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Control of Scalable Wet SMA Actuator Arrays

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***Abstract* - This paper presents a new control method to drive an array of wet Shape Memory Alloy actuators utilizing a Matrix Manifold and Valve system (MMV). The MMV architecture allows a vast DOF robotic system to be controlled using limited number of resources. Using biological inspiration, the robotic system contains a network of "blood vessels" transporting fluid to the various "muscle" actuators. In general, an array of N^2 wet actuators can be controlled by 2N+2 fluidic valves, resulting in a scalable architecture. This would allow robots to contain a vast number of actuators like the human body, and be controlled in a scalable manner. The initial prototype contains a 4x4 array of 16 actuators controlled by 10 solenoid valves, where 25% of the actuators can be activated at any one time.**

Since only a subset of the actuators can be activated at any time, various methods of scheduling the resources (i.e. valves) are investigated, as well as various ways to define the error or difference between the desired and actual states of the array. The fluidic impedance of the system is taken into account in order to optimize the control. Results of simulation show that new scheduler options and definitions of error improve the performance of the system by a factor of 10 when operating the array near its maximum capacity.

Index Terms – Shape Memory Alloys, actuators, scalable, biologically inspired.

I. INTRODUCTION

As humanoid robots become more like the real human body, they will become vast degree-of-freedom (DOF) systems with a need for vast numbers of actuators to power them. While humanoid robots such as the Honda P2 [1] and the Sony SDR-4X [2] already have more than 30 independent actuators or DOF, the human body has more than an order-of-magnitude larger DOF, actuated by over 600 skeletal muscles alone. In addition, countless smooth muscles assist in the circulation of blood by opening and closing vessels to provide energy to the body and regulate the body's temperature. Furthermore, each muscle is not just a single actuator, but consists of numerous segmented muscle fibers that can work in series and in parallel to produce wide ranges of forces and displacements. While the number of actuators is truly vast, the body is not continuously in motion and thus only a small percentage of the muscles are active at any one time. The same will be true for vast DOF humanoid robots, which creates an opportunity to share limited resources such as components for delivery of power.

In order to accommodate hundreds or even thousands of actuators in a compact body, the actuators must have a high power to weight ratio and there must be a scalable architecture for controlling and delivering power to them. If the actuators are structured and managed correctly, a robot could have more DOF by networking its resources. The fluidic heating and cooling of the body has inspired similar methods for artificial muscles. Recently, the idea of a *vasculated robotic flesh* was proposed, where a robot is imbued with a network of "blood vessels" for delivering energy to embedded fluidic actuators [3]. These fluidic actuators consist of compliant vessels containing Shape Memory Alloy (SMA) wires, which are contracted and extended by using combinations of electrical and fluidic power. These wet SMA actuators are capable of 200 MPa strength (800 times higher than human muscle [4]) and power to weight ratios on the order of 1 kW/kg (100 times greater than DC motors), while maintaining bandwidths of at least 2 Hz. Fluidic heating is not as fast as electrical heating, but bandwidths of 0.5 Hz have been achieved [5]. On the other hand, electrical activation yields an extremely low efficiency on the order of 0.1%, while fluidic activation has theoretical efficiencies reaching 3% [5]. Heat conduction with Peltier Modules has also resulted in bandwidths of 0.5 Hz [6], but is also inefficient.

Since SMA actuators are so compact, creating SMA bundles [7] and arrays [8] is a natural extension. In addition, wet SMA actuator arrays have been designed and implemented where networks of fluidic valves are used to direct hot and cold water to any actuator in the array [9]. The architecture allows N^2 actuators to be controlled with 2N valves. In addition, new control methods have been proposed to share the available resources among the actuators requiring attention at any given time. The performance of the wet SMA array has been simulated assuming ideal conditions, however many of the real fluidic characteristics of the system were ignored, such as the effects of the varying fluidic resistance and capacitance of the network.

In this paper, we extend this work by developing matrix control methods tailored for use with fluidic or wet actuator arrays, specifically dealing with the fluidic impedance of the system. We will develop answers to the questions of how to best define a measure of performance for the array as a whole, and how to optimize that performance in the light of the varying fluidic impedance. Finally, the control methods are implemented and verified on an experimental prototype.

