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DESIGN AND CONTROL OF NOVEL EMBEDDED SMA ACTUATORS

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ABSTRACT

A novel shape memory alloy (SMA) actuator consisting of a cylindrical rod with a single off-axis embedded one-way SMA wire is first described. The actuators, acting as both actuating elements and executing elements, are compact enough to be used in miniature robot system. The practical specifications of the SMA wire and the flexible rod were determined based on a series of formulae. The mechanical properties of the actuator are also investigated.

After time domain open loop experiments and simulation, the simple model, a single integrator, is derived. A variable structure controller was then applied to the novel actuator. The feedback switches according to the sign of the curvature error. It was verified that the controller could realize smooth and robust control of the actuators.

Keywords: *SMA; elastomeric rod; actuator; variable structure control*

1. INTRODUCTION

As control and robotic systems continue to decrease in size and weight, so must their respective component. Actuators, the driving mechanism behind these systems, play a critical role in the system design and typically rely on electric, hydraulic, or pneumatic technology. Among most actuators used in robot system, SMA actuators have a clear advantage in strength to weight ratio. With the high inherent strength of SMA comes the advantage of being able to implement direct drive devices. Direct drive devices eliminate the use of gears with their inherent problems of backlash and wear.

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Further, with the increased interest in mechatronics, SMA actuators with their silent, smooth and lifelike motions are easily adapted to miniaturization in design.

A SMA, which is annealed at a certain temperature, can memorize the shape. When it is heated above the transition temperature, the deformed SMA can recover its original shape. We call the special ability of SMA shape memory effect (SME). Materials that exhibit shape memory only upon heating are referred to as have a one-way shape memory. Some materials also undergo a change in shape upon recooling. These materials have a two-way shape memory. Generally, the displacement and force occurred by the one-way SMA is more than that of the two-way SMA. As a representative one-way SMA actuator, Nitinol capable of up to 8.5% strain recovery and 180Mpa stress restoration with many cycles. So, it is used very widely.

In 1984, Honma[1] demonstrated that it is possible to control the amount of actuation by electric heating, thus opening their use in robotic application. Kuribayashi proposed an antagonistic pair of fiber for the operation of a rotary joint in 1986[2]. This is one of the most common configurations for a SMA-actuated joint, as shown in the Fig.1. Example of the use of this actuator mechanism in robotic-type applications include the inverted pendulum described by Hashimoto[3], and an inter-phalangeal actuator for robotics fingers, reported by Bergamasco[4]. A similar mechanism, which replaces one of the active wires bias spring, has been applied to a walking biped robot[3] and a robotic hand[5].

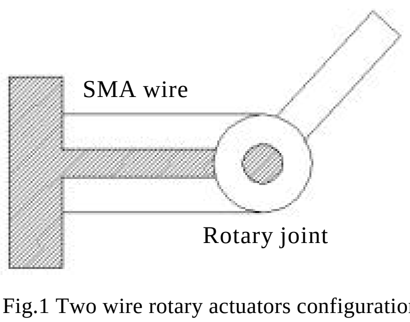

Fig.1 Two wire rotary actuators configuration

Several researchers have implemented shape memory technology for use in articulated hands. In 1984, Hitachi produced a four-fingered robotic hand that incorporated twelve groups of 0.2mm fibers that closed the hand when activated. Dario[6] proposed an articulated finger unit using antagonistic coils and a heat pump in 1987. Gharaybeh and Burdea[7](1995) fit several SMA springs to the Exos Dextrous Hand Master for use as a force feedback controller.

Among most of the designs of robot hand using SMA actuators, we usually see the separation between actuating elements and executing elements. So, the structure is still complex, which hamper the further using in miniature robot system. Moreover, the cartoon motions of traditional SMA-actuated robot hand hamper the using in grasping and fine manipulation. To solve the problem, we present a novel SMA actuator.

2. STRUCTURE AND MECHANISM

The actuator is actually a cylindrical rod with a single off-axis embedded one-way SMA wire. The rod is molded at temperatures below the transition temperature of the SMA wire. And the SMA wire, which is trained to shorten upon heating, embedded to the rod with a constant distance from the geometric center of the rod.

