High-Redundancy Linear Electro-mechanical Actuator for Fault Tolerance

Hasmawati Antong, Roger Dixon, Christopher Ward

Abstract—High-Redundancy Actuator (HRA) refers to an actuator that consists of relatively large number of actuation elements, connected in series and in parallel to form a single actuator. The HRA can provide a high degree of fault tolerance by improving availability and reliability, whilst reducing the need for over-sizing an actuator especially in safety-critical applications.

The HRA is applicable to a wide range of actuation elements but this paper focuses on a linear electro-mechanical actuator (EMA) due to its extensive application not only in industrial machinery but in aircraft and the aerospace industry in general.

This paper presents the current work and future work planned in order to demonstrate the concept of high-redundancy actuator through a 3 by 4 series in parallel linear EMA for fault-tolerant system.

Index Terms—actuator modeling, electro-mechanical actuation, fault tolerance, high-redundancy actuation.

I. INTRODUCTION

HUMAN muscles are well known actuator. They convert energy in the food that a human consumes into motion such as running, dancing or kicking a ball. Human musculature works in an ingenious way because each muscle cell provides only minute contribution to the travel and force of the overall muscle system. The muscle as a whole is highly resilient to the damage of the individual cell.

By adopting the same co-operative principle, the concept of high-redundancy actuator (HRA) is introduced. It focuses on designing a fault-tolerant actuator that comprises of relatively large number of small actuation elements that work together to form a single actuator [1]. Based on this configuration, the travel and force of each element are added up to meet the system required performance.

If an element fails, performance is expected to degrade but overall is still able to satisfy the required task. In other word, the concept of HRA is to prevent element fault from causing systems failure [2].

This paper is organized as follows: it starts with the background and motivation in Section II, followed by the research aim and objectives in Section III. Section IV and V cover the ongoing work and the future work planned in order to achieve the research aim and objectives. Conclusion is presented in Section VI.

II. BACKGROUND AND MOTIVATION

Modern engineering technologies depend strongly on complex design to meet their required performance. Unexpected fault in these system components can be catastrophic not only to the system itself, but also potentially to humans within its vicinity. In response to this, engineers are working on designing fault-tolerant system that can cope with component malfunction and maintain desirable performance and stability properties [3].

Conventional fault tolerance uses over-actuation 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 in faulty [4]. However, this over-actuation increase size and cost and thus reduces the efficiency of the system. Parallel configuration will also be rendered useless when lock-up faults occur.

HRA is a new concept for fault tolerant actuators where the elements are connected both in series and in parallel to improve reliability and availability, and at the same time prevent over-sizing. Parallel configurations increase the produced force and improve loose fault tolerance, while series configurations increase travel and improve lock-up fault tolerance.

Previous work by the Control Systems Research Group has realized a (4 elements) 2 by 2 series in parallel (SP) HRA using electro-mechanical actuator [5]. This HRA was controlled through passive fault tolerant control methods. 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 its required task.

The current research aims to expand upon this work. A HRA with higher order (12 elements) through a 3 by 4 series in parallel configuration is considered. A linear electro-mechanical actuator, as shown in Figure 1, will be used as the actuation element. Both passive and active fault tolerant control methods are to be designed for the HRA as well as health monitoring algorithm to achieve better performance.

Fig 1. Electro-mechanical actuator used as the actuation element for the high-redundancy actuator. (Image courtesy of Firgelli Tecnologies).
III. AIM AND OBJECTIVES

The aim of this research is to demonstrate the concept of a high-redundancy actuator through a 3 by 4 series in parallel electro-mechanical actuator. The objectives of this research are:

- Develop mathematical and simulation model of a single element EMA and a 3 by 4 HRA.
- Validate the simulation results of the single element actuator and the 3 by 4 HRA through experiments.
- Develop simulation model of a single element EMA and a 3 by 4 HRA under locked and loose faults.
- Validate the simulation results under locked and loose faults.
- Design a fault-tolerant controller to be used with the HRA.
- Design a conditional health monitoring algorithm to be integrated with the HRA.
- Evaluate the performance of the HRA actuator with controller and health monitoring algorithm under both health and faulty condition.

IV. WORK TO DATE

The following is a summary of the research started in early April 2013.

A. Modeling of individual actuator

Figure 2 shows the basic components of a linear EMA. It consists of an electric motor, a gearbox and a nut/screw mechanism. The electric motor drives the actuator by generating torque while the gearbox provides coupling between the electric motor and the nut/screw mechanism. The nut/screw mechanism then translates the motor torque into axial force to move any load connected to the actuator. By changing the voltage supplied to the motor, the actuator can be controlled to obtain the desired force and speed.