II. DESIGN CONCEPTS

A. Wet SMA Actuators

Fluidic heating and cooling of SMA wires appears to be an ideal method to active them, but there are challenges to be addressed. The delivery of water to each actuator is affected by the fluidic resistance of vessels and valves the efficiency is affected by the heat lost to the environment. To reduce the amount of heat lost, it would be ideal to reduce the surface area of the fluid vessels. On the other hand, the fluidic resistance is a function of dimensions of the vessels and larger dimension would reduce the resistance. If a one to one ratio of actuator to control valve were used, the power to weight ratio and cost would suffer. By developing new network architectures, the ratio of valves to actuators can be decreased, and allow more actuators to be placed in a compact volume.

The wet SMA actuator consists of an SMA wire that is suspended in a hollow compliant capillary vessel that is able to accommodate the strain produced by the SMA when heated and allows fluid to encompass the wire. Each end of the wire and capillary is connected to a manifold that allows fluid to pass through the capillary and transfer the mechanical connection to the exterior of the actuator.

B. Matrix Manifold and Valve (MMV) System

Networked Actuation Architecture (NAA) has been proposed where multiple actuators are driven by a single switch (in this case a fluidic valve). Taking advantage of the fact that not all of the actuators in the system must be active at the same time, the NAA can greatly reduce the number of valves in the system; therefore significantly decreasing the size, the weight and the cost of the new system [2]. A Matrix Manifold and Valve (MMV) system is built on the basis of NAA and arranges the wet SMA actuators in an N-by-N array.

The structure of the MMV is scalable, such that 2N+2 valves route the hot and cold fluid and can activate any of the N^2 the actuators in the array individually. The array can also have multiple valves open allowing multiple actuators to be driven at the same time. The control commands to the system can be designed to maximize the performance of the system as a whole.

Row valves provide fluid to each row of the array (all actuators in a row have the same source line) and the exit end of the actuator is connected to its respective column valve (all actuators in a column have the same return) as seen in Fig 1. Turning a single row and column should exclusively activate the actuator at the intersection. To ensure that no fluid can flow backwards and take an alternate path through the array, influencing other actuators, every actuator requires a check valve. Multiple actuators in a single row or column can be simultaneously activated, as well as certain subsets of the matrix.

An additional 3-way valve has been installed to select between the hot and cold source and a second 3-way valve is used to return the hot and cold to the appropriate reservoir. This recycles the energy not absorbed by the actuators to maximize the efficiency.

Fig. 2 shows the implementation of a 4x4 actuator array, which is 100 mm x 100 mm x 200 mm in size. There are 16 silicone rubber capillaries of 1.6 mm inner diameter with 0.25 diameter SMA wire inside. There are 10 solenoid valves that control the fluid flow and a check valve at the end of each actuator.

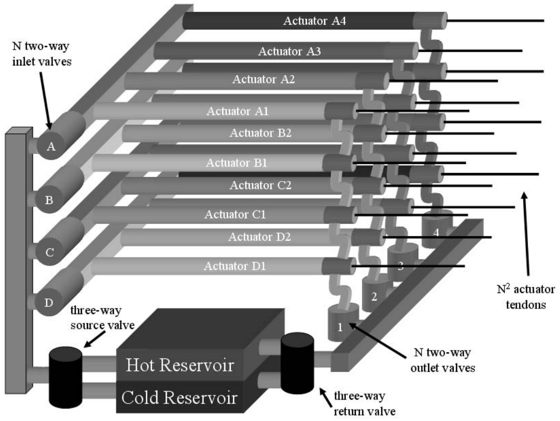

Fig.1 System diagram of wet SMA actuator arrays using matrix manifold and valve structure

