Developing an Adaptive Controller for a Shape Memory Alloy Walking Assistive Device

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Abstract: The Shape Memory Alloy is a lightweight, compact and biocompatible actuation mechanism which is considered here to replace the current actuation technologies in assistive locomotion devices. This paper is aimed toward the development of an adaptive robust controller to deal with control problems in the actuation of shape memory alloys (SMA). In this research the ankle joint is considered to be actuated by SMA but it can be extended to the other joints as well. To check the performance of the controller, the dynamics of the ankle joint during walking is studied and an SMA manipulator with a similar behavior is used for the experiment. Nonlinear behavior of SMA wires requires nonlinear control techniques for tracking the desired ankle angle. Since the device is subjected to several uncertainties and unmodeled parameters, it is also necessary for the implemented control technique to be robust and adaptive. To this end, the proposed control technique consists of two parts. The first part is an adaptive PID controller which is motivated from a sliding mode control. The control gains are adjusted based on an adaptation mechanism to minimize the sliding condition. The second part of the controller is a supervisory control that guarantees the stability of the system.

Key words: Adaptive control, nonlinear system, shape memory alloy, walking.

1. INTRODUCTION

There are millions of individuals who have missed the pleasure of walking. They require either rehabilitation or permanent assistance in the form of assistive devices. Walking problems are not limited to the amputee population; there are a large number of patients who lost muscular force control due to a disruption of major neural pathways at some point along the spinal column or due to aging. An orthosis is a device for helping this kind of patient. In the US only, around 0.9 million individuals use an orthosis on a lower extremity and 8 million people are in desperate need of new technologies that will help them walk (US Dept of Commerce, 1994).

The main objective in developing active orthoses for the lower extremity is to enable patients to walk closer to normal. The first efforts in building a powered assistive device go
Recently, Mckibben muscles and Series Elastic Actuators have been used to provide active assistance to individuals with paraplegia. Blaya and Herr at MIT developed an active ankle foot orthosis device (AAFO) (Blaya and Herr, 2004). The basic idea of this AAFO is to change the orthosis impedance (stiffness). A control algorithm was developed to adjust proper stiffness for each part of the walking (gait) cycle. Although this AAFO shows promising results in a laboratory environment, the actuator weighs 2.6 Kg and requires bulky batteries and electronics for operation. In addition, patient may face difficulties sitting while wearing this AAFO.

Ferris et al. (2005a,b) have used pneumatic actuators called Mckibben muscles to develop an alternative AAFO. One pneumatic actuator provides plantar flexion torque and the second one provides dorsiflexion torque. The study concluded that it is feasible to construct a lightweight powered orthosis to provide substantial external torque to the ankle joint.

The need of lightweight and flexible actuation with a high power to mass ratio brings the idea of using novel actuation such as Shape Memory Alloys (SMA).

The key feature of this material is its ability to undergo large plastic strains and subsequently to recover these strains when a load is removed or the material is heated. The feature allows SMAs to serve as very compact actuators. A secondary useful feature of many SMAs is their biocompatibility characteristic which makes them an excellent choice for medical applications such as stent, orthopedic implant and bone substitution materials (Yahia, 2000; Lagoudas, 2008).

Several researchers have implemented shape memory alloy actuations for use in articulated hands. An SMA actuator has even been used in an eye prosthesis to execute horizontal and vertical actuation (Wolfe et al., 2005).

Several studies have also been done using SMA wires as artificial limbs in finger joints and shoulder (Gorbet and Wang, 1995; Van der Wijst et al., 1997; Dilibal et al., 2002; Lucas dos Santos et al., 2003; Price et al., 2007; Bundhoo et al., 2009).

SMA actuation has disadvantages such as low efficiency, low bandwidth and control difficulties. Shape memory effect, which is the main actuation mechanism, is a highly nonlinear phenomenon. Nonlinearities enter the process through the hysteresis behavior, nonlinear heat transfer, and any nonlinear change in the parameters that affects the phase composition of the material (temperature, stress).

Several nonlinear control schemes such as fuzzy logic, neural networks, feedback linearization, sliding mode control, and variable structure control have also been explored by different researchers (Nakazato et al., 1993; Song et al., 2000, 2003a,b; Elahinia and Ashrafiuon 2002, Elahinia et al., 2005a). However, most of these control methods are either difficult to implement in a real time system or they are inefficient in a system such as walking which can be easily disturbed.

