ABSTRACT

In this paper we present a novel controller for Shape Memory Alloy (SMA) actuated robotic systems. The new controller, called BAC (B-spline based Adaptive Control), is based on a hybrid combination of gain scheduling, B-spline approximation, variable structure control and integral control. The proposed controller shows excellent positioning accuracy and speed throughout the full range of motion of a SMA actuated robotic system in large-scale applications. To demonstrate the validity of BAC, a novel anthropomorphic SMA Actuated forearm / wrist mechanism is utilized in real-time PC based control experiments. BAC is experimentally compared to PID and integral variable structure controllers and it is shown that its performance is superior.

1 INTRODUCTION

In many applications of robotic and mechanical systems, such as space exploration, medical operations, entertainment industry and military tasks, there is an increasing need for developing small size and lightweight devices that will be able to apply large forces, develop high speeds, achieve large displacements and be highly energy efficient. Advancing such robotic systems, in part, requires using new actuators, since classical forms of actuators, such as DC motors, hydraulics, or pneumatics, are heavy and cumbersome. Utilizing advanced actuators based on smart materials can make possible the development of innovative robotic systems that would satisfy many of the requirements stated above.

In this research, the key methodology in drastically reducing the weight and size of robotic systems is the use of Shape Memory Alloy (SMA) wires as actuators of the robot joints. SMAs consist of a group of metallic materials that demonstrate the ability to return to some previously defined shape or size when subjected to the appropriate thermal procedure. This phenomenon is known as the Shape Memory Effect (SME). Some examples of these alloys are Ag-Cd, Au-Cd, Cu-Al-Ni, Cu-Sn, Cu-Zn-(X), In-Ti, Ni-Al, Ni-Ti, Fe-Pt, Mn-Cu, and Fe-Mn-Si. The SME occurs due to a temperature and stress dependent shift in the material’s crystalline structure between two different phases called martensite and austenite. Martensite, the low temperature phase, is relatively soft whereas Austenite, the high temperature phase, is relatively hard. The change that occurs within a SMA’s crystalline structure during the SME is not a thermodynamically reversible process. In other words there is energy dissipation due to internal friction and creation of structural defects. As a result, a temperature hysteresis occurs that translates directly into hysteresis in the
strain/temperature relationship. The hysteresis behavior makes it challenging to develop modeling and control schemes for SMA actuators.

Heating, and thus actuation, of an SMA wire is easily accomplished by applying a voltage drop across the wire causing current to flow through the material, resulting in joule heating. Ease of actuation is not the only advantage of SMA actuators. Other advantages are their incredibly small size, volume, and weight, their high force to weight ratio, their low cost and their noiseless operation. Their limitations include a relatively small bandwidth and low energy efficiency. Despite of these limitations, SMAs have one of the highest payload to weight ratios among "smart material" based actuators. Therefore, SMAs are one of the few "smart materials" that, at the present time, can be used in applications that require small size and large forces from the actuators.

Since 1983, SMA artificial muscles have been used in micro-robotics [1]. It was proposed that their small size and displacement was ideal for micro-robots, i.e. robots smaller than 1 mm. In this context, SMAs have been used in many different robotic systems as micro-actuators [2-4]. Additional information on the principle of operation of SMAs can be found in [5-7].

Developing a mathematical model that captures the behavior of a SMA as it undergoes temperature, stress, and phase changes is a complicated and challenging problem. Researchers continue to study how best to model and control actuators that use this unique family of materials. Gorbet and Wang [8] provide an excellent summary of SMA actuator modeling efforts to date.

Some researchers have chosen to greatly simplify the material's behavior by creating a dynamic model where the phase transition temperature is the same for heating and cooling, completely ignoring the effects of the large hysteresis. To improve the accuracy, the model must be non-linear. The complete model must capture the major hysteresis loop that occurs for changes from 100% martensite to 100% austenite (and vice versa) as well as the minor hysteresis loops that occur in between. Minor hysteresis loops are inherent in position control systems where heating and cooling cycles back and forth as the control system holds the actuator at the desired position. Kuribayashi [4] took the next step and developed a linear first-order model that estimates the hysteresis in the stress-strain behavior. Tanaka [9], using studies of SME from the point of view of solid mechanics, developed a constitutive model. He employed the energy balance and the Clausius-Duhem inequality equation and derived the rate form of the equations. Shu, Lagoudas, Hughes and Wen [10] developed a model, which expanded Tanaka's model with more variables in strains. Ikuta et al. [11] developed a novel "variable sublayer model" where, at a given time, the percentages of the different phases (including the intermediary Rhombohedral phase) are mathematically described. As a result, for a given load, strain in the wire can be calculated from corresponding weightings of the respective strains of the different phases. Madill and Wang [12] developed extensions to the Ikuta's variable sublayer model that refined the modeling of the minor hysteresis loops making it suitable for modeling position control systems where electricity is the source of heating.