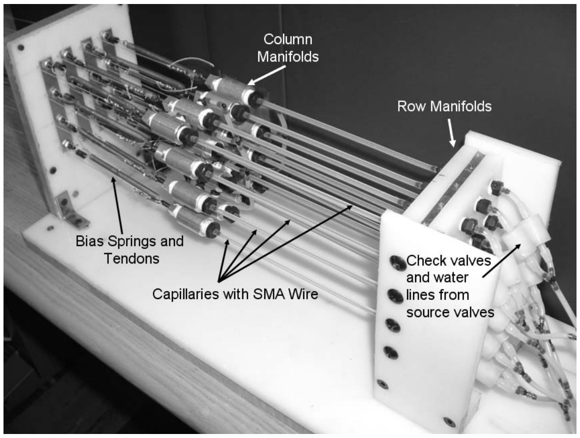

Fig. 2 Implementation of wet SMA actuator array

When multiple actuators are activated, the fluidic resistance of the array changes, and thus the flow rates within each actuator are subject to change depending on how many actuators are open. Since the controller must take into account the time it takes for fluid to propagate through the actuators, these changing resistances complicate the constraints on the controller. For our implementation, the valves are connected to a constant pressure source (170kPa). Due to various fluidic resistances, the flow rates when 2 valves are open compared to 4 valves are not equivalent, but the scheduler can accommodate to allow just enough time for the fluid to propagate through the system, given the equivalent fluidic resistance of the array.

III. CONTROL

A. Scheduler

The proposed MMV system has minimized the valves to 2N+2 with the ability of controlling N^2 actuators individually. With the ability of the MMV system to drive actuators at the intersections of the active rows and columns, a variety of combination of valves can be turned on. The SMA wire dictates that this is a ternary system (Hot / Cold / None) and requires at least one more control valve to switch between the hot and cold water sources. The SMA actuator is an analog device, that can take on any position between fully contracted to fully extended and to achieve this, each actuator may be driven with a hot water (contract), cold water(expand), or remain steady with no water. In order to maximize the response of the system, it is not desirable to control a single actuator and even less desirable to drive them in a sequential order. A scheduler must take the reference commands (IN) and maximize the control commands (OUT). In previous work [9], we proposed that the control command activate one row and any number of columns. This has been expanded to include multiple rows and columns and this would activate the actuators at the intersections. The final element that dictates the control command is the desired source of water (Hot/Cold or H/C). The scheduler identifies the maximum error (E) and then selects the row(R), column(C) and hot/cold valves that correlates to the errors.

$$[R, C, H/L] = \underset{i,H/L}{\arg} \underset{1 \le i \le N}{Max}[E^H_{Ri}, E^L_{Ri}, E^H_{Cj}, E^L_{Cj}, E^H_{Bijkl}, E^L_{Bijkl}] \tag{1}$$

The total errors are determined by the following equations; identifying the rows, columns and high or low power source.

High Error

$$e^H_{ij} = \begin{cases} e^H_{ij} = (x^d_{ij} - x_{ij}) & if\,(x^d_{ij} - x_{ij}) > 0 \\ e^H_{ij} = 0 & if\,(x^d_{ij} - x_{ij}) \le 0 \end{cases} \tag{2}$$

Low Error

$$e^L_{ij} = \begin{cases} e^L_{ij} = -(x^d_{ij} - x_{ij}) & if\,(x^d_{ij} - x_{ij}) < 0 \\ e^L_{ij} = 0 & if\,(x^d_{ij} - x_{ij}) \ge 0 \end{cases} \tag{3}$$

Total Low Error - E^L

Row (i) $E^L_{Ri} = \sum_{j=1}^{N} e^L_{ij}$ (4)

Column (j) $E^L_{Cj} = \sum_{i=1}^{N} e^L_{ij}$ (5)

Box (i,j,l,k) $E^L_{Bijkl} = e^L_{ij} + e^L_{il} + e^L_{kj} + e^L_{kl}$ (6)

- for all i,j,k,l where i < k and j < l

Total High Error E^H

Row (i) $E^H_{Ri} = \sum_{j=1}^{N} e^H_{ij}$ (7)

Column (j) $E^H_{Cj} = \sum_{i=1}^{N} e^H_{ij}$ (8)

Box (i,j,l,k) $E^H_{Bijkl} = e^H_{ij} + e^H_{il} + e^H_{kj} + e^H_{kl}$ (9)

- for all i,j,k,l where i < k and j < l

Multiple factors can influence the overall response of the MMV system. It has been proposed that the actuators be mechanically connected to one another in series or in parallel to achieve higher force or displacement. It may be more desirable to drive the column actuators or the row actuators, depending on how they are mechanically connected. These are examined in the modeling found in the next section and this will influence the overall response of the system.