In this paper the control problem of an SMA actuator for walking assistive devices is investigated. To evaluate the controller, an experimental set-up is chosen based on the dynamic of human walking. The proposed control algorithm has an adaptation method for the controller gains.

The next section presents a brief introduction to SMA actuation and current control problems. The following sections include the control technique to overcome some of these problems. The experimental and simulation results are provided in the result section.
2. WALKING MODEL

Human walking is a process of locomotion in which the erect, moving body is first supported by one leg and then by the other leg. As the moving body passes over the supporting leg, the other leg swings forward in preparation for its next support phase. There are two basic requisites for a walking cycle to be formed (Rose and Gamble, 2006):

1. Continuing ground reaction forces (GRF) that support the body.
2. Periodic movement of each foot from one position of support to the other in the direction of progression.

These elements are necessary for any form of bipedal walking regardless of the existence and the level of physical disability (Hansen et al., 2004). These requirements therefore should be satisfied by prosthesis or orthosis devices developed for walking assistance. To understand the relationship between ankle moments versus ankle angle a combination of ground reaction force and the periodic motion of a foot can be studied to form the stiffness plot of the joint. Figure 1 shows the ankle moment versus angle curve during a healthy walking. As it appears, there is a hysteresis loop in ankle behavior in each walking cycle (From first toe off to second one). It is shown by Hensen et al., that as the walking speed increases the quasi-stiffness of the ankle changes such as the hysteresis loop changes from clockwise at low walking speed to a counter clockwise at higher walking speed (Hansen et al., 2004). This behavior should be reproduced by active or passive assistive devices.

Figure 1 also shows that ankle function during controlled plantar flexion closely resembles a linear spring as ankle moment is proportional to ankle position. Thus by using a rotation spring at the orthosis joint, it is possible to produce the unloading part of the curve which occurs between mid-stance and second toe off. The remaining part of the curve demonstrates the swinging phase, in which the SMA actuation can be used to produce enough force to mimic the curvature.
3. SMA ACTUATION

The actuation of shape memory alloys is due to a phenomenon known as shape memory effect (SME). The SME occurs due to a temperature and stress dependent shift in the materials crystalline structure between two different phases called Martensite and Austenite. Martensite is the relatively soft and easily deformed phase which exists at lower temperatures. The molecular structure in this phase is twinned and SMA can be easily deformed to new shapes. By increasing the temperature, molecular structure of the SMA begins to change from Martensite to Austenite where SMA can be formed to its memorized shape. This behavior is governed by four stress-dependent temperatures, starting and final temperature of Martensite transformation ($M_s$, $M_f$) as well as Austenite transformation temperatures ($A_s$, $A_f$).

Figure 2(a) shows the temperature of the wire as well as the four transformation temperatures. Figure 2(b) shows the phase of the SMA actuator used in this study which start from 1 (fully Martensite) and can go to zero (fully Austenite). This data are plotted for a sine wave as a voltage source with amplitude of 20 V and frequency of 1 rad/s. At point (p)
Figure 3. (a) The experimental set-up (one degree-of-freedom SMA arm). (b) Stiffness plot of SMA arm during tracking a sine wave as a desired trajectory with a proposed controller in this paper.

the temperature reaches the Austenite starting transformation temperature. That is why the Martensite fraction starts to decrease from 1 toward zero but it does not reach zero because the temperature does not cross ‘\(A_f\)’. At point (q) the temperature of the wire crosses ‘\(M_s\)’ and the Martensite fraction starts increasing again.

4. EXPERIMENTAL SET-UP

The system shown in Figure 3(a) is a one degree-of-freedom shape memory alloy actuator. Initially this system is used to investigate the possibility of using SMA wires to actuate the AAFO. The main reason for choosing this system is the similarity between the torque-angle at the ankle (Figure 1) and the torque-angle of this device as shown in Figure 3(b). The shape memory effect is a one way actuation and therefore there should be a spring or another set of SMA wires to act as a bias force. Due to the linear behavior of the ankle’s moment-angle plot during the unloading part, a bias spring is used in the experimental set-up.

