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HRA – High Redundancy Actuation Overview

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Abstract:
This paper presents an overview of recent research into a new method of providing fault tolerant actuators for high-integrity and safety-critical applications. The High Redundancy Actuator (HRA) uses a large number of small actuation elements to make up a single actuator. It provides superior reliability and efficiency over current technology, by configuring and controlling the elements so that faults are inherently accommodated. Simulation and experimental results demonstrate feasible active and passive fault tolerant control.

Keywords: fault tolerant control, mechanical actuator, redundancy, parallel series configurations

1. INTRODUCTION
Unexpected faults can cost companies large sums of money and in extremis can lead to loss of life. In response, modern engineering applications demand high levels of availability and reliability. Fault tolerant control [1] is about technical systems capable of tolerating component malfunctions whilst still maintaining performance and stability [9].

Conventional Fault Tolerance
Many fault tolerant control methods (such as triple vote or soft sensors) work well for sensors, but are not applicable to actuation systems. The reason is that the essential function of an actuator is energy conversion, and the flow of energy needs to be carefully managed in case of a fault.

The common solution [10] is to use some form of over-actuation in which 3 or 4 actuators are used in parallel. In this approach, each actuator must be capable of performing the task alone. Further conditions apply: it needs to be possible to override a faulty actuator, and the energy supply needs to be unaffected. These approaches incur penalties as cost, weight and complexity are increased while efficiency is reduced.

Fig. 1: The HRA concept

The High Redundancy Actuation Approach
The High Redundancy Actuator (HRA) concept is a fundamentally different approach to actuator fault tolerance, inspired by biomimetics. Just like a muscle is composed of many individual fibres, an HRA consists of many tiny actuation elements. This makes the HRA highly resilient to localised damage, because each element contributes only a tiny amount to the overall actuation task (see Fig. 1). Faults will affect the maximum capability, but through robust control full performance can be maintained without adaptive control or reconfiguration. Moreover, through appropriate health monitoring it is possible to identify if the current state is close to the required performance limit (e.g., the capacity is down to 85%, while 80% is required).

Potential Benefits
Three significant benefits of the HRA approach have been identified:
1. improved availability: it can do its job when asked and will warn maintainers when it starts to approach a critical level of faults;
2. improved efficiency: in terms of actuator sizing (over sizing) for fault tolerance;
3. graceful degradation: if fault levels exceed the critical point, system failure will not be sudden and unexpected.

The main challenges identified fall in the areas of actuator design and configuration, control, health monitoring, demonstration and identifying suitable technologies for the HRA. All but the latter are being addressed by the current project, and progress in each area will be summarised in sections 2 to 6.

Fig 2: Series and Parallel Configurations
2. CONFIGURATIONS & DESIGN METHODS

The HRA improves efficiency by using a greater number of smaller actuation elements. For example, a system with ten elements may still work with only eight of them operational, and the overall capacity is only over-dimensioned by 25% (as compared to 100% or 200% for conventional duplex or triplex redundancy). But it is not immediately clear how many elements are required, how they can be used in series and parallel, and which specific configuration is suitable. Parallel elements provide redundancy against loose faults, while serial elements provide redundancy against lock-up faults. The grid combination has both aggregations, which makes it robust towards both fault modes (see Fig. 2). There are further choices with the lateral connections as shown in Fig. 3.

Using multi-state system analysis, it is possible to determine the reliability of any given configuration. This depends both on the capability and the required performance of the actuator. The analysis can also be used to identify appropriate configurations for a given actuation task.

Application of this analysis to selected configurations leads to the results in Table 1.

3. CONTROL CHALLENGES

The control of an HRA is an interesting challenge. On one hand the number of elements and potential input and output signals is high, but on the other hand a robust low complexity solution is desirable.

There are two essential distinctions for the potential control schemes. The first is whether each element is controlled individually (leading to a multiple input/multiple output or MIME control scheme), or whether only the summative external behaviour of the HRA is controlled (leading to single input/single output or SISE control). A possible combination is the use of local controllers per element, combined with a cascaded global controller.

The second distinction is how the control scheme responds to faults. In the order of growing complexity, there is a wide range of options available: starting from feed-forward control (faults are not compensated) over robust feed-back control (faults are partially compensated) to adaptive control (the control structure adapts automatically to the faults) to control reconfiguration (faults are detected explicitly, and a predesigned controller is used to deal with it).

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Table 2 shows the resulting combinations available for the control scheme. The two highlighted fields (robust SISO control and a reconfigurable cascaded control scheme) are discussed below.

