

# Control of a Scalable Matrix Vasoconstrictor Device for Wet Actuator Arrays

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*Abstract* – The Matrix Vasoconstriction Device (MVD) is a scalable mechanism that can control the fluid flow through a vascular network with  $n^2$  wet shape memory alloy (SMA) actuators using  $2n+2$  constrictors (control elements). This vascular network delivers hot and cold fluid to conductively heat and cool Shape Memory Alloy (SMA) muscles embedded in compliant vessels. The MVD mimics smooth muscles found in biological systems by constricting fluidic vessels to prevent flow. When released, the MVD does not add any fluidic resistance to the system, which has reduced the effective fluid resistance of the vascular network to 20% of the previous vascular system controlled by solenoid valves, therefore increasing the flow rate by a factor of 5.

With the MVD's increased flow rates, a cycling rate of one Hz has been achieved for a single actuator. The MVD has  $(2n-1)^2$  possible configurations, which allow fluid flow through a single or multiple vessels at the intersection of one or more released row and column constrictors. As the number of released vessels increases, the total fluid resistance of the system decreases and the total flow through the system increases. Releasing all the constrictors, the flow through a 4x4 array can produce 3.5 actuations per unit time (where the unit time is the time necessary to drive a single actuator).

This paper examines the operation of the MVD as it controls the ternary fluid flow (hot, cold, no flow) to an  $n \times n$  array of wet SMA actuators operating independently and operating columns of actuators that are connected mechanically series with each other.

Index Terms – Shape Memory Alloy, Matrix Vasoconstrictor Device, Wet SMA Actuator, Ternary Control.

## I. INTRODUCTION

In order for robots and exoskeletons to mimic humans and other creatures, they must have similar degrees of freedom (DOF) and be able to manipulate linkages to produce a wide range motion and forces. Many of the today's humanoid robots such as the Honda Asimo [1] and the Sony SDR-X [2] are operating with about 30 DOF, which is still an order of magnitude less than that of the human body [3]. These robots are also significantly heavier than a human of comparable size, due to heavy electric motors, gearing and batteries. When operating at the fastest rates, these robots have only enough power to operate for about 30 minutes. In order for these robots to approach the DOFs of humans, hundreds or even thousands of actuators will be needed and these actuators will need to be compact and have high power to weight ratios. Shape Memory Alloy (SMA) wires [4] and electro-active polymers [5] have been described as artificial muscles because they are able to contract when activated. SMA wires contract and extend as their crystalline structure changes due to temperature, and are capable of 200 MPa strength (800 times higher than human muscle) and strain between 4 and 8% [6]. But SMA actuators have limited cycling rates due to the cooling. Resistive heating and air cooling has achieved cycling rates of 2 Hz, but resistive heating has an efficiency of 0.1%. Heat conduction with Peltier modules has also resulted in bandwidths of 0.5 Hz [7], but is also inefficient. Fluidic heating and cooling has produced 1 Hz cycling rate and has a theoretical efficiency of 3% [8].

Biological muscles are supported by a circulatory system that delivers energy, removes waste and regulates temperature. Using this as inspiration, robotic vascular networks [9] have been implemented to deliver/remove heat from SMA actuators, and could also deliver the chemicals to activate electro-active polymers. Circulatory systems use smooth muscles to constrict blood vessels controlling the flow of blood through the system. This principle and was applied to the newly developed Matrix Vasoconstriction Device (MVD)[10], which controls the fluid flow through a vascular network by crushing the vessels.

Tied mechanically in series or parallel, these artificial muscles could be bundled like biological muscles to produce a variety of displacements and forces. To implement large systems of actuators, scalable control architecture must be used to manage the control inputs and hardware. The MVD was developed based on a scalable architecture that controls the flow to  $n^2$  vessels using  $2n$  constrictors. A 4x4 MVD has been used to control the fluid flow to 16 wet SMA actuators that are each able to produce a 10 N / 10 mm stroke [10].

