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Shape Memory Alloy Actuator Controller Design for Tactile Displays

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Abstract

This paper describes the design of a controller for a tactile shape display for dexterous telemanipulation applications. This device consists of an array of pin elements which rest against the human finger tip. Shape memory alloy (SMA) wire actuators raise individual pins to approximate the desired surface shape on the skin. To overcome the slow response times of SMA actuators we have implemented a feed-forward derivative compensator and pneumatic cooling. The hysteretic and nonlinear response of the SMA actuators required the use of a closed loop controller with position feedback using an optical emitter-receiver pair. This also improves robustness to the load variations which result from human interaction.

1 Introduction

In teleoperated manipulation systems, a human operator controls a robot located in a distant, hazardous, or difficult to reach worksite. These systems have been used for many years in the nuclear industry and for submarine exploration, and new applications are emerging in extravehicular activities in space and minimally invasive surgical procedures (Sheridan 1992). Most attention has focused on manipulation at the arm level, although recent work on multi-fingered hands promises to increase dexterity in complex and delicate manipulation tasks. Because humans rely on tactile information to control these types of manipulation tasks (Johansson and Westling 1984), tactile feedback from the remote robot to the human operator is essential for good performance.

Our research is aimed at developing this tactile feedback capability. We are working to identify the physical parameters that must be sensed at the remote manipulator, to develop sensors to measure these parameters, and to build displays to convey them to a human operator. In our tactile shape relay system, the shape of an object in contact with the remote robot's finger tip is measured by a tactile array sensor. This shape is recreated on the human operator's finger tip by a tactile shape display. This device consists of an array of pin elements or "tactors" which are raised and lowered to approximate the desired shape. Further details of the design and performance the overall shape relay system, with results of experimental tests in telemanipulation tasks, can be found in (Kontarinis et al. 1995).

In this paper we present the controller design for the tactile shape display device. Our goal was to develop a tactile shape display for use in t he

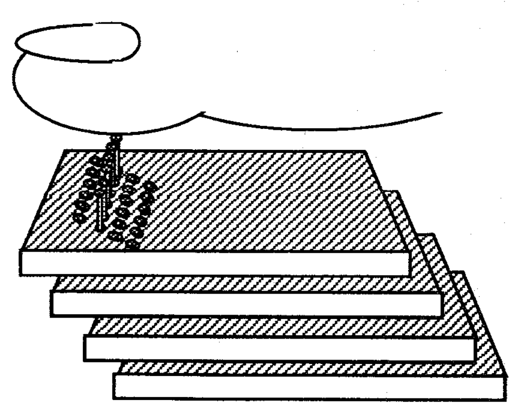

Figure 1. Shape display and human finger tip.

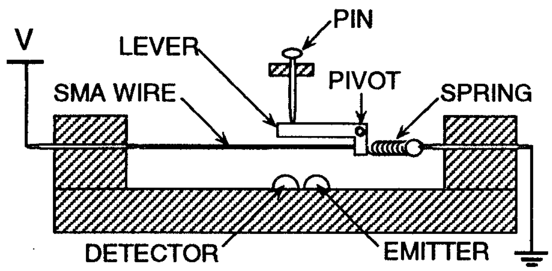

Figure 2. Side view of one actuator.

grasping surface of a force-reflecting teleoperated master robot hand. This poses extremely difficult design challenges. First, the display must be small enough that it fits between the fingers when manipulating an object, and light enough to avoid loading the master and limiting force reflection range and responsiveness. In addition, because it is located at the point of contact between the manipulator and the operator's finger tip, it must be strong enough that the entire contact force can be supported by the display elements while maintaining the desired shape. Finally, the display's spatial and temporal bandwidth should approach the capabilities of the human cutaneous system. Based on a survey of psychophysical and neurophysiological data (e.g. Johansson and Vallbo 1983, Loomis and Lederman 1986), we selected design goals of approximately 2 mm center-to-center element spacing, 3 mm total vertical excursion, 10 Hz bandwidth, and at least 1 N force per tactor.