The complexity of the SMA models described above makes it difficult to mathematically design controllers for SMA actuated robotic systems. Despite the modeling difficulties, researchers have produced some very important results after applying several different controllers. Classical PID controllers have been studied by Reynaerts and Van Brussel [13]. Hashimoto et al [14] applied a PD control scheme to the SMA wires used as actuators of a biped-walking robot. Ikuta et al [15] used active PID control on a segmented active endoscope made with SMA springs. A PI controller including a temperature feedback has been studied by Troisfontaine et al. [16]. Madill and Wang [12] used a very simple Proportional control to verify their SMA system model and studied its stability. The control gains were tuned either on-line or through simulations with trial and error method. The drawback of linear $P$, $PI$ or $PID$ control is that the controller may perform well in the range where the control gains are tuned, but deteriorates dramatically once outside the range. Various adaptive control algorithms have been used on SMA actuators in order to compensate the material's non-linearities [17-19]. Grant and Hayward [20, 21] applied variable structure/sliding mode control methods to perform position and force control tasks. Abd-Elrahman and Butler [22] studied state-space multivariable control in large flexible smart structures using either Eigenvalue pole placement or $LQR$ methods.

Control of SMA actuated systems is an open and very difficult problem to solve for two main reasons: a) SMA actuators present complex thermal-electrical-mechanical dynamics that are difficult to model; b) due to their temperature dependency, SMA actuators are very sensitive in temperature changes. Controllers for SMA actuators need to be robust in system and environmental changes and modeling errors. In addition the controllers need to be able to handle both position and force control tasks and be simple in implementation. Achieving accurate and robust performance of SMA actuators, is very important since it will allow their use in many important applications.

In this paper we present a novel controller for SMA actuated robotic systems. The new controller, called $BAC$ (B-spline based Adaptive Control), is based on a hybrid combination of gain scheduling, B-spline approximation, variable structure control and integral control. The proposed controller shows excellent positioning accuracy and speed throughout the full range of motion of a SMA actuated robotic system in large-scale applications. To demonstrate the validity of the new controller, a novel anthropomorphic forearm / wrist mechanism is utilized in real-
time PC based control experiments. BAC is experimentally compared to PID and integral variable structure controllers and it is shown that its performance is superior.

2 EXPERIMENTAL SYSTEM

In this paper the SMA actuated mechanical system that will be used to experimentally validate the new controller is a three-degree of freedom forearm mechanism, shown in Figure 1, emulating the spherical motion of a human wrist. This system consists of a palm shown on the left of Figure 1 that is attached to a universal joint. The universal joint is attached on a 1.5-inch radius disk, which is connected to a fixed support stand using a 16-inch, fixed shaft (a counterpart to the ulna). The disk and the shaft are inter-connected using ball bearings so that the platform can rotate (twist) around the shaft. Two prismatic links, that play the role of the radius in human forearms, connect two symmetrically located points on the circumference of the disk to the fixed stand (see Figure 2). Spherical joints connect the prismatic links to the stand and the disc, creating an acute angle to the axis of the tube. The prismatic links, when they are actuated, create the required moment to rotate the disk creating thus, a pronation / supination motion.

Three pairs of antagonistically placed SMA artificial muscles generate the motion of the two rotational degrees of freedom of the universal joint and of the "twisting" motion of the platform. Encoders provide the position feedback. The mobility of the system mimics the extension / flexion and abduction / adduction of the human wrist and the pronation / supination of the human forearm. This prototype is controlled using the WinRec v.1 software developed at the Robotics and Mechatronics Laboratory at Rutgers University [23]. This control software provides deterministic fast timers based on the MSDN library under Windows NT platforms and can be used in both real-time control and data acquisition. The control hardware includes a PC running on Windows NT, power supplies, Digital to Analog and Analog to Digital Converter boards and custom made amplifiers.