This paper will expand the control of MVD from previous work on  $n \times n$  wet array [11], to maximize the actuation rate of an  $n^2$  wet SMA actuators accounting for increased flow rates. The possible MVD configurations are identified and their influence on the fluid propagation through the system. Two methods of identifying the best control command will be defined to maximize the actuation rate, thereby reducing the error the fastest. Finally, the actuators will be linked mechanically in series and an algorithm to produce the most time effective control command will be described.

## II. BACKGROUND

### A. Wet Shape Memory Alloy (SMA) Actuator

The wet SMA actuator [9] imbeds an SMA wire in an axial compliant vessel that allows fluid to pass over the wire. The ends of the actuator provide the mechanical, electric and fluidic inputs/outputs to the actuators. The mechanical connections transfer the force and strain of the wire to exterior attachment points. Electrical power can be used to resistively heat the SMA wire above the transformation temperature, and fluid can convectively heat or cool the SMA wire above or below the transformation temperature respectively. Controlling the exact temperature of the SMA wire, and therefore the strain of the wire, is extremely difficult. Thus for many applications the controlled state of the wire is treated as binary, either completely contracted (1) or extended (0). In this paper, the actuators will be controlled in a binary fashion, producing discrete displacements.

### B. Bundling Large Number of Wet SMA Actuators

These wet SMA actuators are very compact, suggesting that they can easily be bundled together in arrays. However to individually control the electric current and the fluid flow, each

actuator would require a power transistor and fluidic valve, increasing the size and weight of the actuator array and the number control outputs in proportion to the number of actuators. Assuming that on average, only a small percentage of the actuators must operate at a given time, Network Array Architecture (NAA) [12] has been selected to allow  $2n$  switches to control the  $n^2$  devices, where the transistors/valves could be shared by multiple actuators allowing the system to be more scalable. The wet SMA actuators are arranged in an  $n \times n$  array. On the source side of the actuators, each row of actuators has a common connection and the flow from the source is controlled by a single-throw single pole switch. On the sink side of the actuators, each column of actuators has a common connection and the flow to the sink is controlled by a switch. In order for an actuator to operate, it must have a path from the source to the sink, so at least one row and one column switch must be activated to allow flow through an actuator. One problem with NAA is that there is the potential that flow may find an alternative path through the system, and therefore diodes/check valves must be inserted in series with each device to prevent this. When multiple switches are activated, the actuators that intersect those switches are active and so there are only certain patterns that can be produced. With this architecture, 100 ( $10^2$ ) devices can be controlled by 20 switches.

### C. Matrix Vasoconstrictor Device (MVD)

Fluidic NAA was first applied to wet SMA actuators in the Matrix Manifold Valve (MMV) system as seen in Fig. 1, but parasitic effects were observed. The fluidic system is not analogous to the electrical system, having differences in the networked impedances causing the parasitic effects. First, unlike an electrical switch, solenoid valves have significant fluidic resistance; and second, the axial compliance of the vessel stores fluid when under pressure, creating a fluidic capacitance. To eliminate the fluidic resistance of the solenoid valve, a pneumatic constrictor valve was developed that crushes the wet SMA actuator vessel and when released it does not introduce any fluidic resistance to the system. To minimize the build up of pressure (increasing volume of the capillary), the constrictor valves were collocated at the source side of the actuators by expanding the constrictors to single-throw multi-pole valves as seen in Fig. 2 and 3. These two features were built in to the newly developed Matrix Vasoconstrictor Device (MVD), Fig. 4. The arrangement of the multi-pole constrictors in the MVD prevents undesired flow and eliminates the need for check valves. The total fluidic resistance of the MVD system has been decreased by a factor of 5 over the MMV system, increasing the fluid rate by 500%. A 4x4 MVD has been prototyped with 500mm wet SMA actuators that can contract and extend at a rate of 1 Hz. Since the MVD only controls the fluid flow through the system, two additional vasoconstrictor valves are added to the system to control the hot and cold water.

