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Multi-agent control of a 10x10 High Redundancy Actuator

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Abstract: The High Redundancy Actuator (HRA) project investigates the use of a relatively high number of small actuation elements, assembled in series and parallel in order to form a single actuator which has intrinsic fault tolerance. Both passive and active methods of control are planned for use with the HRA. This paper presents a multiple-model control scheme for a 10x10 HRA applied through the framework of multi-agent control.

1. INTRODUCTION

1.1 Traditional Approaches to Fault Tolerant Actuation

In automated processes, faults in hardware or software will often produce undesired reactions. These faults could result in failures, where the system as a whole does not complete an expected action. Failures can cause damage to the plant, its environment, or people in the vicinity of that plant [Blanke et al., 2001]. Fault Tolerant Control (FTC) aims to prevent failures and their consequences by providing adequate system performance in the presence of faults.

The majority of FTC research to date has concentrated on sensor faults. Significant advances have been made in this area, but most of these strategies are not applicable to actuator faults. This is attributable to the fundamental differences between actuators and sensors. Sensors deal with information, and measurements may be processed or replicated analytically to provide fault tolerance. Actuators, however, must deal with energy conversion, and as a result actuator redundancy is essential if fault tolerance is to be achieved in the presence of actuator faults. Actuation force will always be required to keep the system in control and bring it to the desired state [Patton, 1991].

The common solution for fault tolerant actuation in critical systems involves straightforward parallel replication of actuators. Each redundant actuator must be capable of performing the task alone and possibly override the other faulty actuators. This solution is over-engineered, reducing the efficiency of the system i.e. in triplex systems 200% more capability, cost and weight than required is introduced to ensure a certain level of reliability.

1.2 High Redundancy Actuation

High Redundancy Actuation (HRA) is a novel approach to actuator fault tolerance that aims to reduce the over-engineering incurred by traditional approaches. The HRA concept is inspired by musculature, where the tissue is composed of many individual cells, each of which provides a minute contribution to the overall contraction of the muscle. These characteristics allows the muscle, as a whole, to be highly resilient to individual cell damage.

This principle of co-operation in large numbers of low capability modules can be used in fault tolerant actuation to provide intrinsic fault tolerance. The HRA uses a high number of small actuator elements, assembled in parallel and series to form one high redundancy actuator (see Figure 1). Faults in elements will affect the maximum

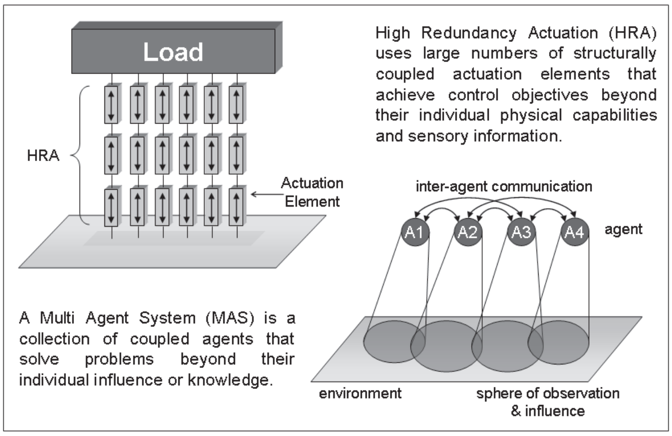

Figure 1. HRA and MAS.

capability, but through control techniques, the required performance can be maintained. This allows the same level of reliability to be attained in exchange for less over-dimensioning.

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 operate at close to nominal performance even in the presence of multiple faults in the elements.

1.3 Control of High Redundancy Actuation

The main focus of the HRA project thus far has utilised robust control methods. These techniques have been shown to be theoretically viable for fault tolerant control of low levels of redundancy [Du et al., 2007], and successful practical testing of these results on a two-by-two electromechanical HRA was achieved.