Heating the SMA wire specimen with the proper thermo-mechanical treatment will result in strain recovery with the ability to perform work, and, in the case of a rod embedded with axis SMA wires, the contraction of the wire will cause a distributed force to act upon the rod. Since the wire is not located on the neutral axis of the rod, the actuation force also results in a moment, which causes the rod to bend. Upon cooling, the SMA wires are stretched out by the flexible rod through interfacial shear, the rod return to a straight shape. So this constructs the two-way reversible actuating elements.

3. MODELING AND PARAMETRIC DESIGN

The theory of flexible rods with embedded line wires has been developed by Lagoudas and Tafjbakhsh[8] to account for the deformations of elastomeric rods with shape memory alloy (SMA) wires envisioned for shape control applications. Our actuator is the specific case of plane deformations of a rod, as shown in Fig.2 and Fig.3.

$$\frac{dF_1}{ds} + k_2(F_3 + F^a) = 0 \quad (1)$$

$$\frac{dF_3}{ds} - k_2 F_1 + \frac{dF^a}{ds} = 0 \quad (2)$$

$$\frac{dM_2}{ds} + (1+e)F_1 - d^a \frac{dF^a}{ds} = 0 \quad (3)$$

The equilibrium equation of the rod reduce in this case to the set of three Eqs.(1)-(3)

$$M_2 = EI_2 k_2 \quad (4)$$

$$F_3 = AEe + EI_2 k_2^2 \approx EAe \quad (5)$$

for the shear force F_1, axial force F_3, and bending moment M_2.

The constitutive equation for the rod are assumed to be:

$$F^a = A^a \sigma^a = A^a E^a [e - k_2 d - \varepsilon^t - \alpha^a (T - T_0)] \quad (6)$$

And the constitutive equation for the line SMA wire is approximated by the following:

Where k_2 is the bending curvature, e is the elongation of the rod, and F^a is the actuation force of the SMA wire, E^a, E are young's modulus of the line wire and rod, and A^a, A are their cross-sections, respectively, I_2 is the moment of inertia of the cross-section of the rod. The distance of the wire form the axis of the rod is denoted by d.

Since the average shear stress on the cross section of the rod has insignificant effects upon the elastomer[9], an approximation F_1=0 may be introduced to simplify the solution.

$$F_3 + F^a = 0 \quad (7) \qquad M_2 - F^a d = 0 \quad (8)$$

The expressions from Lagoudas and Tadjbakhsh are now revisited. The rod equations can be simplified to :

$$k_2 = \frac{\alpha\beta d}{1 + \beta(1 + \alpha d^2)} [\varepsilon^t + \alpha^a (T - T_0)] \quad (9)$$

After substituting the constitutive equations into Eqs.(7)-(8), the curvature is

$$e = \frac{\beta}{1 + \beta(1 + \alpha d^2)} [\varepsilon^t + \alpha^a (T - T_0)] \quad (10)$$

found to have the following expression:

And elongation e of the centroidal line of the rod is given by:

The constant are defined as $á=A/I_2$ and $â=E^aA^a/EA$. The deformation of the rod is then calculated in terms of the curvature k_2, ie:

$$k_2 = \frac{d\theta}{ds} \quad (11)$$

$$u_1 = \int_0^s (1+e)\sin\theta\, ds + u_1(0) \quad (12)$$

$$u_3 = \int_0^s (1+e)\cos\theta\, ds + u_3(0) \quad (13)$$

For our actuator, the boundary conditions are: $u_1(0)=u_3(0)=0$, since k_2 is constant, the deflections u_1 and u_3 can be explicitly integrated:

$$u_1(s) = \frac{1+e}{k_2}(1 - \cos k_2 s) \quad (14)$$

$$u_3(s) = \frac{1+e}{k_2}\sin(k_2 s) \quad (15)$$

Fig.4 is the curve of the normalized curvature, k_2R, versus the normalized distance, d/k_2, of the wire to the centroid of the rod. It is interesting to see that the curvature, k_2, is not always increasing monotonically with increasing of the distance d. The reason is that the wire is a strain-acting element. Although it can generate a larger moment for given amount of actuation force if placed farther away from the center of the rod, it also relaxed more by bending. Thus the total actuation effect may be less. The optimal distance depends on the ratio **b**.