2 Mechanical Design

The shape display raises pins against the human finger tip skin to approximate the desired shape (Figure 1). We selected shape memory alloy (SMA) wires as actuators because of their very high force-to-volume and force-to-weight ratios. The mechanical design of one element of the shape display is shown in Figure 2. A length of SMA wire is attached to a rigid frame at one end and to a small lever at the other. A spring connected between the lever and the frame keeps the wire in tension and provides a restoring force. The SMA wires are actuated by heating with an electric current. The elevated temperature results in a material phase change which increases the tension and/or shortens the length between the ends of the wire. This causes the lever to pivot about a fixed shaft. The other end of the lever then forces up a pin which rests against the tip of the operator's finger.

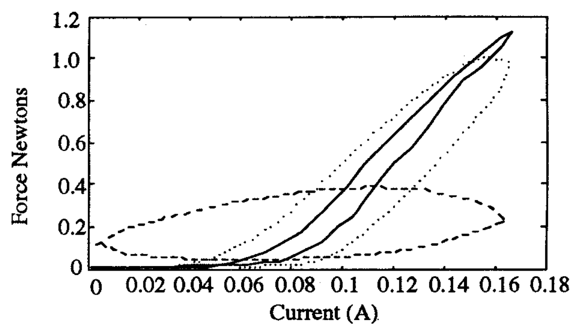

Figure 3. Force versus current for triangle wave inputs of 0.01 Hz (-), 0.1 Hz (..), and 1 Hz (- -).

The levers provide a 3:1 reduction in force and amplification in displacement. The wires we use are 30 mm long and 0.075 mm in diameter, with a 90° C critical temperature. The shape display consists of four layers, slightly offset, each layer having six actuators. The center-to-center spacing of the tactors is approximately 2.1 mm.

3 SMA Characteristics

SMA actuators are difficult to accurately control due to long thermal time constants, hysteresis, and other nonlinear characteristics. To illustrate these difficulties and to motivate our controller design, we describe a basic performance measurement for the SMA wires used in our display. We measured isometric forces as a function of input current directly at the lever of the display. Figure 3 shows the output force generated by applying triangle wave current inputs to the wire. The solid curve represents a 0.01 Hz triangle wave current input (i. e. 50 sec ramp up and 50 sec ramp down). At this slow time scale the wire is almost in thermal equilibrium at each instant, so this represents the "steady state" dependence of force on current. Hysteresis of 10-20% of the full force range is evident in this curve; this hysteresis is intrinsic to the phase change which produces the shape memory effect used for actuation.

The other curves, which represent 0.1 and 1.0 Hz frequencies, show an increasing phase lag. This is due to the slow thermal response of the SMA wires. There is a significant delay between the increase of the input current and the appearance of the force increase due to the integrating effect of the thermal mass of the wire. On the descending phase, the delay is due to the slow cooling rate, so that the temperature drops more slowly than the current. Results for free motion

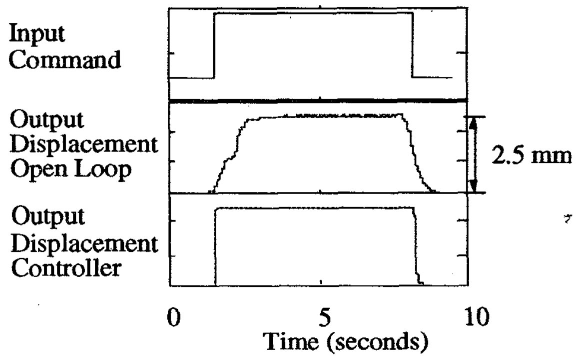

Figure 4. Time response improvement with feedforward compensation and air cooling.

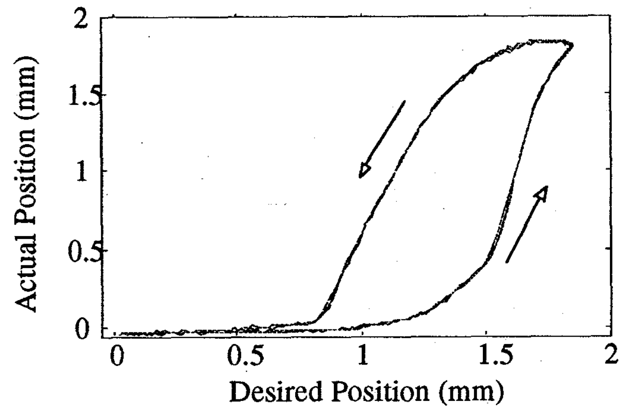

Figure 5. Hysteresis in displacement response to a triangle wave input with feedforward compensation and air cooling.