More recently, electromagnetic actuation has been used as elements of the HRA, the modelling of which in both nominal and fault condition has been detailed in [Davies et al., 2008b]. Research is ongoing into the robust control of these elements at higher levels of redundancy [Steffen et al., 2007]. Results to date suggest that robust control should be a satisfactory method of achieving fault tolerant control of these structures. Indeed in most cases, the robust, passive [1] control approach is attractive, as its simplicity and constancy mitigate many of the associated problems with active control methods. However, research into more intelligent, active approaches is also an objective of the HRA project, to ascertain the levels of fault tolerance and nominal performance attainable in comparison to passive methods.

Multi-Agent Systems (MAS) are the focus of this active fault tolerance scheme. MAS was chosen as an intelligent approach to controlling the HRA as the two concepts are strongly related (Figure 1).

1.4 Overview

[Davies et al., 2008a] presented a Multi-Agent Control (MAC) scheme for a 4x4 HRA, which was found to be advantageous in terms of fault tolerance in comparison to a passive approach. However, it was questioned whether the approach would still provide tangible benefits at higher, more realistic levels of redundancy. Hence, this paper extends the application of MAC concepts to a 10x10 HRA to address this issue. In addition, the possibility of fault misdiagnosis is also considered. Section 2 briefly introduces agent concepts and discusses the rationale behind MAC of HRA. The current MAC scheme is described in Section 3. Section 4 then provides details of the control of a 10x10 HRA using passive and MAC means.

2. MULTI-AGENT CONTROL OF A HIGH REDUNDANCY ACTUATOR (MACHRA)

2.1 Multi-Agent Control

An agent is a physical or virtual entity situated in its environment, which acts autonomously and flexibly within its purview to achieve goals in a real-time manner [Jennings et al., 1998]. A MAS, therefore, is a collection of agents that are socially coupled and collaborate to achieve objectives, which in the case of MAC are the control objectives of the application.

These agent characteristics resemble the concept of closed-loop control, which achieves objectives through sensing and acting. However, there are important differences within the agent concept. The most obvious difference is the social interaction and negotiation that exists between agents. Also, the agent philosophy is strongly associated with localisation, a point emphasised by [Ferber, 1999].

2.2 Rationale for Multi-Agent Control of HRA

MAS and HRA are conceptually similar (Figure 1). Both are inspired by natural mechanisms which utilise vast numbers of relatively simple cells/processes to form complex structures/behaviours.

[1] In this context, passive refers to a static control structure and algorithm.

This similarity in their structuring is the key rationale for combining MA ideas with HRA. The structuring of control is often neglected in the field of control engineering as the problem is stated in the form of a single plant model [van Breemen and de Vries, 2000]. The process industry acknowledges that the structuring of control is an important issue when applied to a decomposed system, thus it is given more attention in this field and numerous MACS have been proposed in this application area e.g. [Wang and Wang, 1997].

The HRA is a complex, highly structured system, with well-defined interactions between simple elements. An unstructured approach will have difficulties dealing with this complexity. However, if the HRA is viewed as a collection of simpler, similar (if not identical), physically distributed modules, the complexity and changeable nature of the system's dynamics and structure can be handled at a local level, allowing objectives to be met with greater speed and efficiency. MASs facilitate the control of such decompositions, allowing simple control algorithms in conjunction with simple fault detection methods at a local level to achieve greater robustness and adaptability in fault situations.

Agents also avoid some of the issues associated with active control. Multiple-model control schemes often have one active global controller, and a supervisor that decides which controller should be active. A centralised supervisor becomes a single point of failure, increasing the systems reliance upon fault detection. In addition to this, a global view on the system can make faults more complex to diagnose. These centralisation issues are negated by MAC, as are issues associated with adaptive control.

The unpredictability of centralised adaptive control schemes should be alleviated by the decentralisation MAC offers. Undesirable changes within modules will affect the system as a whole to a lesser extent, perhaps even with other agents adapting to counter-balance the unwanted behaviours. Localisation of control may also improve on response speed issues associated with adaptive control.