Fig.5 presents the comparison of the theoretical prediction with experimental data. The geometry and material data of the rod are r_0=0.25mm, R=8mm, d^{max}=0.08, l=40mm, E^A=120Gpa, E^M=50Gpa. The maximum displacement error in x_1 direction is about 1.5mm.

4. CONTROLLER DESIGN

4.1 Background

A considerable amount of work has been concerned with the modeling of shape memory alloy actuators, while relatively less attention has been paid to the design of feedback control laws. Many feedback control techniques reported in the literature applied to shape memory alloy actuators are in fact linear compensators such as P, PD or PID controllers, or close cousins.

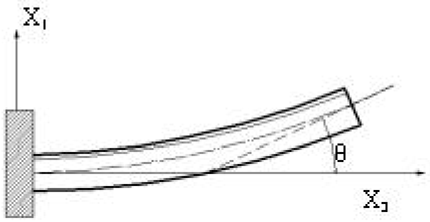

Fig.2 Configuration of rod

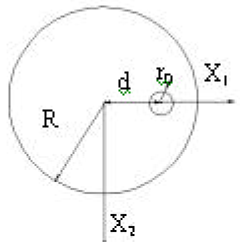

Fig.3 Cross section of rod

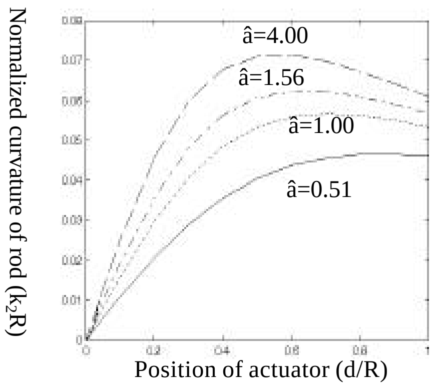

Fig.4 Maximum deflection of the rod versus the normalized position of the actuator

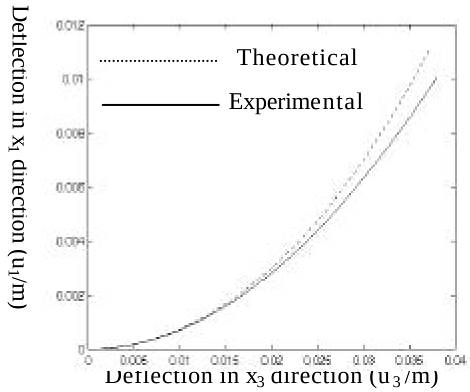

Fig.5 Deflection of the rod

The dynamics of shape memory actuators are predominantly nonlinear since the energy conversion principle, from heat to mechanical, relies on exploiting phase transitions in a metal. This creates at least significant hysteresis in addition to many other nonlinear effects with or without memory. In addition, the detailed properties of the dynamics of shape memory alloys vary widely with their metallurgy content, fabrication process, training techniques, aging, and ambient conditional thus a great deal of parametric uncertainty is involved. Moreover, most of the detailed descriptions of their underlying physics are often not very useful for controller design, and in the case of linear controllers one usually ends up with an overly conservative design.

There are several nonlinear control techniques available, however, due to the large uncertainty in plant parameters, several were immediately discarded, such as those relying on precise nonlinear identification, adaption, and feedback linearization. Using describing functions was also ruled out as this would again result in an overly conservative controller. This naturally led to the use of robust variable structure control.