This system can provide up to 135° angular displacement. By adjusting the electrical current to the SMA wire it is possible to rotate the mechanical linkage to track desired trajectories. The SMA wire is Flexinol with the diameter of 150 μm. Heating the SMA wire induces a negative strain in the material creating a positive torque and the arm rotates counterclockwise.

Conversely, cooling the wire induces a positive strain causing the arm to rotate in a clockwise direction. It should be noted that the wire is cooled down passively, and the only act of the controller is not to apply a voltage and let the spring bring the arm down. The cooling rate of an SMA wire is proportional to the ratio of the surface area to the heat capacity. The generating force on the other hand is proportional to the sectional area of the wire. The surface area/volume is in inverse proportion to the diameter. Therefore, if the diameter is small,
the cooling rate is fast and the generated force is small. In order to produce enough force to rotate the foot around the ankle and to do it fast the actuator should have a large number of thin wires.

Figure 3(a) shows the experimental set-up used for this research. The only input of the system is the applied voltage to the SMA wire while the digital encoder sends the rotational angle as the only output of the system. The built-in code in real time workshop MATLAB is used in dSPACE experimental set-up to run the control strategy.

The advantage of using the current experimental set-up is to reduce the number of wires (and required power) necessary to actuate an AAFO. Since the dynamics of the system is very similar to the dynamics of the ankle joint, the experimental results of controlling the current set-up will provide enough information for a real AAFO with SMA actuation.

5. MODELING

An accurate model of the experimental system is required for simulation and evaluation of different control algorithms. The model consists of a SMA actuator model in addition to a dynamic and kinematic model of the experimental set-up. The input is voltage and the outputs are the actuator angular velocity and position.

5.1. Kinematics and Dynamics

The dynamics of the system, including spring and payload effect, is represented by

\[ I_{e} \dot{\theta} + c \dot{\theta} + [\tau_{g}(\theta) + \tau_{s}(\theta)] = \tau_{w}(\sigma). \]  

(1)

Where ‘\( \tau_{w} \)’, ‘\( \tau_{g} \)’, and ‘\( \tau_{s} \)’ are the resulting torques from the SMA wire, gravitational loads, and spring, respectively and ‘\( \sigma \)’ is the wire stress. ‘\( I_{e} \)’ is the effective moment of inertia of the system, and ‘\( c \)’ is the torsional damping coefficient approximating the net joint friction. For simplicity, the above dynamic equation can be expressed as:

\[ I_{e} \dot{\theta} + h(\theta, \dot{\theta}) = a \sigma. \]  

(2)

The kinematics model includes relationship between strain and angular displacement. Measuring the positive angle clockwise, the equation is:

\[ \dot{\varepsilon} = -\frac{2r \dot{\theta}}{l_{0}}. \]  

(3)

Where ‘\( r \)’ is pulleys radius and ‘\( l_{0} \)’ is wire initial length.

5.2. SMA Actuator Model

The SMA actuator model consists of three parts: phase transformation, heat transfer and the constitutive model (Figure 4). The heat transfer model determines the SMA tempera-
Figure 4. Block diagram of SMA actuator.

Figure 5. (a) Comparing simulation and experimental results for a sine wave. (b) Constant voltage as in input to SMA arm.

ture which is increased due to passing electrical current through the wire. The SMA wire heat transfer equation consists of electrical (joule) heating and natural convection. The wire constitutive model shows the relationship between stress, strain and temperature (Liang and Rogers, 1990; Elahinia and Ahmadian, 2005b,c).

The elements of the models are bilaterally connected forming an algebraic loop. One reason is that physical properties of the SMA wire are dependent on the stress and temperature of the wire. Thus bilateral causality exists between the dynamic model and constitutive equation and also between the constitutive model and phase transformation kinetics.

The simulation model is built in the Dymola environment and for the experiments the dSPACE hardware-in-the-loop solution is used.

To verify the model, a series of experiments was done for various inputs to the system. These results demonstrate reasonable accuracy of the actuator model, as shown in Figure 5.