Generally, a linear EMA can be divided into two parts; electrical part (motor armature circuit) and mechanical part (mechanical loading of the motor). Based on these, the EMA is modeled and the equations are as follow

\[ i = \frac{1}{L} [V_a - RI - K_e \dot{\theta}] \]  
\[ \dot{\theta} = \frac{1}{J} [K_t I_l - D \dot{\theta} - \frac{cl}{2\pi N} (X_a - X_L) - \frac{cl}{2\pi N} (X_a - X_L)] \]  
\[ X_L' = \frac{1}{M_L} [c(X_a - X_L) + k(X_a - X_L)] \]

Fig 2. Components of electro-mechanical actuator. \( \theta \) refers to the angular displacement of the motor while \( X \) refers to the linear displacement of the actuator.

Equation (1) for the motor armature circuit, equation (2) for the motor mechanical loading and equation (3) for the applied load. \( \theta \) and \( \dot{\theta} \) are the motor angular velocity and acceleration, \( I \) is the current through the motor windings, \( X_a \) and \( X_e \) are the actuator linear speed and displacement. \( X_L' \), \( X_l \) and \( X_a \) are the load acceleration, speed and displacement, \( M_L \) is the mass of the load, \( c \) is the damping coefficient and \( k \) is spring constant. Other parameters are defined in Table 1.

B. Modeling of high-redundancy actuator

The actuators in the HRA are connected in series and parallel as shown in Figure 3. The series elements are connected end to end to increase travel and velocity. Parallel elements are connected to push/pull the same load and thus increasing the output force. Actuator 1, 4, 7 and 10 have a fixed base while the other actuators have a moving base. Changes have been made in the actuator equation to include the moving base.

Equation (1) is applicable to all actuators because the armature circuit of an individual motor is not connected to the other motors. The following equation is for the actuators with a fixed base.

\[ \dot{X}_a = \frac{1}{J} [K_t I_l - D \dot{X}_a - \frac{cl}{2\pi N} (X_a - X_{bi+1}) - \frac{kl}{2\pi N} (X_a - X_{bi+1})] \]

where \( X_{bi+1} \) and \( X_{bi+1} \) refers to the base of the next actuator and \( i \) is an integer representing the actuation elements. The following equations are for the actuators with a moving base.

\[ \dot{X}_a = \frac{1}{J} [K_t I_l - D \dot{X}_a - \frac{cl}{2\pi N} (X_a + X_{bi+1} + X_{bi+1}) + \frac{kl}{2\pi N} (X_a + X_{bi+1} + X_{bi+1})] \]

\[ X_L' = \frac{1}{M_L} [c(X_a - X_L) + k(X_a - X_L)] \]

where \( M_L \) refers to the actuator mass.

Four actuators will push/pull the same load so the applied load equation is also modified as follow

\[ X_L' = \frac{1}{M_L} [\sum_{i=1}^{12} (c(X_a - X_L) + k(X_a - X_L))] \]

Based on the derived equation of motion, a Simulink model was developed to test the behavior of the actuator.

C. Simulation Results

Simulation results for a healthy individual actuator and HRA is shown in Figure 4. The result shows that the
individual actuator produces approximately 12.4mm displacement and 0.3N force while the HRA produces approximately 37.1mm which is approximately three times the individual actuator force as there are 4 actuators connected in parallel. The output force is much smaller compared to the expected value of 100N (for an individual actuator). This could be due to un-correct parameter value used in the simulation especially the motor inertia. Experiment and calibration will be carried out to perform parameter estimation of the key motor parameters. However, the simulation model exhibits the expected actuator behavior which means that the equation of motion derived to represent the actuator is correct.

V. FUTURE WORKS

Experimental setup for a single actuator is under progress. Once all the required elements are available (load cell and current sensor), experiments will be performed to validate the simulation results and to do parameter estimation. Experiments with the 3 by 4 SP HRA will then be undertaken to evaluate the performance of the HRA under both healthy and faulty condition.

Design of fault tolerant control, both passive and active as well as health monitoring algorithms to be integrated with the HRA and evaluation of overall performance is planned during the second year of the research.

The third year will be focusing on thesis writing and minor experiments to be made for further adjustment to improve the performance of the HRA.

VI. CONCLUSION

Presented in this paper is works carried out to realize a 3 by 4 SP HRA. The actuator model has been developed but simulation results show that adjustment on the motor parameter must be made. Also presented here are the future works planned for the next 2 years and 6 months in order to achieve the research aim and objectives.

![Fig 4. Simulation results of an individual EMA and the HRA. Top graph shows displacement result and bottom graph shows force result.](image-url)