4.2 Motivation for variable structure control

The over whelming advantage of variable structure control is that relatively few parameters representing the knowledge of the physical properties of the plant need to be known, since only inequality conditions need to be satis fied in the design [10]. It is often stated that a disadvantage of variable structure control is the discontinuous nature of the control signal, which may cause problems in actuators in terms of ringing, excessive dissipation, and excitation of unwanted dynamics in the plant being driven by these actuators. These problems sometimes can be solved by the introduction of smooth switching laws and boundary layers in the vicinity of the so-called sliding surfaces.

For shape memory alloy actuation, switching is not a problem: the mechanical energy is derived from heat which makes the actuators naturally low pass and thus the higher order dynamics are undisturbed by step or impulse inputs. Moreover, the robustness properties of variable structure control combined with the modeling difficulties of shape memory alloy actuators creates considerable incentive to apply the former to the later. As previously mentioned, one great attraction of shape memory allow actuators is the possibility for miniaturization. With variable structure control, the energy throttling device can be as simple as a single FET switching current on and off from a power bus, thereby opening a path toward a mechatronic-type high degree of integration with actuation, sensing, control and energy throttling including in a single unit.

4.3 Coarse Modeling from the Open Loop Response

The time domain open loop response to a step of input current applied to the actuator can be seen in Figure 6. The Figure shows the results of heating the actuator with a constant current of 3A and varying the duration of the between pulse 400ms and 200ms.

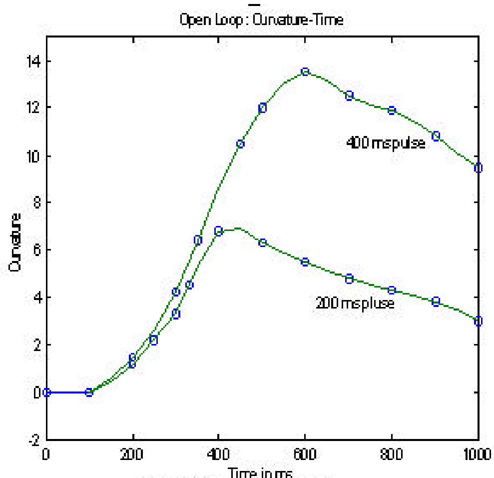

Fig.6 Open loop response

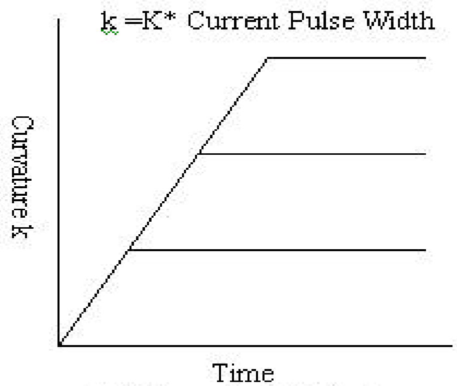

Fig.7 Curve of an ideal integrator

Adopting a black box modeling approach, the open loop step response of the actuator reveals that a markedly linear relationship between heating time and curvature can be observed in a large portion of the graph. A coarse model can be written as:

Curvature = K* t

where t is the length of the current pulse and K the slope of the line. The slope depends monotonically on the magnitude of the current pulse used to heat the SMA wire. The higher this current the faster the temperature increase, and therefore the faster the response.

Ignoring the time delay, the higher order response, and the various distortions, our open loop model is represented by the trajectory curves shown in Figure 7, which are the response curves of an ideal integrator.

However, the actual open loop response does not match the ideal integrator in that the curvature is not held when the current is turned off. Upon cooling, the SMA wires are stretched out by the flexible rod through interfacial shear, the rod return to a straight shape. This effect can be modeled with a first order system, which is in essence a "leaky" integrator. Therefore using a first order plant and representing the duty ratio-to-temperature relationship also as a first order, we get the open loop model shown in Figure 8. The input to the model is duty ratio with the output given by curvature.

4.4 Variable Structure Control Design

A switching control law makes it possible to drive the state trajectory of a nonlinear plant along a user-chosen surface in the state space. The simplest switching surface involves changing the feedback control according to the sign of the error. In the phase plot of error this corresponds to a vertical switching surface along the y-axis as shown in Figure 9.