### D. Ternary Control of Wet SMA Actuators

As stated before, each SMA actuator will operate as a binary actuator, and therefore an  $n \times n$  array of wet actuators has the same number of configurations as a binary number with  $n^2$  dimension. For a 4x4 array of actuators, there are 65536 unique states that the complete system can be in. For

this work, the state of each actuator will be controlled by fluid flow through the capillaries and no resistive heating will be used. For the wet SMA actuator to change states, heat must be added or removed to achieve the desired transition temperature; to remain in the same state, the temperature must remain constant. Therefore the control system must be ternary, allowing for positive, negative and zero heat transfer. A 4x4 array will have  $3^{16}$  or 43,046,721 possible desired independent heat transfer processes.

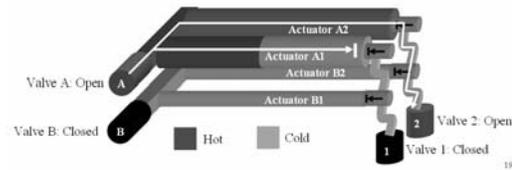


Fig. 1 Matrix Manifold and Valve System with parasitic effects.

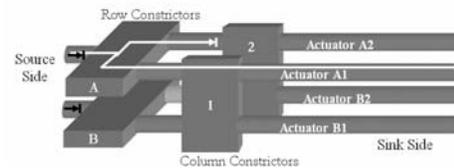


Fig. 2 Matrix Vasoconstriction Device.

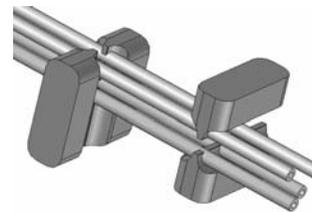


Fig. 3 Collocated single-throw multi-pole constrictors of the MVD.

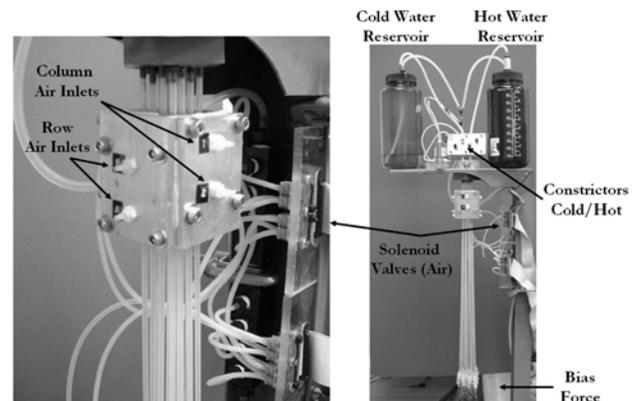


Fig. 4 MVD and complete system.

### E. Operating the Actuators Mechanically in Series

The MVD provides a scalable solution to deliver fluid to an array of wet SMA actuators, but each actuator can only produce a binary output, limiting the applications where it can be implemented. However, if a column of actuators were joined mechanically in series to one another, e.g. in a pulley assembly (Fig. 5), this would allow a tendon to take on  $n+1$  discrete positions between 0 and  $n$ . The pulley assembly doubles the displacement of each actuator, but the applied force by the tendon will be cut in half. This could be compensated by increasing the diameter of the SMA wire.

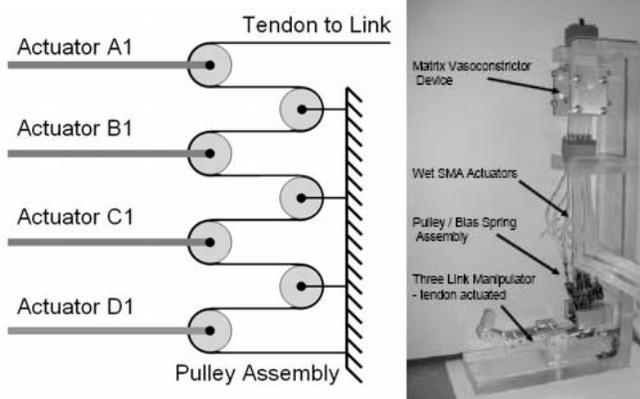


Fig. 5 Actuators attached mechanically in series and 3-DOF robotic finger powered by wet SMA array.