The experimental results that are presented in this paper only deal with the position control of the pronation / supination motion (i.e. rotation of the disk). This motion is achieved by the activation (via electrical voltage) of a dual SMA wire actuator attached to the end of each one of the prismatic links and a vertically offset position on the wall. In order to visualize the actuation of the supination/pronation motion, it is important to note the distribution of the force created by the wire and the effect this will have on the initial and final position of the actuating wire. It can be seen in Figure 2a that the wires responsible for the actuation are fastened on one end to the prismatic link, with the other end attached to the wall. Although difficult to present on the top down view, the connection on the wall is positioned higher in the vertical direction (z-axis). Upon contraction of the shape memory alloy, a force component is created along the axis of the wire illustrated in Figure 2b. Due to the acute angle between the prismatic link and the wire, as well as the vertical offset, the force may be broken down into two components, one along the axis of the link (F₁) and another component radial to the disc (Fᵣ). The force component along the link, F₁, is opposed by a reaction force that runs along the spherical joint which rotates itself to align with the prismatic link. Yet the presence of the ball bearing makes the disc incapable of resisting the moment induced by the radial component Fᵣ, thus creating the rotational motion that is the counterpart of the supination / pronation motion of the forearm. The range of motion of the forearm rotation is ±90 degrees.
3 B-SPLINE BASED ADAPTIVE CONTROL

Shape Memory Alloy actuated systems are very sensitive to small changes in operating conditions. Simple Proportional-Integral-Derivative (PID) controllers could be designed to have a good performance for one set of operating conditions. However, these controllers will perform poorly when small changes in the operating conditions occur. Therefore an adaptation algorithm is needed to change the controller gains as a function of the system operating conditions.

The B-spline based Adaptive Control (BAC) is a hybrid control scheme where an Integral Variable Structure Controller (IVSC) is enhanced with a B-splines based gain scheduling function that selects the IVSC controller gains from a predetermined function according to the offset from the desired position and the system operating conditions. The IVSC with gain scheduling provides robustness to disturbances occurred from SMA modeling errors, or from SMA's sensitivities to environmental changes or from changes in the operating conditions of the system (i.e. different configurations and/or different payloads.) The combined IVSC with gain scheduling is further improved with the addition of a simple adaptation routine that modifies the gain scheduling function based on the performance of the controller. This adaptation routine not only allows for the initial training of the controller for a specific system but also allows the controller to continuously adapt the gain scheduling function whenever there is a change in the external conditions or the system physical properties. In this section we describe the fundamentals of the component techniques of BAC and how they have been modified to be applied to SMA actuated systems.

3.1 Integral Variable Structure Control

Variable Structure Control (VSC) is a high-speed switching feedback controller that utilizes what is known as “sliding motion” to allow for the deterministic control of uncertain systems. The sliding motion can be described as a repeated crossing of subspaces (sliding hyperplanes) in the state space. In other words the structure of the controller changes as the system crosses over the manifold, hence the name Variable Structure Control. The nature of the controller is to drive the system towards the manifold. In the ideal case, switching between the controls structures occur instantaneously, thus allowing the system to “slide” along the chosen manifold. In reality the switching requires a finite lag that will keep the system from displaying the ideal behavior. Added to this lag is the sampling period of discrete time systems that limit the rate at which the control signal can be changed and the input signal can be read. This frequent crossing and re-crossing of the manifold with finite offsets termed chattering and is a problem that must be overcome. Therefore the defining characteristic of the VSC can be stated as an algorithm that switches between a set of fixed nonlinear and/or linear controllers as the state crosses discontinuity surfaces. The design of VSC can be broken into two main segments; construction of the switching surfaces and the design of feedback gains that drive the plant state trajectory to this surface. It must be noted that the behavior of the system (including stability and convergence properties) depends heavily on the choice of switching surfaces. Yet, this trend will be downplayed somewhat for position control, where the switching surfaces can be defined synonymously with the desired position.