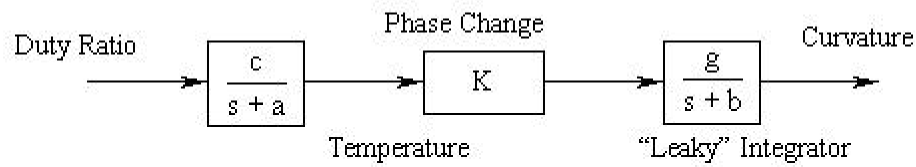

Fig.8 Simplified model

Starting from any initial conditions, the state trajectory is driven towards the switching surface, s. This is a result of constructing the control gains such that the gradient of the state space vector is always directed towards the switching surface.

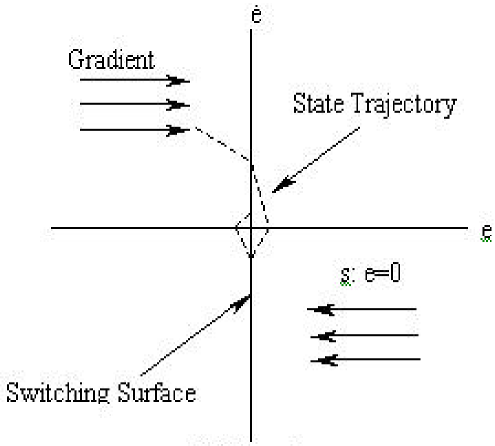

Fig.9 Phase plot

With properly chosen feedback gains, the state trajectory can be constrained to move along the switching surface after the initial intersection with the switching surface. Such a motion along a switching surface is referred to as a "sliding mode", and exists on a discontinuity surface whenever the distance to this surface and the velocity of its change are of opposite signs [10]. More specifically:

$$\lim_{s \to 0^-} \dot{s} > 0 \quad \text{and} \quad \lim_{s \to 0^+} \dot{s} < 0 \qquad (16)$$

Where s is defined as the switching surface. Given that our model is an integrator, and choosing s, the switching surface to be equal to the curvature error (s=e) we have:

$$x = x_0 + \int_0^t K * u \, dt \qquad (17)$$

$$\dot{x} = \dot{e} = K * u \qquad (18)$$

Where x is the curvature, u is the duty ratio, and K is the actuator gain. The equivalent control, u_{eq}, the control needed to stay on the switching surface is then simply given by:

$$\dot{s} = \dot{e} = K * u = 0 \qquad (19)$$

$$u_{eq} = 0 \qquad (20)$$

The value of $u_{eq}=0$ makes sense due to the fact that our model is an integrator. Once an integrator has a value, it will hold this value if the input is zero.

Any perturbations from the switching surface results in an immediate control signal that forces the trajectory back on to the switching surface. In the time optimal sense, switching is the most efficient way to drive the plant since the maximum realizable gain is used. To maintain the stability of the system, the gain must be chosen so that it is large enough to drive the plant as quickly as required to the set point, yet be small enough so as to not cause oscillation larger than a specified limit.

Since using a single gain in the feedback path results in a controller that is too conservative, A two stage hybrid controller has been explored for the control of the SMA actuator. If the error is large then the maximum constant feedback is used. As the state trajectory approaches the set point the control is switched to the linear proportional controller. This results in a smoother motion as the state trajectory slows down as it approaches the set point switching surface. The adjustable parameters for the two stage controller are: 1) location of the boundary layer; 2) the amplitude of the constant current pulse; and 3) the gain of the linear proportional controller.

The block diagram of the controller can be seen in Fig.10.