Joining a column of actuators in series does reduce the number of output possibilities of the entire system to  $n(n+1)$ , but there are multiple actuator combinations that can produce the desired output. If the desired output of entire column is  $d$  (contracted actuators) and the number of actuators in the column is  $n$ , then the number of possible combinations of a single column is described by:

$${}_n C_d = \frac{n!}{(n-d)!d!} \quad (1)$$

For  $n=4$  and  $d=2$ , the possible configurations are:

$\begin{bmatrix} 1 \\ 1 \\ 0 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 1 \\ 0 \\ 1 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 1 \\ 0 \\ 0 \\ 1 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 1 \\ 1 \\ 0 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 1 \\ 0 \\ 1 \end{bmatrix}$	$\begin{bmatrix} 0 \\ 0 \\ 1 \\ 1 \end{bmatrix}$
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Accounting for the  $n$  columns of the array, the maximum number possible desired states ( $p_{max}$ ) that can produce a desired  $1 \times n$  reference command is defined by:

$$p_{max} = \left( \frac{n!}{(n-d)!d!} \right)^n \quad (2)$$

The algorithm for operating the wet actuators will be developed in the following section based on how the MVD can control the fluid flow through the system

### III. CONTROL LOGIC

#### A. MVD Configuration

Each constrictor of the MVD is a binary device that is either open (1) or closed (0) and the MVD arranges them into  $n$  rows and  $n$  columns. When a set of constrictors are arranged into a row or column, the set can be considered to be binary number and therefore each set would have  $2^n$  configurations. Table 1 shows the configurations that a set of 4 column constrictors can be in; the transpose of these would define the configurations of a set of row constrictors. When there are zero constrictors open, there would be no flow through the system, so 0000 would not produce any change in the system and leave  $2^n-1$  active configurations. Since the MVD arranges the constrictors in an  $n \times n$  array based on NAA, at least one row and one column constrictor must be open to produce flow through the actuator at the intersection. When this is expanded to allow multiple rows/columns to be released,  $(2^n-1)^2$  configurations of open constrictors can allow fluid flow to some submatrix of the system. Table 2 shows the number of occurrences for each of

the possible configurations in a  $4 \times 4$  array. The two additional constrictors, controlling the hot and cold fluid, double the number of configurations that the MVD can operate in.

Table 1 Binary number representation of open(1)/closed(2) constrictors.

Number of Open Constrictors	Column Configurations					
	0	0000				
1	1000	0100	0010	0001		
2	1100	1010	1001	0110	0101	0011
3	1110	1101	1011	0111		
4	1111					

Table 2 Submatrix Configurations of  $4 \times 4$  MVD.

Submatrix Configuration	1x1	1x2 2x1	1x3 3x1	1x4 4x1	2x2	2x3 3x2	2x4 4x2	3x3	3x4 4x3	4x4
Occurrences	16	24 24	16 16	4 4	36	24 24	6 6	16	4 4	1

Since the number of control configurations of the MVD system is only a small percentage of the  $3^{n^2}$  actuator configurations that may be desired, there is an understanding that a complete solution may not be achieved with a single control cycle, as seen in Fig. 6. The best solution will be based on material explored in following sections.

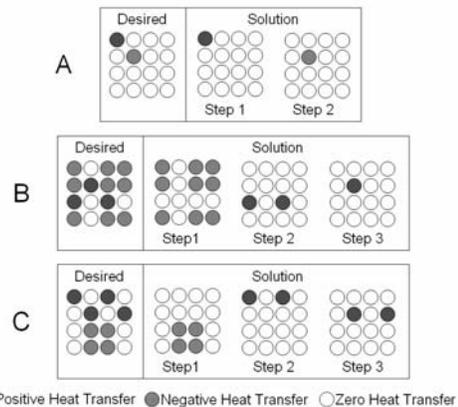


Fig. 6 Desired heat transfer processes vs. output of MVD.

