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Invariant Control of Non-Linear Elements in a Stacked High Redundancy Actuator

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***Abstract*—The High Redundancy Actuator (HRA) concept aims to provide a single actuator comprising many cooperating actuation elements. The potential benefits of this include improved overall reliability, availability, and reduced need for oversizing of actuators in safety critical applications. This paper deals with the question of distributing the load evenly between a stack of elements despite non-linear characteristics.**

The approach is to separate the state space into a high dimensional internal and a low dimensional invariant (or external) subspace. If the internal states can be decoupled and damped, the input-output behaviour only depends on the few states of the invariant subspace. In other words: the high redundancy actuator with many redundant elements behaves just like a conventional single actuator, and classical control strategies can then be applied.

This approach is demonstrated here for an HRA constructed from simple spring-damper-actuator elements. The non-linear behaviour is required to simulate the element behaviour at the end of the available travel. Without equalisation, excessive accelerations are caused by individual elements hitting the end stop, and this can be avoided by applying the proposed element tuning.

***Index Terms*—electromagnetic actuation, fault tolerance, multi-variable control, non-linear control**

I. High Redundancy Actuation

High Redundancy Actuation (HRA) is a novel approach for designing a fault tolerant actuator that comprises a relatively large number of actuation elements (see Figure 1). As a result, faults in the individual elements can be inherently accommodated without resulting in a failure of the complete actuator system.[1]

The concept of the High Redundancy Actuation (HRA) is inspired by the 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 co-operation with existing technology to provide intrinsic fault tolerance.

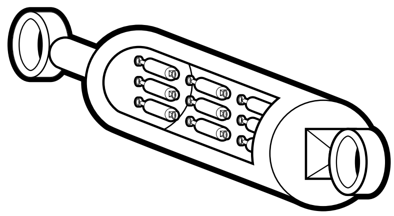

Figure 1. High Redundancy Actuator

An important feature of the High Redundancy Actuator is that the elements are connected both in parallel and in series. While the parallel arrangement is commonly used, the serial configuration is rarely employed, because it is perceived to be less efficient. However, the use of elements in series is the only configuration that can deal with the lock-up of an element. In a parallel configuration, this would immediately render all elements useless, but in the series configuration it only leads to a slight reduction of available travel (see Steffen et al. 2007, 2008a for details).

The paper is organised as follows: it starts with the motivation and background in Section 2, followed by the non-linear model of an actuator stack consisting of elements with a non-linear characteristic in Section 3. The control goal is presented in Section 4, followed by the solution in Section 5. Sections 6 presents a simulation example, and Section 7 proposes an extension for more complex HRA configurations.

II. Motivation

While the parallel configuration of actuation elements is well established and researched, the dynamic behaviour of elements in series is very different. The

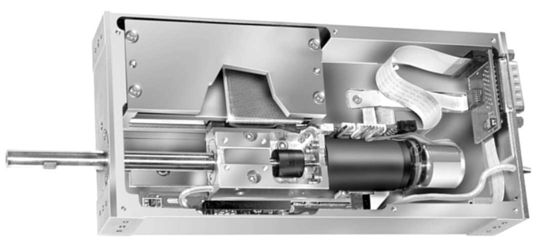

Figure 2. Electromechanical actuator

[1]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 was funded by the Engineering and Physical Sciences Research Council (EPSRC) of the UK under reference EP/D078350/1.

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reason is that between each element in series, there is a moving mass. This creates a high number of mechanical degrees of freedom, in turn leading to a high order dynamic model. The model needs to describe the position and speed of each mass separately, and there may also be further states internal to each element.

For the envisioned number of elements (10x10 or more), this may lead to a model with hundreds of states. Dealing with this complexity constructively is crucial for the success of the high redundancy actuator, because the standard approach of using sophisticated instrumentation may not be suitable. The goal of this paper is to reduce the model and instrumentation complexity to a level comparable to a conventional actuator.

A. Approach

The basic idea is to split the travel equally between all actuation elements. If this is achieved, the states of the elements are no longer individual variables, and they can all be reduced into a single simple model. In other words: because the whole system behaves like a single conventional actuator, a simple conventional actuator model is sufficient to describe it.

This approach is not trivial, because the elements experience different effective loads. The element at the bottom of the assembly for example experiences a higher load, because it needs to move all the other elements in addition to the load. This paper will present a number of ways to address this problem using active and passive, feedforward and feedback approaches. The relative advantages and disadvantages are discussed, and two approaches are considered in more detail. Based on this set of options, a specific solution or combination of solutions can be selected as appropriate according to the practical requirements.

B. Literature Overview

High Redundancy Actuation is a novel approach to fault tolerance, and consequently the specific problem formulated in this paper has not been previously considered.

Previous work on High Redundancy Actuation did look into the possibility of aligning dynamics using different methods (see Steffen et al., 2008b, 2010), but without using the geometric approach. This leads to results that are much less general than the approach presented here.

A similar approach is used in rotary actuation with torque summing and velocity summing gears, see for example Ting et al. [1994], Bennett et al. [2004]. The approach has a number of characteristic differences to the systems studied in this paper: it only works for rotary motion, and the problem of complexity is much less prominent because, due to the symmetrical structure, all elements act and behave in exactly the same way. Thus the parameter tuning described in this paper is not applicable.

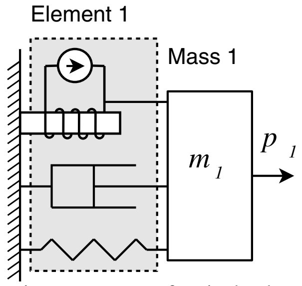

Figure 3. Dynamic components of a single element

A related problem has been studied in the dynamic behaviour of axial stacks of piezoelectric actuators by Jalili [2009]. The author models the stack as a distributed system with partial differential equations (compared to the lumped elements in this paper), which leads to similar results concerning the internal mode. However, the author makes no apttempt to control or decouple these modes internally.

The basis for decoupling internal modes is the geometric approach, because it creates a connection between the dynamics of the system and constraints formulated in terms of the states of the system. This approach was introduced by Wonham [1985] and later extended by Basile and Marro [1992]. It provides the standard solution for the disturbance decoupling problem (see Commault et al., 1997), which is the class of control problems at the heart of this paper. The geometric approach has previously been used for adaptive control of a High Redundancy Actuator in Steffen et al. [2009].

C. Symbols

$\mathrm{diag}\{\}$	diagonal matrix
f_j	force produced by element j
g_j	strength factor for element j
F_i	force total for mass m_i
f	characteristic element function (non-linear model)
$k_d\, k_r$	damping and force constant (linear model)
m_i	mass of moving mass number i
$n_i\; n_j$	number of masses and elements
$\mathbf{Q}$	the connection matrix $\in \{-1,0,-1\}^{j\times i}$
$\mathbb{R}$	set of real numbers
t	time
u_j	input of element j
$x_i\; \dot{x}_i\; \ddot{x}_i$	position, speed and acceleration of mass m_i

III. System Model

The basic components of an electromechanical actuation element are shown in Figure 3. From a modelling perspective, it is a typical actuated spring-mass-damper system, which can be described by NEWTONian mechanics. Three forces act upon the mass: the electromagnetic force F_{el}, the damping force F_d, and the