The figure compares simulation and experimental results in an open loop system with constant voltage in Figure 5(a) and half a rectified sine wave with an amplitude of 18 volts and frequency of 0.1 rad/s in Figure 5(b) as an input.
Some of the differences between the simulation and experimental results are due to parameter uncertainties and model simplifications. Specifically, the modulus, transformational tensor and thermal coefficient were all assumed to be constant. The assumptions of a linear spring force and viscous friction contributed to the discrepancy of the results.

5.3. Control Challenges

It is important to recognize the co-dependent relationship between stress, Martensite fraction, and transformation temperature, for it is this complex nonlinear relationship that causes many difficulties with regards to control design for SMA actuators.

Considering the temperature plots in Figures 2(a) and 2(b), it seems that by increasing the applied voltage and elevating the temperature it is possible to position the actuators at different desired positions. In other words, it seems there is a monotonic linear relationship between the applied voltage (temperature) and the position of the SMA actuator. As shown in the following, this is not the case and therefore the control of SMA rotary actuators is challenge ridden.

Another control issue is that the entire deflection of an SMA element occurs over a small temperature range making accurate control in partial contraction difficult. This is shown in Figure 5(b) where there is a sudden jump in the actuation from 14 to 14.6 V.

The temperature of the wire is almost the same in the two experiments but as Figure 6(a) shows, the phase transformation temperatures are decreased in the second experiment. Having a lower temperature to pass for finishing the Austenite transformation, the wire can get to fully Austenite mode in the second experiment (Figure 6(b)).

This occurs because the required torque and hence the SMA wire stress starts decreasing after a certain angle. Recalling that the actuation limit temperatures are a function of stress, their values also decrease.
The other challenge in controlling SMA wires is a number of state variables which are not easy to measure. This lack of information makes the implementing of model-based controllers more difficult. For example, in the proposed experimental set-up, to have a model based controller, it is essential to have information about state variables such as the stress and temperature of the wire, Martensite fraction, joint angle and angular velocity. Among these variables only the angle and angular velocity of the arm can readily be measured.

6. CONTROL METHOD

A robust adaptive PID controller design motivated from sliding mode control is used here for the SMA actuator. In this approach, the PID control gains, $K_p$, $K_i$, and $K_d$ are adjustable parameters and will be updated online with an adaptation mechanism to minimize a sliding condition. By introducing a supervisory controller, the stability of the closed-loop PID control system under the effect of plant uncertainty and external disturbance can be guaranteed (Chang and Yan, 2005).

Based on equation (2), the dynamic model of the SMA actuator can be represented by a second order single input single output system:

$$
\dot{x}_1(t) = x_2(t)
$$

$$
\dot{x}_2(t) = f(X, t) + \Delta f(X, t) + \delta(t) + u(t)
$$

$$
X = \begin{bmatrix} x_1 & x_2 \end{bmatrix}^T.
$$

(4)

Where $X = \begin{bmatrix} \theta & \dot{\theta} \end{bmatrix}^T$ is the state vector, $f(X, t) = \frac{h(\theta, \dot{\theta}, t)}{I_e}$ and $\Delta f(X, t)$ and $\delta(t)$ are uncertainty of the system and external disturbance respectively.

Finally $u(t)$ is the input of the system which is the stress of the wire and can be defined as a function of the applied voltage to the wire.

Using an adaptive PID controller, the input of the system is composed of two parts, the adaptive PID and a supervisory controller:

$$
u(t) = u_{PID} + u_s
$$

(5)

‘$u_{PID}(\cdot)$’ is an adaptive PID controller based on the concept of sliding mode control. The adaptation law that is based on the use of the gradient method and minimizes a designed sliding condition for updating the PID control gains.

‘$u_s(\cdot)$’ is the extra supervisory controller that will be fired only when the states of the system exceed some bound in order to guarantee stability of the system (Chang and Yan, 2005).