#### B. Fluidic Resistance / Actuation Rates / Time Constants

The convective heating and cooling of the SMA wire is a function of the fluid temperature along the length of the wire. In order for the fluid surrounding the wire to change temperature, the original water must be displaced by a new volume of fluid, which takes a discrete amount of time based on the volumetric flow rate. Fig. 7 shows the MVD wet actuator array assembly and an equivalent electrical circuit model where the actuators are in parallel with one another. Since the actuators are the primary source of fluidic resistance and are operating in parallel, the hot and cold reservoirs provide fluid at a constant pressure, delivering the most effective fluid flow. The manifold resistances are lumped into the actuator resistances because the variance in paths in the manifold is insignificant. The constrictors are shown as single-throw single-pole switches for convenience, but the letters and number refer to the row and column constrictors and both must be released to complete the circuit. For example in order to have flow through B2, B4, D2, D4, the row constrictors B and D and column constrictors 2 and 4 must be released.

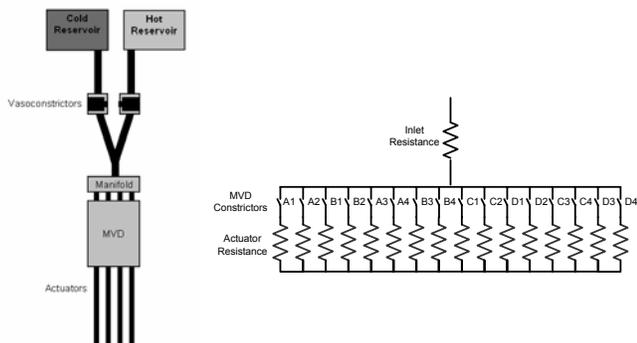


Fig. 7 MVD wet SMA actuator array and electric circuit schematic.

The total equivalent resistance,  $R_{eq}$  of the system can be defined by the resistance of the inlet,  $R_{inlet}$ , the resistance of single actuator,  $R_{actuator}$ , and the number of actuators being driven,  $d$ , as seen in Equation 3.

$$R_{eq} = R_{inlet} + \frac{R_{actuator}}{d} \quad (3)$$

Fig. 8 shows how the equivalent resistance of the entire system varies with respect to the number of actuators being driven. With a constant pressure fluid source, the total fluid flow of the system is inversely proportional to the resistance and therefore the total flow increases with the number of driven actuators. Fig. 9 shows that as the number of driven actuators increases, the actuation rate (actuators per unit time) increases, and therefore it is beneficial to drive more actuators simultaneously. Re-examining Fig. 6, the error of the system is eliminated faster when the larger submatrix is controlled first, followed by the remaining smaller submatrix. Table 3 shows the time factor,  $\tau$ , for each MVD that will allow the fluid to completely propagate through the system relative to the time for it to propagate through a single actuator.

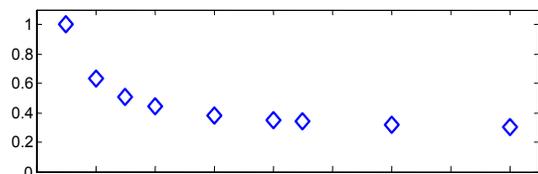


Fig. 8 Relative fluidic resistance vs number of driven actuators

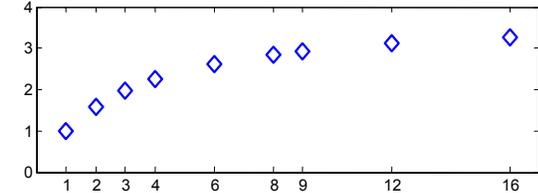


Fig. 9 Relative actuation rate vs number of driven actuators

Table 3 Time constant relative to single actuator

# of actuators	1	2	3	4	6	8	9	12	16
T	1	1.3	1.5	1.8	2.3	2.8	3.1	3.9	4.9

C. Identifying the Most Effective Configuration

In order to identify the largest configuration/submatrix that will produce the highest actuation rates and reduce the error the fastest, all of the  $2(2^n-1)^2$  configurations that the  $2n+2$  MVD