(zero force) are similar. These effects necessitate the use of appropriate control schemes to achieve the desired performance.

4 Bandwidth Considerations

Our first consideration was the need to improve response times. Our compensator is based on a simple thermal model of the wire. Note that the control input is unilateral in this case: we can only heat the wire with electrical current, while cooling is due to almost exclusively to convective heat transfer to surrounding air. This requires the use of different strategies for increasing and decreasing commands.

Based on the thermal model, a proportional-derivative (PD) feedforward control law with a large derivative term has been implemented. This scheme introduces large current peaks at rapid positive changes in the command to heat the wires quickly. The duration of the peak is critical since a long high current input to the wire will lead to overshoot and even damage to the wire by overheating. To heat the wire at a desired temperature both the amplitude and the duration of the "overload" current must be modulated to compensate for the new heat energy state reached at every servo cycle.

As a first order compensation for the changing initial conditions in heat, the input current to the wire is modulated by adding a weighted average of the previous and present inputs. The feedforward compensation can be described as

$$I_{out}[t] = K_p \cdot F_d + K_v \cdot \dot{F}_d + K_{old} \cdot I_{out}[t - \Delta t]$$

where $I_{out}[t]$ is the current input to the wire, $I_{out}[t\text{-}Dt]$ is the previous input to the wire, F_d is the desired force, K_p is a proportional gain, K_v is a velocity gain and K_{old} is a weighting factor that averages the present and previous commands. This control law results in a rapid response to a step command (derivative term) with a geometric decay (weighted average term), which is tuned to the thermal mass of the wire.

The feedforward compensation also decreases the response time to decreasing commands by diminishing the current at a faster rate due to the derivative term. However, the response to decreasing commands is fundamentally limited by the rate at which heat leaves the wire. Decreasing this time constant requires a higher convective cooling rate. For this purpose we have added small pneumatic jets which force air across the wires.

Based on the thermal model, the cooling rate and derivative feedforward compensation can be balanced to produce a quasi-linear system with symmetric response to rising and falling commands. Even faster response can be obtained by liquid cooling, at the expense of a more complex mechanical design. Figure 4 shows the performance improvement that results from use of the feedforward derivative compensator and pneumatic cooling. Step response rise time (0 to 63%) decreases from 1200 to 65 ms, and fall time from 500 to 65 ms.

5 Hysteresis Considerations

These bandwidth compensation techniques do not eliminate hysteresis, as illustrated by the response

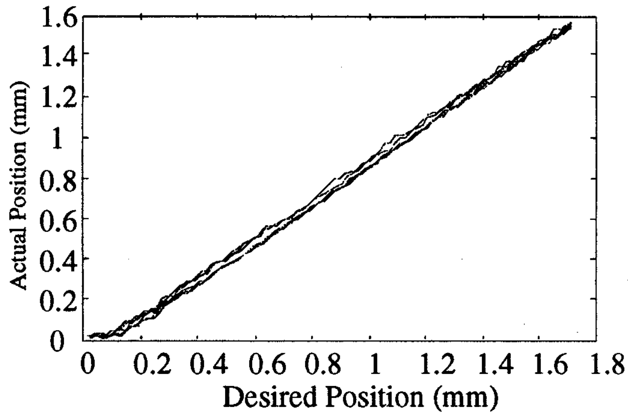

Figure 6. Response to a triangular wave input with position feedback.

