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High Redundancy Actuator with 12 Elements: Open- and Closed-loop Model Validation

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Abstract: The high-redundancy actuator concept that is inspired by biomimetic is an approach to fault tolerant actuator that aims to provide fault tolerance using relatively large numbers of small actuation elements. The actuation elements are assembled in parallel and series configurations to form a single actuator that has intrinsic fault tolerance. During normal operations, it is possible that some of these elements are operational and some are faulty. In this situation, the high-redundancy actuator will still work, but with graceful degradation. This paper discusses the modelling aspect of the high-redundancy actuator that consists of 12 actuation elements based on linear electromechanical actuation technology. Simulation results are validated with real-time experimental results using both a single actuator and the full high-redundancy actuator in open-loop and closed-loop.

Keywords: actuator modelling, fault-tolerant actuator, high-redundancy actuator, parallel redundancy, lock-up fault, loose fault.

1. INTRODUCTION

Modern engineering technologies depend strongly on complex automatic control system to meet their peformance aims. Over the past few decades, automatic control systems have become widely used in manufacturing (Kato et al. (2001)), automotive and aerospace industries (Jensen (2000)), and critical infrustructures. In the aerospace industry for example, Flight Control System (FCS) that consists of sensors, actuators and digital flight control computers (as the system's core) have long been used to provide aircraft control and envelope protection in pitch, roll, and yaw axes (Sghairi et al. (2008)). This control system is the key in determining the efficiency and safety of the aircraft operation. In a safety critical system like this, unexpected faults in the system components can be catastrophic not only to the system itself, but also potentially to humans within its vicinity.

Traditionally, over-actuation is used for fault tolerance in which two or more actuators are connected in parallel and each actuator is capable of performing the task alone if the other actuators are faulty (Davies (2009)). However, over actuation reduces the efficiency of the system because it increases size and cost to build the system. A purely parallel configuration will also be rendered useless in the presence of lock-up faults.

In response to the issues faced by the traditional parallel redundancy, the concept of the high-redundancy actuator (HRA) is introduced for fault tolerance. The HRA is a concept for fault tolerance that is inspired by human musculature (Davies et al. (2008)). There are similarities between human muscles and an actuator in the sense that both converts energy into motion. Human muscles convert energy from food consumed into complex motion such as running and walking while electromechanical actuators converts electrical energy into mechanical motion. Human musculature works in an ingenious way because each muscle cell provides only a minute contribution to the travel and force of the overall muscle system making the muscle highly resilient to damage of individual cells.

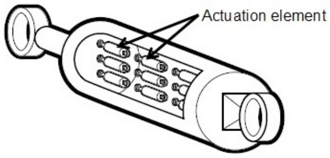

Fig. 1. Example of high redundancy actuator.

By adopting the same cooperative principle, the HRA concept focuses on designing a fault tolerant actuator comprised of a relatively large number of small actuation elements that work together to form a single actuator as shown in Fig. 1 (Davies (2009)). Actuation elements are connected in parallel and series configuration to improve their reliability and availability, and at the same time reduce the need for over-sizing. Parallel configurations increase the generated force and improve loose fault tolerance, while series configurations increase travel and improve lock-up fault tolerance (Steffen et al. (2012)).

If one or more of the actuation elements fail, overall performance is expected to degrade gracefully but the system is still able to achieve the required task. In other

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word, the HRA concept is to prevent elements fault from causing a system failure (Blanke et al. (2006)).

This paper aims to explain the model of a single electromechanical actuator and the HRA, and shows some simulation and experimental results that describe the performance of the actuator in open- and closed-loop. This paper is structured as follows: Mathematical model of a single electromechanical actuator (EMA) and the HRA is explained briefly in Section 3. In Section 4 a selection of simulation results are presented to give indication of the performance of the HRA. Section 5 discusses some experimental results for model validation in open-loop as well as in closed-loop using proportional controller. The paper concludes in Section 6 which includes comment on the future direction of this research.

2. BACKGROUND AND MOTIVATION

Research to date has concentrated on HRA based on electromechanical actuator with relatively low number of actuation elements. An early example had 4 elements which were controlled through passive fault tolerant methods (Du (2008)). The actuation elements were connected using a 2-by-2 series-in-parallel configuration. The performance of the HRA was evaluated under both healthy and faulty conditions and the results show that performance degradation occurs when faults are injected into one or more of the actuation elements, but the HRA can still complete the required task.