system can produce must be evaluated against the error of the system. The flow chart shown in Fig. 10 illustrates the method used to identify the most effective configuration of the MVD.

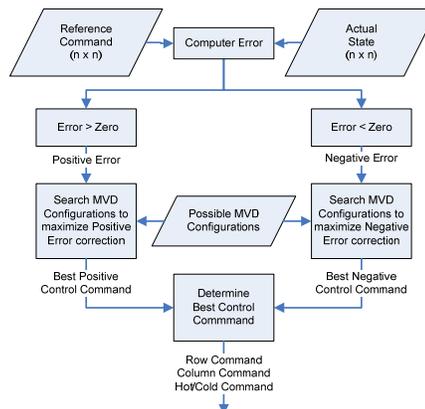


Fig. 10 Flow chart for standard control method.

The error is defined by difference in the desired state (reference command) and the actual state of each actuator. Since the MVD system has a single fluidic input, the best configuration can only provide either hot or cold fluid; therefore a solution for both positive and negative heat transfer processes may be found. Each possible configuration is tested against the positive/error and is considered valid if it only produces the desired heat transfer process. The best configuration is then determined by which valid solution maximizes the error reduction and then compared against the other heat transfer process. The best configuration is then sent to the MVD by activating the row, column and hot/cold constrictors.

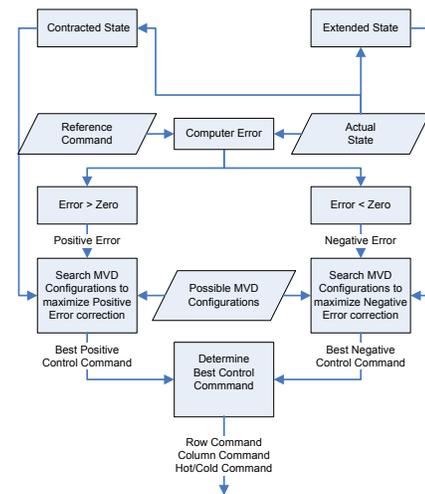


Fig. 11 Flow chart for overdrive control method.

A variation of the standard method, called the Overdrive method (Fig. 11), identifies larger MVD configurations that will on average have higher actuation rates than the standard method. The standard method allows only control commands in which fluid is delivered to actuators whose states need to be changed, whereas the overdrive method allows for superfluous flow to be delivered to other actuators that are already at that desired temperature. This is less efficient, but potentially faster. Using Fig. 12 as an example, the standard method would

involve two steps to produce the desired state, while the overdrive completes the process in a single step because it can pass hot fluid across the already contracted actuator without influencing its state.

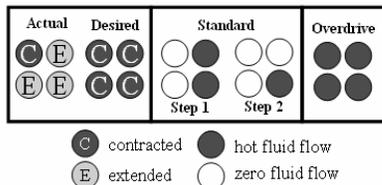


Fig. 12 Standard and overdrive method comparison.

The relative times to complete these solutions are  $2.3\tau$  and  $1.8\tau$  respectively, showing that it is faster to use the overdrive method. However there are certain cases where the standard method is at least as fast, and the process for selecting the best configuration must manage these cases. Both methods will be examined in next section.

When a column of actuators are joined mechanically in series, the reference command for the system will be a  $1 \times n$  array. Since there may be multiple combinations of desired states that will produce the desired displacement, each of the possible combination of desired states should be tested. The possible desired states can be identified by comparing the actual state of the system to the reference command. These possible desired states can then be examined by the standard or overdrive methods to identify the control command that will maximize the output of the MVD (Fig. 13).