B. Error selection

The scheduler is structured to maximize the control command; in turn reducing the error in the actual system to that of the desired. In previous work [9], two methods were used to determine the error that would be input to the scheduler. The first definition of error was focused on the position of the actuator and the second insured that no actuator was ignored for an extended amount of time. These have been re-examined and improvements have been identified when other definitions of error are used.

For now, the system is being analyzed as individual binary actuators with no relationship to one another. Each actuator receives a time stamped reference command and these are stored in a queue, so an actuator may have multiple reference commands waiting for the scheduler to address them. This structure allows for a variety of errors to be defined and the following ones will be explored in the modeling section of this paper.

1. Position Error – the error between the desired and actual position.
2. Delay – the time difference between the current time and that of the reference command's time stamp.
3. Delay Squared – the delay multiplied by the absolute value of the delay , insuring the direction is preserved
4. Sum of the Delays – the sum of all the delay for reference commands within the queue.
5. Queue length – This is the number of reference commands in queue.

These are only a few of the errors that can be defined and there is the possibility that they could be used together in some weighted fashion. Once the scheduler addresses the reference command, it is removed form the queue.

IV. Modeling and Results

A. Modeling and Constraints

The proposed system was modeled with MATLAB and the reference command and control commands are driven by the duty ratio, error selection and control selection. The system starts in a zero/cold state, in the extended position. Each actuator is commanded to change states (contract / expand) with a probability equal to the duty ratio. The duty ratio is defined as the average percentage of the actuators that change states in a single cycle. The change state command is given a time stamp and stored in a queue. The error is computed from the reference queue and sent to control selection. Once the actuator is selected and the control command is sent, the reference command is removed from the queue. The control command consists of three elements: rows, columns, and hot/cold.

Acknowledging that size and power limits are both constraints that must be addressed, the simulation of the 4x4 array limits the number of actuators that can change states at any one time to 4. The modeling takes the stance that time between reference commands is equal to the time for the fluid to propagate through the array when a 1x4 subset of actuators is addressed.

The constraint that at most four actuators can change states during one control command suggests three primary configurations that maximize the array structure. The first proposed is activating one row and any combination of column valves. The second is the transverse of the first; one column and any combination of row valves are selected. The final method is to turn two rows and two columns on; the intersection of these would active the four corners of a box. The columns and row do not need to be adjacent, so rows 1 and 4 and columns 2 and 3 could be turned on.

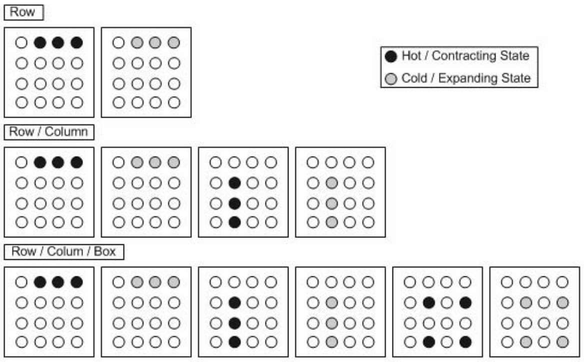

Fig. 3 Possible Scheduling Structure

If the scheduler is limited to only activate any of the actuators in a single row or column and the 4 corners of a box, the number of possible control commands that are available for the scheduler are:

Single Row / Multiple Columns

$$N(2^N-1) \tag{10}$$

Multiple Rows/ Single Column

$$N(2^N-N-1) \tag{11}$$

2 Rows / 2 Columns

$$[\tfrac{1}{2}N(N-1)]^2 \tag{12}$$

Since the control selection is ternary, there are twice as many control commands as that of a binary system. The possibilities may be reduced if the power source can not support that number of actuators and additional possibilities could be available if the restriction that more than 4 actuators at once is removed (2 rows by 3 columns, etc).