Another work modelled, controlled and monitored a HRA based on electromagnetic actuators with 16 actuation elements (Davies (2009)). The element model for a moving coil actuator is derived from first principles, verified experimentally and then used to form higher-order, nonlinear HRA models for simulation. For control purposes, a reduced order representation of the model is used. Controller design involves passive fault tolerant control (PFTC) design and multi-agent system inspired active fault tolerant control (AFTC) design for the HRA to achieve near-nominal performance under fault conditions. This work also discussed two types of fault detection and identification (FDI) methods: a rule-based approach for the AFTC and an interacting multiple-model method for condition monitoring. The condition monitoring ensures that the HRA can be repaired as the degraded performance get close to critical capability level.

The current research aims to expand upon the work of Du (2008) by considering a 12 elements HRA based on electromechanical actuation as shown in Fig. 2, and to explore different FDI and condition monitoring methods that has been introduced by (Davies (2009)). This work, however is not simply an expansion of the work of (Du (2008)) because the way the mathematical model was derived in Section 3 is significantly different from the previous work (refer to Du et al. (2010) for further detail on the mathematical model of the 2-by-2 HRA).

3. MODELLING OF ELECTROMECHANICAL ACTUATOR

This section covers the mathematical modelling of a single actuator and the HRA. Detail of the derivation of the mathematical equation of the single element actuator can be found in Hasmawati et al. (2014).

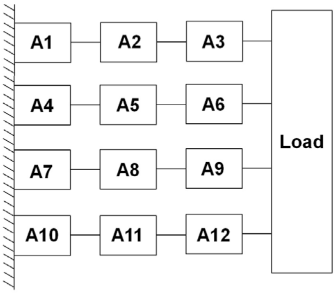


Fig. 2. Schematic diagram of the high-redundancy actuator.

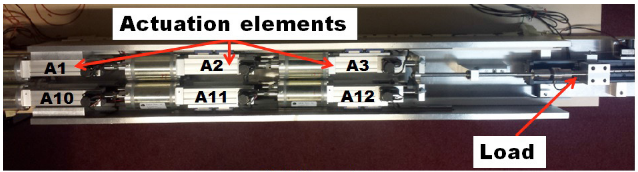
3.1 Mathematical Model of A Single Actuator

Equation of the single EMA represented in state-space form is shown below.

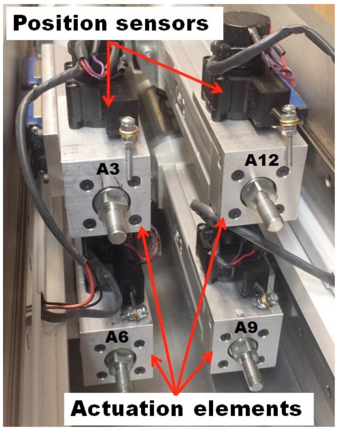
$$\begin{bmatrix} \dot{I} \\ \dot{\theta} \\ \ddot{\theta} \\ \dot{X_L} \\ \ddot{X_L} \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & 0 & -\frac{K_e}{L} & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ \frac{K_T}{J} & -\frac{kh^2}{J} & -\frac{(D+ch^2)}{J} & \frac{kh}{J} & \frac{ch}{J} \\ 0 & 0 & 0 & 0 & 1 \\ 0 & \frac{kh}{M_L} & \frac{ch}{M_L} & -\frac{k}{M_L} & -\frac{c}{M_L} \end{bmatrix} \begin{bmatrix} I \\ \theta \\ \dot{\theta} \\ X_L \\ \dot{X_L} \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} V_s \tag{1}$$

$$y = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} I \\ \theta \\ \dot{\theta} \\ X_L \\ \dot{X_L} \end{bmatrix} + [0]V_s$$

where I is the armature current, θ is the motor (angular) displacement, $\dot{\theta}$ is the motor speed, $\ddot{\theta}$ is the motor acceler-



(a) Top view



(b) Side view

Fig. 3. Implementation of the HRA in experimental rig.