Nonetheless, there are a number of potential issues associated with MASs that require careful attention such as deliberation, communication and negotiation delays, agent non-consensus and communication failure.

2.3 MACHRA Objectives

The HRA project's objectives include:

- Control of the elements resulting in a unified dynamic for the HRA.
- Nominal or acceptable behaviour of the HRA in element fault conditions.
- Graceful degradation of the HRA as fault levels increase beyond their critical point.

If the inclusion of intelligence in the control scheme is to be justified then the MA controlled HRA must achieve tangibly more in comparison to passive methods. Thus, the objective for MAC of an HRA also include:

Increased reliability - Robust techniques can be limited in the number of faults or fault types they can accommodate. The structure of the HRA alleviates this problem, as the number of elements reduces the overall affect of faults on the system. Nevertheless, a more intelligent strategy may accommodate even greater fault levels and fault types.

Improved nominal performance - Passive fault accommodation methods require the controller design to be robust enough to produce adequate performance during faulty conditions. This can lead to conservative performance in nominal conditions. An active control scheme can offer an increase in nominal performance as the control action can be changed in fault situations.

3. MACHRA SCHEME

The MACHRA scheme is currently in the investigative stage, concentrating on parallel in series (PS) configurations with lock-up and loose faults. Initial agent architectures and agency structures have been designed and simulated.

At present, Matlab/Simulink is used to create and simulate HRA assemblies, details of which can be found in [Davies et al., 2008b]. Stateflow is used to simulate the inner rule-based logic of the agents and their communication. This provides a fast prototyping tool of the agents for use with Matlab/Simulink.

The agent configuration and internal structuring was detailed in [Davies et al., 2008a]. A brief overview of the MACHRA scheme is provided here.

3.1 Agency Architecture

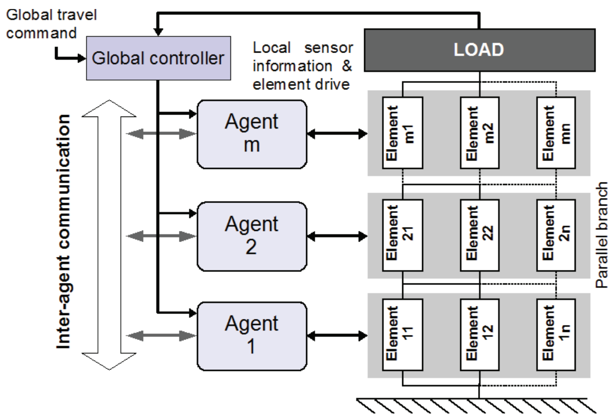

Figure 2. MACHRA agency architecture

The architecture of an agency is the configuration of multiple agents on a macro scale. Figure 2 displays the MACHRA scheme's agency architecture for a $m \times n$ HRA PS configuration. There is an agent per parallel branch of elements, each of which is responsible for the control and detection of faults within its elements and communication of faults to other agents.

All agents within this scheme are identical and peers, consistent with the spirit of MAC where no hierarchy should exist. A fixed outer control loop provides each agent with an identical set-point. Communication between agents is broadcasted via a bus. However, agents only consider messages from structural neighbours. If lock-up faults occur, the agent's structural neighbours will change and thus different messages become relevant.

3.2 Agent Architecture

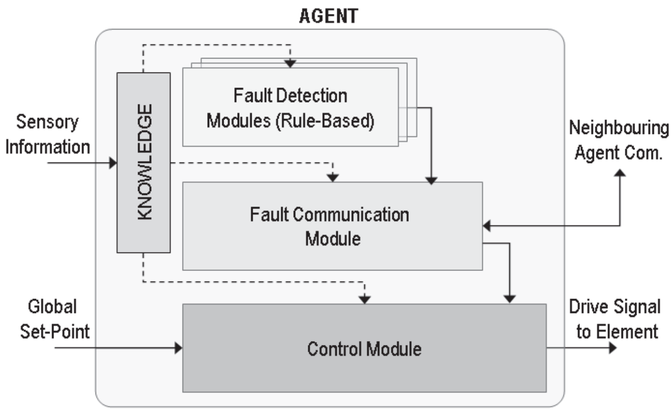

Figure 3. MACHRA agent architecture

The current agent architecture is illustrated in Figure 3. This architecture has similarities with subsumption, first introduced by [Brooks, 1986], that uses behaviours layered in order of abstraction to produce more complex emergent behaviors in a reactive time-frame. This reactivity is key in the HRA as, due to the fast dynamics of the electromagnetic elements, a purely deliberative architecture may not provide the response times needed.