The continuous form of a PID controller, with input ‘$e(\cdot)$’ and output ‘$u_{PID}(\cdot)$’, is generally given as:

$$
u_{PID}(t) = K_p(t)e(t) + K_i(t) \int_0^t e(\tau)d\tau + K_d \frac{d}{dt}e(t).
$$

(6)
Where ‘$K_P$, $K_I$, $K_D$’ are proportional, integral and derivative gains, respectively and ‘$e(\cdot)$’ is the tracking error defined as ‘$e = \theta - \theta_d$’. In order to derive a proper adaptation law to update the PID controller gains, a sliding surface is used which is defined as:

$$S = \dot{e}(t) - k_1 e(t) - k_0 \int_0^t e(\tau) d\tau.$$  \hspace{1cm} (7)

Where ‘$k_1$’ and ‘$k_0$’ are designed in such a way that roots of equation (8) are placed at the open left-hand side of the complex plane (Kuo et al., 2006).

$$S^2 + k_1 S + k_0 = 0.$$  \hspace{1cm} (8)

To derive an adequate adaptation mechanism for tuning three PID control gains, a gradient search method is used to minimize the sliding condition:

‘$\dot{S} = 0$’, then $\ddot{e} + k_1 \dot{e} + k_0 e = 0$. \hspace{1cm} (9)

The gradient search algorithm is calculated in the direction opposite to the energy flow and obtains the convergence properties of the PID controller for tuning. Based on the gradient method, the adaptation laws for three control gains ‘$K_P$, $K_I$, $K_D$’ is defined:

$$\dot{K}_P = -\gamma \frac{\partial S \dot{S}}{\partial K_p} = -\gamma S e$$  \hspace{1cm} (10)

$$\dot{K}_I = -\gamma \frac{\partial S \dot{S}}{\partial K_I} = -\gamma S \int_0^t e(\tau) d\tau$$  \hspace{1cm} (11)

$$\dot{K}_D = -\gamma \frac{\partial S \dot{S}}{\partial K_D} = -\gamma \frac{d e}{d t}.$$  \hspace{1cm} (12)

Where ‘$\gamma > 0$’ is the learning rate. It is worth noting that if the learning rate or the initial values of the PID control gains are not selected adequately, the resulted PID controller could potentially make the states of the system divergent. Using equations (10) to (12) it is possible to update the gains of the controller in order to reduce the predefined sliding condition.

On the other hand the supervisory controller in equation (5) is defined based on a criterion which the states of the system cannot exceed a predefined limit ‘$M_x$’. This constraint can be defined as equation (13).

$$X \in \mathbb{R}^2 : \|X\| \leq M_x.$$  \hspace{1cm} (13)

It is desired that the state trajectory of system never reach the boundary of the constraint during the control procedure. In this work it is assumed that $M_x \geq \|X_d\|_\infty$. It is also assumed that there exist two positive upper bounds $f^u$ and $\Delta f^u$ satisfying $|f| \leq f^u$ and $|\Delta f| \leq \Delta f^u$, and a positive constant $\alpha$ that satisfies $|\delta| \leq \alpha$. Based on these assumptions the supervisory control is defined as:
Figure 7. Block diagram of proposed controller.

\[ u_s = I^* \text{sgn}(e_p + \dot{e}_p) \left| f^* + \Delta f^* + \alpha + |\dot{\theta}_d| + |k_0 e + k_1 \dot{e}| + |u_{pid}| \right|. \quad (14) \]

Where \( 'P' \) is a positive definite symmetric matrix satisfying the Lyapunov equation:

\[ \Lambda^T P + P \Lambda = -Q, \quad P = \begin{bmatrix} p_{11} & p_{12} \\ p_{21} & p_{22} \end{bmatrix}, \quad \Lambda = \begin{bmatrix} 0 & 1 \\ k_0 & k_1 \end{bmatrix}. \quad (15) \]

Where \( Q \) is another definite symmetric matrix selected by the designer. Finally \( I^* \) is an identification function described in equation (16).

\[ I^* = \begin{cases} 0 & \text{if } E^T P E < \lambda (M_x - \|X_d\|_\infty)^2 \\ 1 & \text{if } E^T P E \geq \lambda (M_x - \|X_d\|_\infty)^2 \end{cases}. \quad (16) \]

Where \( E = [e \quad \dot{e}]^T \) and \( \lambda \) is the minimum eigenvalue of matrix \( 'P' \).

The supervisory controller as defined in equation (14) will play an important role that provides an extra input to force the states to the pre-specified constraint set and also guarantees the stability of the system. The block diagram of the robust adaptive PID control with a supervisory controller for our uncertain system is depicted in Figure 7.