For the position control of SMA actuated systems based on VSC techniques presented in this paper, the manifold selection is made in a manner that allows the user to optimize the system performance in terms of actuation speed and minimum overshoot independent of each other. A main characteristic of the proposed controller is the existence of a Proportional-Integral (PI) controller at the internal layer and hence the name Integral Variable Structure Control (IVSC). Using the SMA actuated system of Figure 1 and its pronation / supination motions shown in Figure 2 as a demonstration example, two manifolds are selected as it is shown in Figure 3.

![FIGURE 3: IVSC Manifolds and Control Schemes as they are Applied to the System of Figures 1 and 2.](image-url)
actuator is in the martensite phase and undergoes deformation. Yet within the PI region, crossing of the switching surface results in an altering of the activated wire, the gains proportional to the error and the integral of the error.

3.2 B-Splines Based Gain Scheduling

The IVSC achieves robust position control for SMA actuated systems even in the presence of disturbances due to modeling and measuring errors or small variations in the operating conditions. However, the controller gains are fixed for any value of operating conditions. For SMA actuated systems, it turns out that different desired joint configurations and trajectories or different payloads will require completely different sets of controller gains to maintain a good performance. Therefore an adaptation algorithm is needed to modify the IVSC gains as the operating conditions are changing. A simple way to do this is by using Gain Scheduling [24]. To implement Gain Scheduling the system operating conditions need to be monitored on-line and off-line. In off-line experiments prior to the application of the controller a modifying function needs to be identified that relates the controller gains to the system parameters and operating conditions. Figure 4 illustrates the Gain Scheduling approach.

![Figure 4: Gain Scheduling Control [24.]](image)

In this work, we are employing non-rational B-splines to identify the adaptation curves that will relate the IVSC gains to the system operating conditions. For the specific example that is used in this paper, i.e. the wrist rotation of the system shown in Figure 2, the control gains are the fixed voltages in the two manifolds and the proportional and integral gains of the PI controller in the internal layer. The operating condition is the desired angular position of the wrist. The definition of a non-rational B-spline is presented in Equation (1):

\[ C(u) = \sum_{i=0}^{n} N_{i,p}(u)P_i \]  

(1)

where: C is a gain curve function; \( N_{i,p} \) is a basis function; \( P_i \) are control points; \( u \) is the variable against which the control gains are calculated.

As shown in Equation (1), the definition of the curve involves a predefined set of \( n+1 \) control points \( P_i \), with \( i \) an integer from 0 to \( n+1 \) and \( p \)-th degree B-Spline basis functions \( N_{i,p} \) [25]. The numbers \( n \) and \( p \) are arbitrarily chosen but as it is obvious the higher these numbers are the more accurate the results are but this increases the computation time. The control points \( P_i \) are values of the control gains that have been calculated by trial and error routines for specific values of the variable \( u \). The basis functions for the B-splines are determined by the following iterations [25]:

\[ N_{i,p}(u) = \begin{cases} 1 & \text{if } u_i \leq u \leq u_{i+1} \\ 0 & \text{otherwise} \end{cases} \]

\[ N_{i,p}(u) = \frac{u-u_{i+1}}{u_{i+1}-u_i} N_{i,p-1}(u) + \frac{u_{i+1}-u}{u_{i+1}-u_{i+1}} N_{i+1,p-1}(u) \]  

(2)

This recursive formulation for the B-Spline basis function lends itself well to computer programming and increasing the precision of the curve is a matter of adding further iterations.

For the control of SMA actuated robotic systems studied in this paper, second degree B-splines are used as they can provide the necessary smoothness while keeping a low computational burden. Once a gain scheduling curve is calculated using the recursive formulation of Equation (2), an additional adaptation algorithm is able to modify/tune the gain values of the control points if the control system understands that its performance has declined over time. This means that the basis functions are calculated only once, and the control system has the capability of retuning (recalibrating) the control points by checking the controller performance. Calculating the system rise time and overshoot checks the control performance. Deviations from a desired behavior results in a modification in the value of the control points via weighting factors. In other words any deviation from a desired rise time and overshoot is multiplied by a weighting factor and modify the control point corresponding to the gain curve at that position. The values of the weighing factors are tuned for each system separately using a trial and error procedure.