The Fault Detection Module (FDM) is the most abstracted layer, and thus affects those below it. As its name suggests, the FDM detects faults in its elements. Currently, only one fault type (lock-up faults) is detected. Future agents will have more than one module, arranged either as peers in a single layer or as separate layers ordered by the severity of the fault type. The module contains rule-based logic which determines the fault status of the element based on sensory information and internal knowledge.

If a fault is detected, this information is passed to the Fault Communication Module (FCM) where it is relayed to other agents. Fault status messages from other agents are also received here.

The most reactive layer is the Control Module (CM), which provides the drive signal to the element based on the set-point, and its knowledge of the system status. A multiple-model control scheme is employed, as the CM contains a look-up table with simple classical control designs based on the number of active elements in the system.

Finally, a knowledge module containing both knowledge given to the agent on start-up and that deduced within the individual modules links the layers.

4. CONTROL OF A 10X10 HRA

This section will consider the control of a 10x10 HRA using MAC concepts and a passive control approach for comparison. [Davies et al., 2008a] gave an example of MAC applied to a 4x4 system. As this system had a relatively low level of modular redundancy in terms of the HRA concept, the effects of faults on the system were relatively large. A 10x10 system is a more appropriate level of redundancy for the HRA concept and thus it is worthwhile reconsidering the effectiveness of active FTC in a system where faults have less affect. In addition, the effects of reconfiguration

Table 1. Requirements

Performance Requirements	
Travel Window	± 0.06m ($6 \times element\, travel$)
Overshoot	$<2\%$
Rise Time	<0.75s
Settling Time	<1.20s

Table 2. Fault Cases

Case	Description	HRA State
Nom.	All elements are healthy	Healthy & capable
FC1	Branch nearest load locked	Faulty, but capable
FC2	2 branches nearest load locked	Faulty, but capable
FC3	3 branches nearest load locked	Faulty, but capable
FC4	4 branches nearest load locked	Critical fault level

delays and fault detection errors will be considered in the MAC scheme.

4.1 Case Study System

The HRA system considered in this paper is, as previously stated, a 10x10 system in parallel-series (PS) configuration, which is structured as shown in Figure 2, with ten branches of ten parallel elements arranged serially.

The actuation elements currently being used within the project are SMAC electromagnetic actuators [SMAC, 2004]. The modelling of these actuators was considered in [Davies et al., 2008b], and will not be detailed here. A simplified 2 state element model is used in this example, making the overall system 20th order.

The control is designed to meet some transient requirements, suitable to the system's technology with good stability margins. These requirements are given in Table 1.

The PS configuration of HRA is most affected by lock-up faults, as a locked element will fix its whole parallel branch of elements from the preceding surface to the next. Loose faults are naturally accommodated by this structure, as parallel elements compensate for loose elements in the branch. Thus, lock-up faults are considered in this example.

It is assumed that this system is designed for an application with travel requirements that need at least 6 of the 10 parallel branches to be operational. Hence, up to 4 lock-up faults in separate branches would be tolerable in this case and this level of faults will be considered here. 1-4 faults are injected in a worst-case manner (in separate branches), as described in Table 2.

4.2 Control Schemes

Figure 4 represents both the passive control and MAC schemes.

