohydraulic actuator with a faulty actuator piston seal", in *Journal of Dynamic Systems, Measurement, and Control*, vol. 125, pp. 413ff, 2003.
- [6] K.J. Reinschke: "Multivariable Control / A Graph-theoretic Approach", ISBN 3-540-18899-1, in *Lecture Notes in Control and Information Sciences*, Springer, New York, 1988.
- [7] R.J. Patton: "Fault detection and diagnosis in aerospace systems using analytical redundancy" in *Computing & Control Engineering Journal*, pp. 127–136, May 1991.
- [8] SMAC Inc: "Actuator Datasheet / Electric Linear/Rotary Moving Coil Actuators LAL90-50", URL <http://www.smac-mca.com/>, 2004.
- [9] M. Staroswiecki: "Fault Tolerant Control Using an Admissible Model Matching Approach" in *Proceedings of the 44th IEEE Conference on Decision and Control, and the European Control Conference 2005*, Seville, Spain, December 12-15, ISBN 0780395670, 2005.
- [10] Th. Steffen: "Control reconfiguration of dynamical systems / linear approaches and structural tests", ISBN 978-3540257301, in *Lecture Notes in Control and Information Sciences*, Springer, New York, 2005.
- [11] R. J. Veillette, J. B. Medanic and W. R. Perkins: "Design of reliable control systems", in *IEEE Transactions on Automatic Control*, vol. 37, pp. 290–304, 1992.
- [12] X. Zhang, M. M. Polycarpou, R. Xu and C. Kwan: "Actuator fault diagnosis and accommodation for flight safety," in *Proceedings of the 2005 IEEE International Symposium on Intelligent Control, Mediterranean Conference on Control and Automation*, pp. 640–645, 2005.