As a demonstration example, we will present the IVSC gain scheduling curves as it was implemented in the SMA actuated wrist rotation of the system shown Figures 1 and 2. To simplify the problem, the proportional (P) and the integral (I) gains of IVSC were determined by trial and error and verified as satisfactory throughout the range of the wrist pronation / supination motion. Thus the parameters that are determined via the B-splines and the on-line adaptation routine are the two gain voltages for the first 70% of the motion and the following 20%. Figures 5a,b,c plot the change in the gain scheduling curve of the first voltage gain for zero, first and second order basis functions. Figures 6a,b,c correspond to the adaptation trends of the gain scheduling function for the voltage gain in the second region for zero, first and second order basis functions.
4 EXPERIMENTAL RESULTS

In this section, experimental results obtained with BAC are shown and compared to results obtained with other controllers such as PID with fixed gains and with empirical gain scheduling and IVSC with fixed gains.

PID Control With Fixed Gains

A representative response of the wrist with a PID controller is shown in Figure 7. In this experiment, the desired joint position of the wrist is 30 degrees. The gains of the controller have been tuned for this configuration so that the wrist reaches its final position accurately with no overshoot. However, if the desired joint angle changes, in order to keep a similar performance, the PID controller gains need to be changed also.

PID Control with Empirical Gain Scheduling

A series of experiments have been performed where different position step inputs represented by a desired pronation angle of the wrist were applied on the system. The desired pronation angles covered a range of motion from 0 degrees to 90 degrees with a step of 10 degrees. For each desired pronation angle, through a trial and error procedure, the values of the gains of the PID controller that gives the best results were identified. The criteria for selecting these optimal gain values for each input were: minimum overshoot, shorter rise time and settling time and higher steady state accuracy. It was found that a fixed value for the derivative gain $K_D$ gave satisfactory response over the range of motion, yet the proportional gain $K_P$ and the integral $K_I$ need to be changed with respect to the position. Gain scheduling curves for $K_P$ and $K_I$ as a function of the position angle, have been calculated using empirical interpolation schemes. Figure 8 shows a representative experimental result that demonstrates the performance of the Gain Scheduling PID controller as it is applied on the SMA actuated wrist. The experimental results indicate that overall this controller had a good performance across a wide range of motion of the system. However, this controller presented an overshoot at lower angles and a slow settling time at higher ones.
A representative result of a step response with IVSC with fixed gains is shown in Figure 9. In order to keep this good performance the IVSC gains should be changed from one configuration to another.

Representative step responses with BAC are shown in Figures 10 and 11. For all positions attempted it can be noted that there is virtually no overshoot with very fast rise times of 0.5-0.7 seconds.

In the testing of controllers for SMA actuators, certain challenges are present for all methods considered. These are: the difficulty posed by the mathematical formulation of the SMA actuation and its high sensitivity to changes in environmental conditions. Thus, analytically determining controller parameters would have required simplifications in formulation (thus leading to errors) and suffer from an inability to cope with changes in the system model due to unpredictable disturbances. The decision was made to implement the conventional control method PID, with fixed and empirically determined gain values, for comparison purposes. Following this, a robust control technique, the Integral Variable Structure Control is implemented, again with fixed gains and switching surfaces. An adaptation algorithm based on B-Spline gain scheduling curves is implemented in order to gratify these issues.

The results from the PID controller, although satisfactory upon reaching steady state, do have mediocre rise times (0.75-1.2 sec) and sometimes high settling times (2 seconds). The results from PID with gain scheduling prove the estimated function capable of achieving positions for which the gains have not been determined, albeit with a loss in performance (max 3° overshoot, 3-5 second settling time).

The experimental determination of the IVSC gain values is a difficult process, yet the plots indicate good rise times (0.4-0.8 seconds) while suffering from over-shooting. Another positive aspect of the IVSC is its good disturbance rejection properties.

The adaptation routine is a process that is automated to determine the optimum gain values and alter the gain
schedules in case of a change in the model of the system. The final control technique is the adaptive-IVSC, which allows for the optimization of two separate gain values. As displayed in Figures 10 and 11 this controller presented an extremely fast and accurate response with no overshoot. This response was achieved in every desired joint angle within the range of motion of the wrist. It presents the best solution for the control of SMA actuators, boasting good rise times, minimal overshoot and virtually no settling time.

6 REFERENCES