B. Results

To examine the proposed scheduling and error selection, a table of random reference commands was generated and used for all modeling results presented. As seen in figure 4, the 4x4 MMV system exhibits instability as the duty ratio approaches 25% or 1/N. This is expected with the control command being limited to activate four actuators at once.

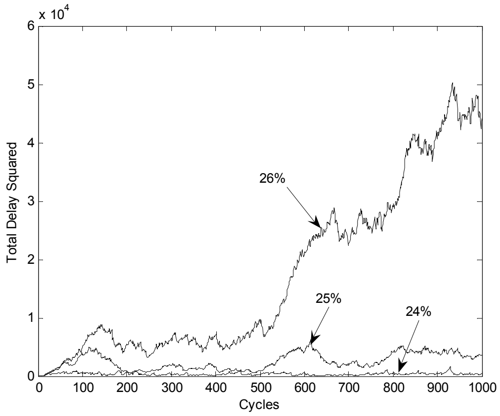

Fig. 4 Total delay squared vs. cycles (duty ratio = 0.25). Queue Length and Sum Delay errors produce similar response at this duty ratio.

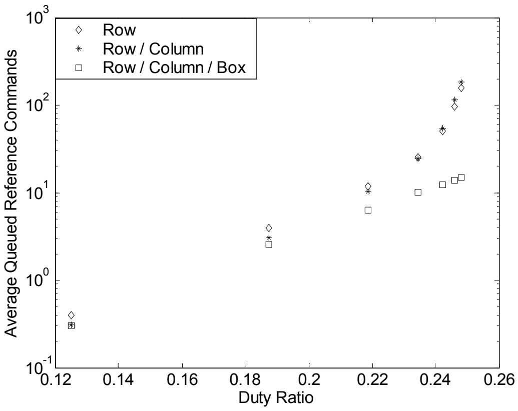

Fig. 5 Scheduler Selection: Average queued reference commands vs. duty ratio

Fig. 5 shows that using the Row/Column/Box scheduler significantly improves the response to the reference commands. The 36 additional control command possibilities from the box structure result in a reduction of a factor of approximately 10 in the average queued reference commands as the duty ratio approaches 25%. Fig 6 demonstrates similar results as the average total delay squared for the Box/Row/Column is about 100 times smaller than that of the Row and Row/Column Schedulers

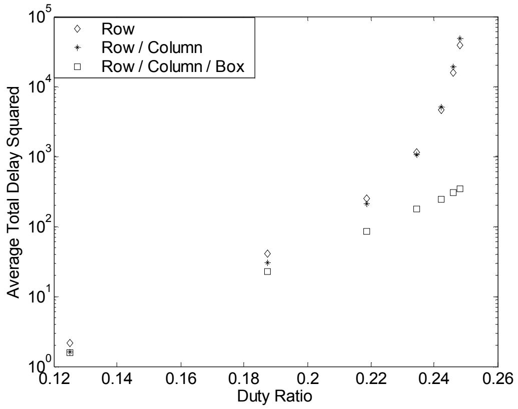

Fig. 6 Scheduler Selection: Average total delay squared vs. duty ratio.

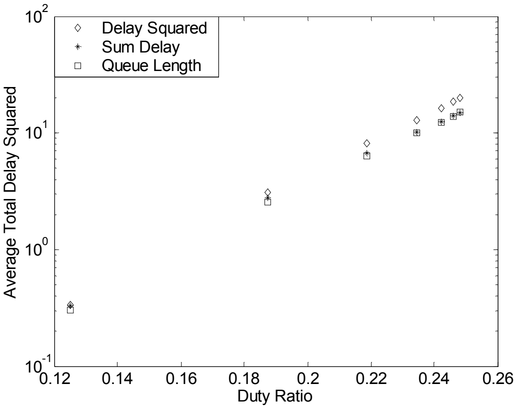

Fig. 7 Error Selection: Average queued reference commands vs. duty ratio.