Table 2: Possible HRA Control Schemes

<table>
<thead>
<tr>
<th>Passive FTC</th>
<th>Active FTC</th>
</tr>
</thead>
<tbody>
<tr>
<td>FF</td>
<td>robust</td>
</tr>
<tr>
<td>SISO</td>
<td></td>
</tr>
<tr>
<td>Cascade</td>
<td>[Highlighted]</td>
</tr>
<tr>
<td>MIMO</td>
<td></td>
</tr>
</tbody>
</table>

4. PASSIVE FAULT TOLERANT CONTROL

The robust passive controller is simple. A state reduction is applied to the model of the HRA, turning it into a 2nd order spring damper system. A single PI controller with phase advance (PA) compensator is acting on the load position error. The control signal $u$ is fed to each of the 16 elements. The controller is designed to be robust to changes in
the actuator behaviour, and it is verified against a number of models for specific fault cases.

This approach has been tested on an electromagnetic experiment as shown in Fig. 4. The HRA contains 16 elements in a 4x4 configuration. Pairs of elements work in parallel in a lateral direction, 4 pairs are stacked (vertically) in series, and two of these stacks work in parallel, making this a PSSP configuration in our terminology.

The elements are tuned so that the bottom elements are stronger than the ones at the top, and each element contains a significant amount of damping and a slight spring action towards the neutral position to help with the equal sharing of travel.

**Fig 4: Experimental 4x4 Setup**

A step response for this experiment is shown in Fig. 5. The graph shows the position displacement of each pair of elements, and it is nice to see how the load displacement (top) is divided equally across the 4 serial pairs in each stack.

Between 2 and 4 seconds, two loose faults are simulated, which have nearly no influence on the overall behaviour. At 4 seconds, a lock-up fault is simulated in the third pair of the first stack (similar to fault 2 in the MAC simulation). The overall behaviour changes very little, but it is nice to see that the remaining 3 pairs in the stack take an equal share of the travel.

**Fig 5: Experimental Results of a 4x4 HRA**

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**5. ACTIVE FAULT TOLERANT CONTROL**

The *active* approach uses a Multi-Agent System to control, detect faults and reconfigure the control laws accordingly. This Multi-Agent Control (MAC) scheme can be thought of as allowing local multiple-model control and fault detection on an individual element level, see [2].

The structure and level of complexity in the two controllers is starkly different.

**Fig. 6: 4x4 Parallel in Series HRA with lock-ups**

**Fig. 7: Multi-Agent Control & monitoring scheme**

The MAC scheme has four agents, each of which controls and monitors one of the four parallel columns of actuators (as shown in Fig. 7). These all receive their local set-points from a global PI controller (similar to the passive approach above). Each agent has a set of controllers that can be applied according to the detected fault state.

The most severe fault case is known to be the lock-up fault. Hence, both controllers are tested with two levels of lock-up – i.e, lock-up of the entire first parallel connection, then in the second parallel connection (as shown in Fig. 6). The step response results with both controllers are compared in Fig. 7.

The results show that both the robust control and the MAC approaches provide fault tolerance to lock-up faults within a HRA. The robust control is simple to implement, but there is a slight effect of faults on the performance of the HRA.

The active fault tolerant control using MAC can fully restore the performance after a fault has been detected, at the cost of higher complexity. This will become more noticeable the more elements are used.
6. HEALTH MONITORING

A key feature of the HRA concept is that failures in individual elements can be inherently accommodated without the need for explicit fault detection, isolation and reconfiguration. However, in order to ensure that a HRA can be replaced/repaired as the degraded performance gets close to a critical capability level, it is essential to have some form of health monitoring. There are two approaches being considered to provide this.

Monitoring of individual sub-actuator elements: development of detection methods for specific faults within the individual actuator elements. Within a MAC framework simple rule-based methods can be used to assess that an element is working or not [3]. Alternative approaches such as parameter identification were also found to work well.

Overall health monitoring: For passive fault tolerant control, it may still be necessary to monitor the performance of an HRA. This task can be formulated as a parameter identification problem, where the capability of the HRA is the parameter in question. Both offline identification and online adaptive control have been successfully used to determine the current capability, which can then be used to issue an advance warning before the performance drops under acceptable levels.

7. CONCLUSIONS

Significant progress has been made in this project in understanding how high redundancy actuation can deliver an intrinsically fault tolerant actuation solution with graceful degradation. The advantages in reliability and efficiency are well demonstrated, and methods have been found to address the complexity inherent in such a high order system.

The main challenge from a control point of view is the model complexity. This can be dealt with by design of controllers for each element (breaking down the problem – as in the MAS approach), or by producing a reduced order model on which to base a single design. It has been experimentally demonstrated that an HRA can be controlled using passive approaches; that is, by relying on robustness in a fixed controller to deal with the faults in sub-actuator elements. However, it has also been shown that post-fault performance can be improved (or maintained close to nominal levels) if an active approach is permitted.

With the basic concept proven and found sound, the next planned step in this research project is to look further into questions of implementation, technology, cost and manufacturability. Beyond this, the main challenge is to find specific applications areas for the HRA.

8. REFERENCES