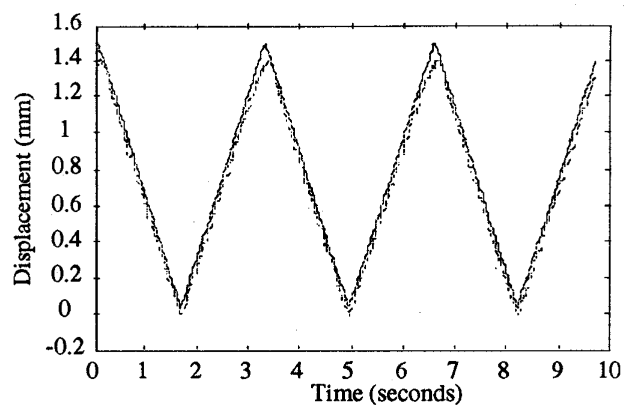

Figure 7. Tracking response with a 27.5 g load with feedforward compensation, air cooling, and position feedback.

to a triangle wave input shown in Figure 5. Previous work on SMA control has shown that it is possible to estimate the phase state of the SMA material through measurements of electrical resistance (Ikuta et al. 1988), which can be used in the design of a controller to minimize hysteresis effects. However, state estimation alone is not sufficient in our application. As the material phase state changes, the effective mechanical modulus and rest length of the wire changes. Thus the phase information specifies the relationship between the length of the wire and the force on the wire, but does not provide a direct measurement of either parameter. The force on the pin elements of the display varies with a number of factors in this application, including the human operator's finger tip skin stiffness, the number of adjacent pins that are raised, and how hard the operator is pushing against the display. Thus direct sensing of either force or displacement is required for good control.

We have elected to sense displacement, as this is the output parameter in most uses of the shape display. The position sensors are infrared LEDs and phototransistors directed at the bottom each lever (Figure 2). As the lever rises, the light reflected back into the phototransistors decreases. The relation between the sensor output and the displacement of the lever has been determined by an independent calibration.

As an initial test of the effectiveness of position feedback in eliminating hysteresis and load dependence, we have used the sensed position signal in a simple proportional position control loop. The addition of position feedback greatly reduces the hysteresis associated with the SMA wires, as shown in Figure 6. In addition, this control scheme reduces the variability between elements (and thus the need to calibrate each element of the display), and decreases sensitivity to variations in human finger tip stiffness.

As a demonstration of the display's ability to follow trajectories under load, we placed a 27.5 g mass on one lever and recorded the response to a triangle wave. Figure 7 shows that even this simple controller results in improved performance in the loaded case. To further improve performance in the loaded case, we have designed a model-based controller which incorporates both SMA and human load terms. The SMA portion includes material phase state estimates based on electrical resistance measurements. This permits inclusion of the effective stiffness and rest length of the wire in calculations of the required actuator force. The human load portion of the model is based on measurements of the mechanical properties of the human finger tip skin. In addition to improving force calculations, the human skin model is used to compensate for skin-mediated interaction between adjacent actuator elements.

6 Conclusions

The techniques used to improve control of the SMA actuators include:

•Faster heating response by feedforward derivative compensation;

•Faster cooling response by pneumatic cooling;

•Reduced hysteresis through the use of position sensing.

These improvements result in a bandwidth with a -3dB point between 6 and 7 Hz (Figure 8). Ongoing work is directed at further raising bandwidth to the desired 10 Hz value through liquid cooling, and implementing the model-based controller using state properties of the SMA material and human skin mechanics.

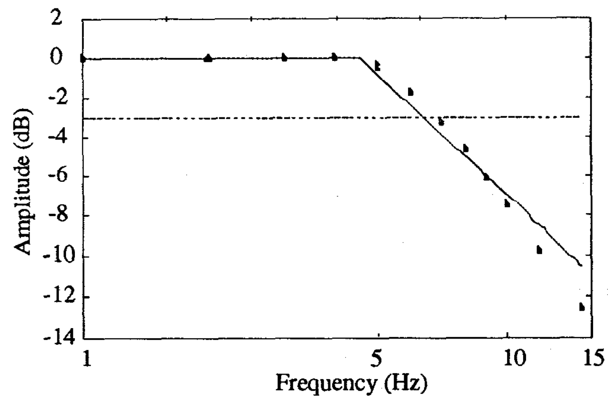

Figure 8. Frequency response with feedforward compensation, air cooling, and position feedback.

Acknowledgments

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