Since the trajectory of the ankle is similar to a sinusoidal wave, sine functions were selected as a desired trajectory. The desired angle and constraint are given in equation (17).

\[ \theta_d = A \sin(\omega t), \quad M_x = A \omega. \quad (17) \]

To simulate the disturbance and uncertainty of the system the payload mass connected to the SMA arm is assumed to have a sudden increase of 15%.

This set the upper bound for \( f(\cdot) \) and \( \Delta f(\cdot) \) equals to 2 and 0.09 respectively.
7. RESULTS

The proposed adaptive PID controller implemented in the simulation environment first for different gain factors. Figure 8 shows the simulation and experimental results of tracking the sine wave with a frequency of 0.2Hz and amplitude of 0.5 (rad). The gain factors ‘$k_0$, $k_1$’ are both equal to $-1$ in this simulation. In the experiment a second order butter-worth filter with a cut-off frequency of 2 Hz is used to filter the feedback of the system. The error at the first peak of the desired trajectory is about 7 Deg. One cycle later this value is decreased to 2 Deg which shows the adaptive behavior of the system.

By changing the location of the roots of equation (16) it is possible to change the performance of the system. This is shown in Figure 9 where by setting ‘$k_1$’ to $-0.1$ the lagging behavior of system during cooling is change to a leading behavior.

It is essential for the SMA actuated AAFO to be able to operate in different environments and under different external loads. To check the robustness of the experimental system three different tests were done. For the robustness test, the SMA wire was cooled down during the actuation through blowing air on the wire. This disturbance caused the controller to apply more voltage to the system to compensate for the lost heat and to establish the required temperature. Since the constraint on the applied voltage did not allow the controller to exceed 20 volts, sometimes the wire could not reach the desired temperature. This can be seen in the second, fourth and seventh cycle of Figure 10.

Figure 11 illustrates the response of the SMA actuator to increasing the mass of the system by 15% during the operation. Adding the extra mass at $t = 6$ causes about 5 Deg fall in the output of the system. However the adaptation law in the controller adjusts the gains in order to overcome the disturbance.
Figure 9. The effect of gain factors on performance of controller.

Figure 10. Performance of the controller in the presence of disturbance (forced convection of the SMA wire).
This experimental result shows the robustness of the controller. The last robustness test was done by applying an external force to the actuator.

In this experiment, as shown in Figure 12, the external force prevented the SMA arm to follow the sine function after the third cycle. By removing the external force in rising part of the fourth cycle, the pre-stress in the wire forces the arm to go down very fast instead of rotating upward. The adaptation law adjusted the PID gains again to get closer to the sliding surface. As shown in Figure 12 that SMA actuator could follow the desired trajectory again after half a cycle.

It is known that PID does not work well in disturbed or uncertain systems. Figure 13 compares the performance of a PID with the adaptive PID controller in regulating the SMA actuated arm to track a sine wave. It can be seen that the adaptive PID has a superior tracking performance. The gain adaptation for the PID controller and the variation of the designed sliding surface are shown in Figures 14(b), (c), (d). In these simulations the controller is tracking a sine wave with frequency of 0.2 Hz. Figure 14(a) shows the performance of the tracking in a phase portrait, where the angle is plotted versus angular velocity. Because of passivity of the system during the cooling process, the system cannot track the unloading rate. However as we discussed in the second section, the main objective of SMA orthosis is to follow the loading by applying torque through SMA wires. The sliding surface of the experiment is shown in Figure 15.
Figure 12. Performance of the controller in presence of obstacle.

Figure 13. Comparing PID and adaptive PID controller.
Figure 14. (a) Phase portrait of the simulation in tracking a sine wave as a desired angle. (b) Proportional gain of the controller. (c) Integral gain of adaptive PID. (d) Derivative gain of the adaptive PID controller.

Figure 15. Sliding surface for the controller (experimental result).

8. CONCLUSIONS

An adaptive PID controller was proposed in this paper to control an experimental model of an AAFO actuated by Shape Memory Alloys. A proposed adaptation law for the PID control gains tuning is to minimize the designed sliding condition. A supervisory controller also forces the state of interest to remain in any possible constrained region.
Experimental and simulation results show the advantage of using this controller in comparison with a PID controller. The robustness of the controller was also demonstrated by testing the controller in presence of different source of disturbance such as external force, increasing the mass and changing the temperature of the wire.

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