The passive scheme has cascaded classical controllers designed to meet the control objectives in nominal conditions. The inner loops have a phase advance compensator controlling the local position of each parallel branch of elements. This spreads the travel between the elements equally. An outer loop controller is then included to control the overall travel of the HRA as a whole. Proportional-

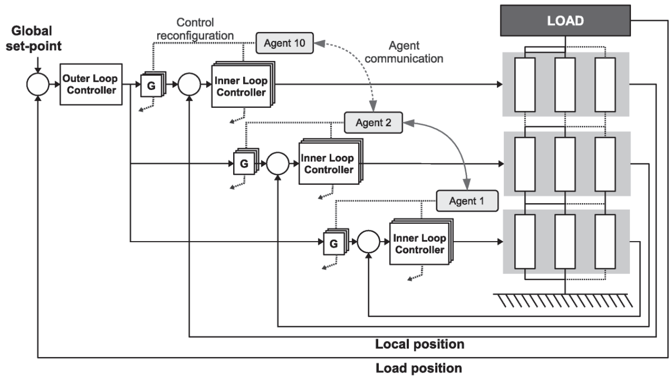

Figure 4. Global and agent control schemes

integral control is used in the outer loop to achieve the steady state requirements.

This passive control scheme is used as the base for the MAC approach. Under nominal conditions, the MA controlled system is identical to the passively controlled system. When a fault is detected by an agent, however, this fault is communicated throughout the agency and the control laws are changed. The outer loop is not reconfigured, as this would compromise the localisation of fault detection and reconfiguration decision, producing a single point of failure, as mentioned previously.

The feed-forward gain in the agent's control module is changed to redistribute the travel demand of the system i.e. if the system was nominal and one element locks then the gain would be changed from 1/10 to 1/9, as there are nine active element branches remaining.

In addition to this, the parameters in the local phase advance controller are also reconfigured. This is necessary as lock-ups in the system effectively increase the mass of the system: operational elements now have to work upon the dead mass of the faulty actuator as well as the load. An increase in the speed of the local controller can improve the performance of the remaining operational elements. Hence, in the agent's control module there is a look-up table of pre-computed control parameters based on the number of locked element branches in the system. In effect, this is a decentralised multiple-model control scheme, as there are a number of local controller designs based on fault models of the system.

It would also be possible to apply adaptive control using this approach. However, a multiple-model based approach was favoured as this aids verification of robustness and stability that would be necessary for high integrity applications for which HRA is intended for.

4.3 Simulation of Fault Cases

Figure 5 displays the response of the passively controlled and MAC schemes under nominal and faulty conditions as previously described in Table 2, when a step change of 0.05m in the reference was applied at t=0. All faults were introduced at the beginning of the simulation. Table 3 gives the gain margins and transient characteristics of these responses.