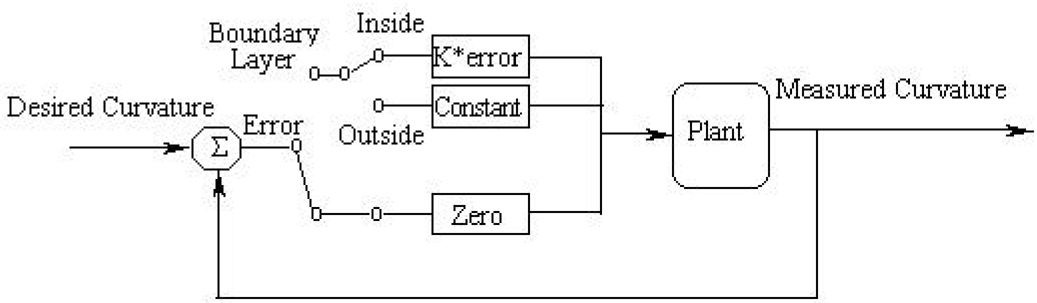

Fig.10 Block diagram of controller

5 EXPERIMENT

Fig.11 and Fig.12 show the step and ramp responses of the two stage linear controller with the parameters set as follows: 1) maximum gain = 0.8; 2) linear proportional gain = 0.1 * error; 3) boundary layer = 2.5. The various parameters have been tuned for the specific input step.

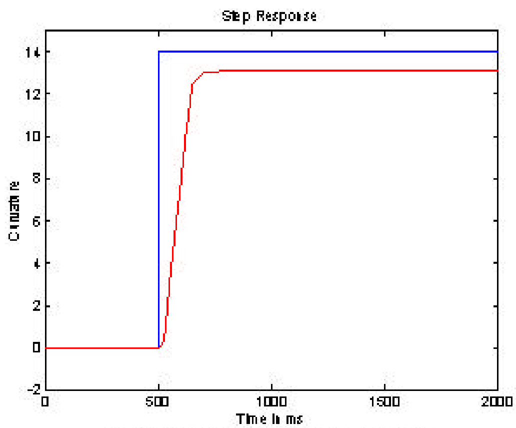

Fig.11 Step response of two stage controller

The step response, although smooth, never reaches the set point, and has a steady state error of 1.15. The rise time, measured from the 10% to the 90% of the final value is, 105 ms with a 85 ms delay.

The tracking response has a time lag of 55 ms due to the delay between applied current and the phase transition. Also note that the slight dip at the beginning of the ramp response is due to the fact that the actuator responds at a lower rate at the beginning of the phase transition as can also be seen in the open loop step response of Figure 6.

The disadvantage of this two stage controller, is that in the vicinity of the set point the feedback signal is low, so the plant is easily disturbed by perturbations. The further work is to justify the controller to be better robust against the perturbations while firmly maintain the stability.

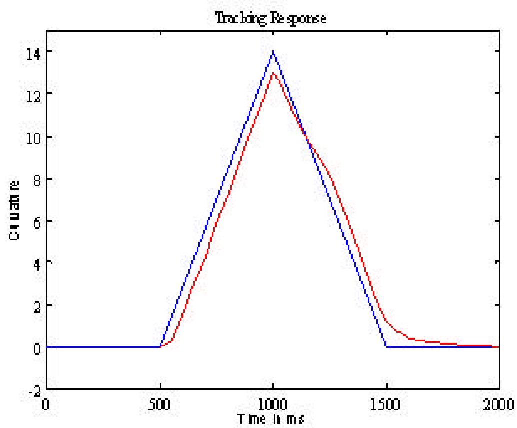

Fig.12 Ramp response of two stage controller

6 CONCLUSIONS

A novel actuator using shape memory alloys has been proposed that overcomes the main drawback of most SMA actuators, whose configuration being complicated. An actuator prototype has been constructed with the following properties:

Light weight – 2 grams
Compact - 8 mm cylinder x 40 mm long
Big curvature - 14
Direct drive actuator
Smooth movements

Open loop experiments were conducted to demonstrate the intrinsic properties of the SMA actuator. Using these graphs and knowledge of the underlying physics a simple model was purposed and further justified through simulation. Two stage switching control laws were then applied to the shape memory alloy actuator. The controllers are based on a simple concept, switching on the sign of the error, and produces rather satisfactory results. Further research has been done on adjustment of the two stage controller to be robust against the perturbations while firmly maintain the stability.

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List of Figures

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