IV. SIMULATIONS

As a basis for testing the performance of the MVD and the control algorithms, a duty ratio is defined as the average percentage of actuators that can change state each reference command cycle. For each reference command cycle, a random number between 0 and 1 is assigned to each actuator. If the random number is less than the duty ratio, the actuator is to change states, producing a difference between the actual and desired states. Because the desired states may not be achieved in a single control command cycle, the references commands are added to a queue. If the change in state for an actuator is achieved, it is removed from the queue. If it has not been addressed and another reference command is sent to the actuator, the new command will be held and addressed once the old command is addressed and removed from the queue. If on average, more elements are added than removed, and the queue grows without bounds, the system will be considered unstable.

Fig. 14 and 15 show the total number of queue elements vs. the number of reference command cycles that have transpired for the standard and overdrive methods, respectively, for a  $4 \times 4$  array of wet SMA actuators. The reference commands were added to the queue at a rate equal to the time necessary to activate a row of 4 actuators. When the duty ratio is below 0.27, the system remains stable. At duty ratios between 0.27 and 0.29, the system exhibits marginal stability. As seen in Fig. 15, the system remains stable until about 3500 cycles, at which this point it goes unstable. Due to lack of foresight, it gets stuck in a repeating

sequence of cycles where only 4 actuators are being commanded to change states, while more than 4 reference commands are added to the system. The cycle at which the system becomes unstable varies with the random reference command. At a duty ratio of greater than 0.29, the system immediately goes unstable. In contrast, using the overdrive method, the system remains stable up to  $\sim 33\%$  and does not exhibit marginal stability at any duty ratio as seen in Fig. 15.

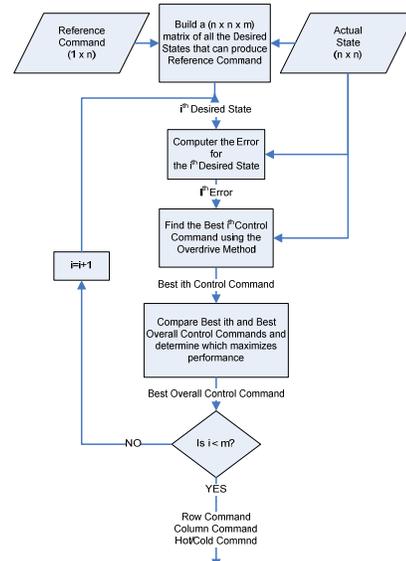


Fig. 13 Method to identify the most effective desired state and control command for series operation.

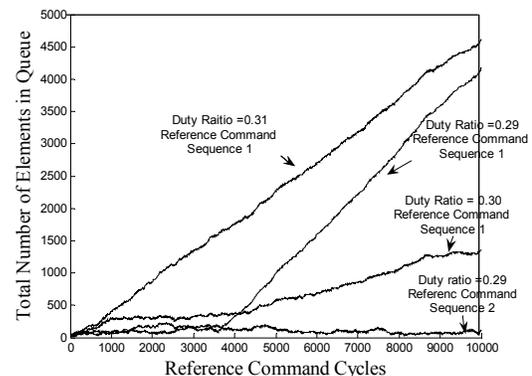


Fig. 14. Standard method system response: total number of elements in the reference command queue vs. the reference command cycle.

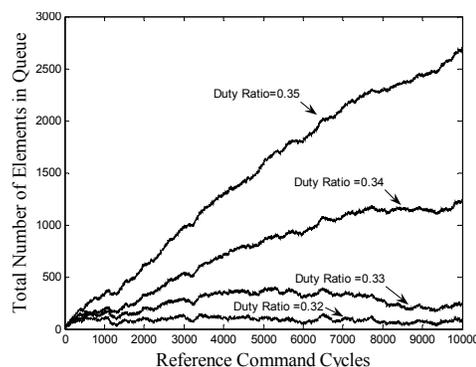


Fig. 15 Overdrive Methods system response: number of elements in the reference command queue vs. the reference command cycle.