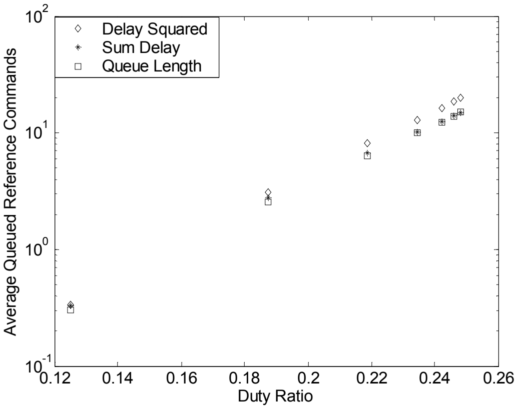

Fig. 8 Error Selection: Average total delay squared vs. duty ratio

Fig. 7 and 8 both demonstrate that the performance of the system improves when the definition of error is defined as the number of commands in the queue rather than as a function of the time stamp. The difference seems to disappear at lower duty ratio, but when the system is operating near capacity, it is clearly better to define the error as the queue length rather than the delay squared. This is significant since up until now, the delay squared was used to define the error [9].

Experimentally implementing this system raises design concerns when operating multiple actuators simultaneously. Even though water is provided by a constant pressure source, the flow rates from the various configurations are not uniform due to the changes in valve and vessel resistance. Experiments demonstrate that the impedance of the array is dominated by the resistance of the solenoid valves. Fig. 9 shows equivalent resistances when the various allowable combinations of valves are opened.

When a single actuator is active (1x1), the equivalent resistance is nearly double that of the 1x4 case, so the total flow is almost halved, but since there is only one actuator, the flow per actuator is increased. Therefore, even though we only activate a single actuator, less time is required for the fluid to propagate through the array, and thus the rate of actuation (number of actuators addressed per unit time) is not much less than the 1x4 case. Table 1 summarizes the experimentally determined flow rates for each case and their corresponding actuation rates.

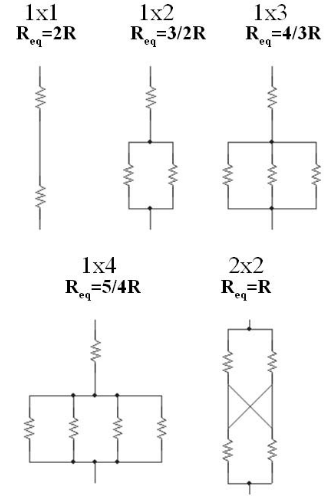

Fig 9 Equivalent Fluidic Resistances

Table 1: Theoretical activation rate (actuation per cycle)

Configuration	Theoretical Flow Rates (mL/min)	Actual Flow Rates (mL/min)	Relative Propagation Time	Actuation Rate (Actuations/Time)
1x1	170	170	T	1/T
1x2	113	105	1.6T	1.33/T
1x3	85	82	2.1T	1.44/T
1x4	68	60	2.8T	1.6/T
2x2	85	76	2.2T	1.79/T

The result is that the new scheduler uses a variable sampling rate that depends on the number of actuators being addressed, where previously the sample rate was constant [9]. The above simulations reflect this new type of scheduling.

IV. CONCLUSIONS

This paper presented the control logic to drive an array of wet SMA actuators utilizing a Matrix Manifold and Valve (MMV) system. This architecture results in a vast DOF system that minimizes the number of valves and optimizes the use of them. The 16 wet SMA actuators assembled in the 4x4 array (200mm x 100mm x 100mm) can produce actuation forces of up to 160 N when connected in parallel and achieve displacements of 64mm of displacement connected in series. 10 valves are used to drive the 4x4 system, but a 10x10 array of 100 actuators would require only 22 valves. In general, an array of N^2 actuators can be controlled by 2N+2 valves, resulting in a scalable architecture.

Results of simulations show that the new scheduler options and definition of error improve the performance of the system, especially as the duty cycle approaches the limit of 1/N for an array of N^2 actuators. Specifically, the new Row/Column/Box scheduling performs 10 times better than the old Row scheduler, and defining the error in terms of queue length is better than the time delay squared. In future work, we will investigate what happens when $N > 4$, and how the application (e.g. are the actuators connected mechanically in series or parallel) might affect the control strategy, and verify experimentally.

These methods could be used to create biologically inspired robots where a central vascular system (heating, cooling, and pumping) could provide the resources necessary to drive multiple arrays of wet SMA actuators located throughout an articulated body with vast DOF.

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