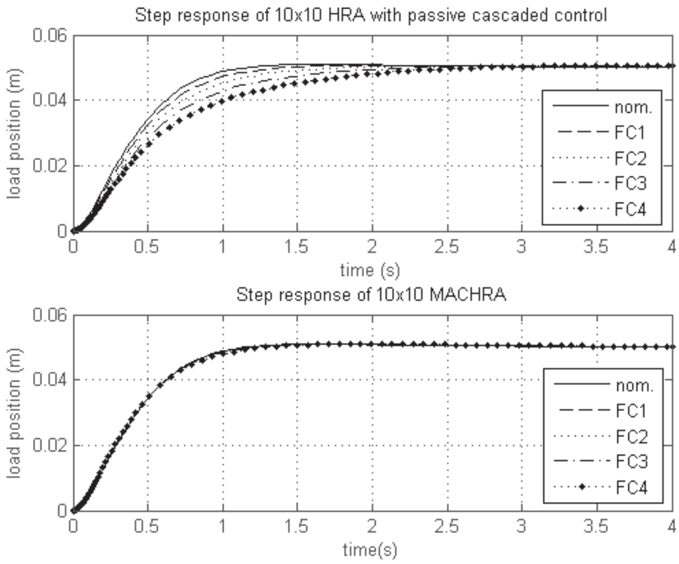

Figure 5. Step response of passive and MAC 10x10 HRA

Table 3. Passive control and MAC HRA

Fault Case	Over-shoot	Rise Time	Settling Time	Gain Margin	Phase Margin
Nominal	1.88%	0.68s	1.03s	∞	74deg
Passive FC1	1.01%	0.75s	1.20s	∞	76deg
Passive FC2	1.01%	0.88s	1.48s	∞	79deg
Passive FC3	1.01%	1.05s	1.85s	∞	82deg
Passive FC4	1.10%	1.33s	2.26s	∞	86deg
MACS FC1	1.68%	0.68s	1.04s	∞	74deg
MACS FC2	1.70%	0.68s	1.04s	∞	75deg
MACS FC3	1.96%	0.71s	1.07s	∞	75deg
MACS FC4	1.94%	0.73s	1.29s	∞	77deg

It can be observed that lock-up faults cause the system to slow. In the passive control case, the rise time and settling time increase significantly, and the requirements are not met when two or more actuation branches are locked.

In the MAC case, the increase in rise time and settling time can be reduced significantly, producing a response that is very similar to nominal conditions. The transient requirements are met in all fault conditions, apart from the settling time requirement in FC4.

These results illustrate that a MAC approach can provide near nominal performance in a realistically scaled HRA under realistic fault levels. This is an improvement on the passive control case.

4.4 Reconfiguration Delays

The MAC results given in Section 4.3 assumed that faults were detected and communicated instantaneously within the MAC architecture. This is not a realistic assumption. The detection of faults will take some finite period, as will the communication of these faults to the other agents. In addition, on receiving fault messages, the agents will take time to change their control parameters, and if multiple faults occur simultaneously, multiple messages get passed throughout the agency, and an agent will effectively step through these parameters until the final fault status has settled.

All of these effects must be considered in the simulation if the results are to resemble reality. Figure 6 shows the transient responses of a more realistic MAC 10x10 HRA in comparison to the previous passive control case and MAC without delays. The fault detection, communication and control reconfiguration are all simulated using Stateflow, which introduced delays into the system.

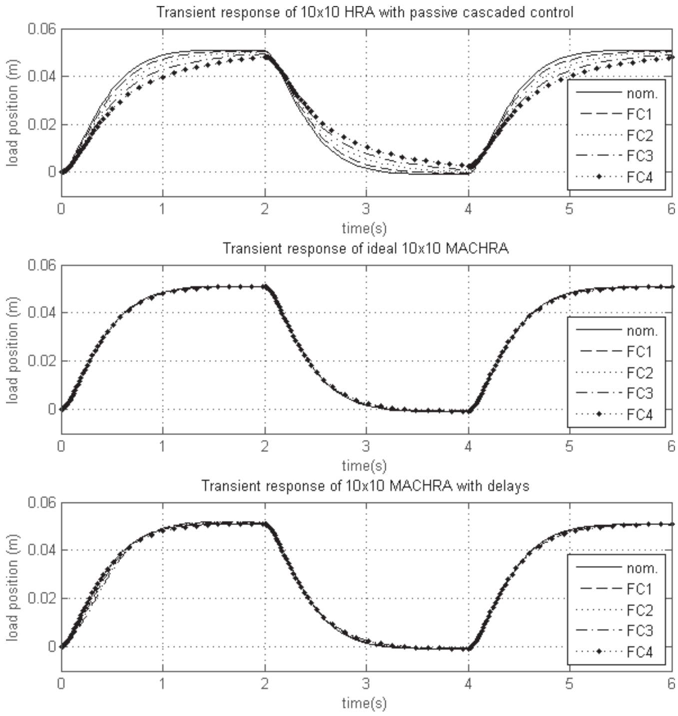

Figure 6. Transient response of passive, ideal MAC and MAC with delays

A square-wave input is applied to the system and all faults were injected at t=0. The response shows that in the first half period of the input, delay effects are present in the more realistic MAC scheme. However, after all faults are detected, communicated and control reconfigured the system's behaviour returns to that of the ideal MAC case.