When a column of  $n$  wet SMA actuators is connected mechanically in series, it functions as a single actuator, where the positional resolution is determined by the number of rows. The algorithm diagrammed in Fig. 14 is able to identify all of the valid desired states that will form the  $1 \times n$  reference command. The  $j^{\text{th}}$  element of the reference command is associated with the desired position of the  $j^{\text{th}}$  column. Fig. 16 shows the system response when each desired actuation is completed before a new reference command is input to system. The peaks occur when a new desired reference command is added to the system and the valleys occur when the system has completed the desired actuation. On average, 1.7 actuations occur per unit time, where 1 unit of time is the time necessary for the fluid to propagate through a single actuator. The actuation rate will increase as greater demand is placed on the system. Currently the concept of a duty cycle is not defined for a system where the actuators are connected in series. This is a focus of current research.

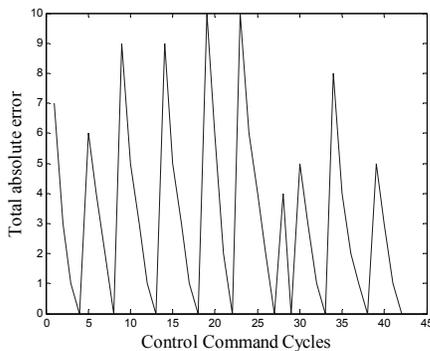


Fig. 16 System responses when column actuators are connected in series.

The difficulty in identifying the best desired state as  $n$  increases is due to the number of possible valid desired states and the possible MVD configurations. The maximum number of iterations ( $i_{\max}$ ) that the algorithm must perform is given by:

$$i_{\max} = 2(2^n - 1)^2 \left( \frac{n!}{(n-d)!d!} \right)^n \quad (4)$$

As evident, this number of computations does not scale well with increasing number of actuators. Future research will focus on identifying a more scalable algorithm for matching possible desired states with possible MVD configurations.

### V. CONCLUSIONS

This paper presented methods for controlling an  $n \times n$  array of wet SMA actuators utilizing a scalable Matrix Vasoconstrictor Device (MVD). The MVD is able to control the flow to  $n^2$  wet SMA actuators with only  $2n+2$  control elements using row and column addressing. An algorithm were developed to search through the  $2(2^n-1)^2$  possible control commands for the one that most quickly reduces the error between the desired and actual actuator states. Furthermore, an optional overdrive algorithm was developed that allows for even faster error reduction by allowing redundant fluid to be delivered in certain configurations. Although this results in faster actuation rates, it does

decrease the energy efficiency of the system. Future work will seek to frame this as an optimal control problem where an optimal combination of speed and efficiency is specified. Using the overdrive method, the system is able to operate at duty ratio of up to 0.33, producing actuations rates that are 3.5 times that of single actuator. Finally, the algorithms were adapted for the case in which whole columns of actuators are connected mechanically in series to create larger actuations with  $n$  intermediate positional states. In this case, there is not a unique reference input corresponding to a given desired state and future research will focus on identifying a more scalable algorithm for matching possible desired states with possible MVD configurations. Propane, liquid nitrogen, or other high energy density power sources could be used to heat and cool the water. Our current wet SMA actuators are 500mm long (20mm stroke, 9N) and have a mass of 0.010 Kg. The  $4 \times 4$  MVD actuator array assembly weighs 0.5 kg (0.03kg/actuator) where a wet SMA actuator controlled by a solenoid valve weighs 0.08kg. Additional research is currently focused on developing a pumping system based on wet SMA actuators to produce the low pressure fluid source that would deliver hot/cold water to the actuators. Overall power densities and energy efficiencies of the entire system including actuators and pump are yet to be determined.

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