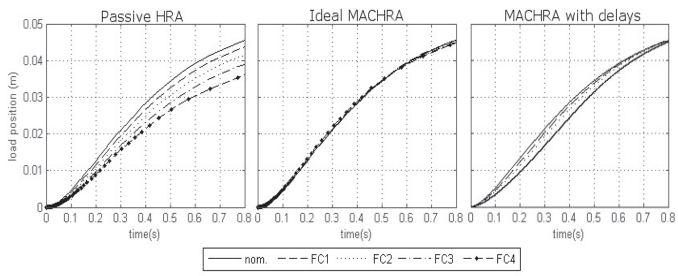

Figure 7. Initial response of passive, ideal MAC and MAC with delays

Figure 7 shows the initial response in more detail. Total reconfiguration of the system was attained after 0.35s. This delay increases the settling time and overshoot of the response in the first half period. The overshoot limit is exceeded in FC1, FC2 and FC3. If this was critical, then the agent's control reconfiguration could be adjusted to slow down reconfiguration, or reduce control gains until the fault state is stable. The effects of delays would also be

Table 4. False detection

No.of False Detects	1	2	3	4
Overshoot	1.88%	4.04%	6.16%	8.18%
Phase Margin	72deg	70deg	68deg	66deg

Table 5. False detection with reconfiguration

No.of False Detects	1	2	3	4
Overshoot	1.58%	1.51%	1.66%	1.57%
Phase Margin	74deg	74deg	74deg	75deg

lessened if the faults did not occur simultaneously, which is likely to be the case in a real situation.

4.5 Misdiagnosis in MACHRA

Misdiagnosis of faults in active FTC systems can be problematic. If the system adapts to a change that has not actually occurred in the system, then the results could degrade performance, cause faults or induce instability. Equally, if the system's control relies upon faults being detected and a fault is not detected then the results could be similar. Misdiagnosis of faults in this particular system will be considered briefly here.

Undetected faults should not cause problems in this particular scheme. At worst, the system's response will be that of the passive case. The system will become slower, but stability will be maintained. This is due to the outer loop control. If no outer loop was in place, the same response under working fault detection conditions could be achieved. However, an undetected fault would result in a significant steady state error for the overall HRA as the feed-forward agent control gains are not reconfigured.

False detection of faults in this MAC scheme will result in gain and inner control law changes, which could lead to instability. Table 4 gives the overshoot, gain and phase margins in the case of 1-4 false lock-up detections. The phase margin decreases, but the system retains stability. The overshoot, however, rises significantly. This is unlikely to be acceptable in an application, however four false detections may also be unlikely given a robust fault detection algorithm.

The flexibility of a MAC scheme can handle this problem through further reconfiguration. If the control law of the 'locked' agent is changed to force those elements into a locked state at time of detection, then this decrease of the stability margins can be avoided. This approach was applied and simulation results are shown in Table 5. On the triggering the FDM, the input reference of the agent is fixed to the local position at time of detection and the controller is changed to a PI compensator. This forces the system to behave as the detected fault case. Subsequently, the phase margin is not eroded and the overshoot limit achieved.

5. CONCLUSIONS AND OUTLOOK

The case for MAC of HRA has been made and the current MAC scheme described. It has been shown that, at this moderately high level of modular redundancy for HRA, MAC still provides significant benefits in comparison to passive control under realistic fault levels. Near nominal performance can be maintained in worst case fault scenarios.

Reconfiguration delays in MAC can affect the response until full reconfiguration has been achieved. These effects may be considered acceptable, due to their ephemeral nature. Non-detection will result in the performance of a passive system. However, false detections will result in decreases in the stability margins. MAC offers a solution to this problem, by reconfiguring the control of agents that have detected a fault.

Practical testing of MAC on a experimental electromagnetic HRA is planned, which should give an indication of such a scheme's performance in a real-world situation.

ACKNOWLEDGEMENTS

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