ภาพผนวก

Output จากโครงการวิจัยที่ได้รับทุน สกว.

ผลงานตีพิมพ์ในงานเสนอผลงานที่ประชุมวิชาการ

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Position Control of SMA Actuator for 3D Tactile Display

Saner Jairakrean and Teeranoot Chanthasopeephan*
Department of Mechanical Engineering
King Mongkut's University of Technology Thonburi
126 Pracha-Utid, Bangmod, Thungkru, Bangkok 10140 Thailand
Email: teeranoot.cha@kmutt.ac.th

Abstract - The purpose of this study is to design and fabricate an actuator system for a 3D tactile display. Small size actuator or portable actuator has many possible applications in medicine and industry. In the past, motors have been widely used to create motion in large-area tactile displays. Thus, the device discussed in this paper uses a shape memory alloy (SMA) which allows us to create a small, lightweight and high-resolution tactile display. However, there are also challenges using SMA as actuator. The nonlinear hysteresis properties of the SMA cause difficulties during the control of the display. Our design is an 8x8 display consists of 64 SMA springs to create motion for 64 pin display. Each of the pin display takes approximately 0.4 seconds to response to the input. The pin displacement can travel up to 25mm.

Keywords: SMA-actuator, 3D tactile display, position control of shape memory alloy

I. INTRODUCTION

With the development of faster data processing, haptic interface technology has been increasing use. These are devices that allow a user especially a blind person to interface with a computer via his or her sense of touch. The device such as commercial haptic interface like Phantom from Sensable is used to provide user with force feedback. To communicate through sense of touch, user such as a blind person can also obtain information through tactile display. Consequently, there is also a need for efficient methods to generate motion in these tactile displays.

Existing haptic displays have used numerous techniques to generate motion, including are servomotors[1], electromagnets[2], piezoelectrics[3], and electrostatic/pneumatic actuators[4]. An alternative to these various designs is a shape memory alloy-based actuator. These SMAs yield high power/weight ratios[5] and can be used to create a simple and small mechanism. As a result, tactile displays using this technology are low-cost, lightweight, noiseless, and highly-portable[6]. In previous studies, the most popular design of an SMA actuator uses helical springs to create motion. Each pin's position is controlled by electrical currents flowing through the SMA spring, while permanent magnets define the default position of the pin. Using magnets rather than another means of setting the pin position helps minimize electrical power consumption [7]. However, this method can cause problems with motion control, including non-linear behavior, low bandwidth, slow response, and large amounts of hysteresis [8].

The response speed and position accuracy of SMA based actuators depend on the heating and cooling method [8], the type of spring used to apply force for opposite direction of motion, and the accuracy of the position sensor. To control the actuator, there are four major parameters: temperature, force, displacement, and electrical resistance[5]. While both temperature and resistance can reduce the hysteresis [9, 10] of the actuator, these properties are difficult to be measured precisely for feeding back to the system due to the small size of SMA wire [11].

A mathematical model[12] has been developed to describe the actuator's behavior based on the nonlinear stress-strain hysteresis characteristic of the SMA. Due to high complexity and large number of parameters required to model the SMA spring for controller, we then separate the model into various sub-models. In this paper, we combine modeling methods based on heat transfer theory, phase transformations, and relationship between power input and mechanical displacement. After combining the sub-models, the simple PID control is applied to control the position of the pin display. The 3D tactile display functions through the displacement input of each pin from the computer. This paper is organized as follows: the modeling in this study is described in section 2. Section 3 describes heat transfer model, phase transformation model, and mechanical model of the SMA spring actuator, and controller designed using Matlab/Simulink. Section 4 presents the discussion, the comparison between the simulation, and experimental results. The final part belongs to concluding remarks and future work.

II. PRINCIPLE AND MODELING OF SMA

Shape Memory Alloy is usually called smart material; it is the combination of nickel and titanium (NiTi). These SMAs can mechanically deformed while in a martensitic phase, and subsequently reformed to a "memorized" austenite shape when heated above its transformation temperature. When the austenite is cooled, it begins to change into martensite. This effect of structural transition between a martensitic phase and an austenitic phase is called a shape memory effect (SME). Therefore, there are three major mechanisms (Figure1) which contribute to the motion of the SMA based actuator. These are the heat transfer, the phase transformation, and the dynamics model of the actuator.

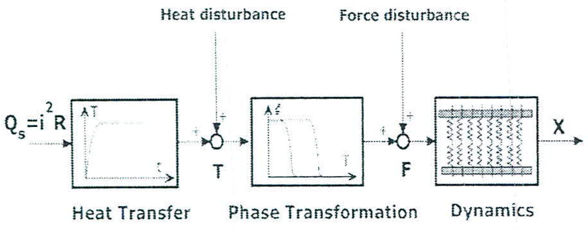

Figure 1: Controlling the SMA actuator through sub-models

A. Heat transfer model of the SMA

Since the response of the SMA actuator depends upon the heat generated by the applied electrical current, it is crucial to model the heat transfer system of the actuator. The rate of heating and cooling of the SMA has an impact on the response time. Thus, we first consider a model of heat transfer derived from conservation of energy. This model consists of the electrical power input, the change of the temperature inside the SMA, and the rate of convection heat transfer from SMA to the ambient environment. The energy equation [13] can be expressed as equation (1):

$$\rho c_p V \frac{dT}{dt} = i^2 R - hA(T - T_\infty) \qquad (1)$$

where: ρ is the density of the SMA, c_p is the specific heat coefficient, V is the volume of the material, T is the SMA temperature, i is the electrical current applied, R is the electrical resistance, h is the convection heat transfer coefficient, A is the surface area of the SMA and T_∞ is the ambient temperature

B. Phase Transformation model of the SMA

The phase transformation model was defined by Liang and Roger [14]to represent the relationship between the input temperature and the martensite fraction. Heating and cooling process causes the change of the matensite fraction between $0 \le \xi \le 1$. The equation of martensite fraction is a function of temperature and can be expressed as equation (2) and (3):
For cooling process

$$\begin{aligned} &\xi(T)=0 && \text{for } T>M_s \\ &\xi(T)=\frac{1}{2}\left[\cos\left(\pi\frac{T-M_f}{M_s-M_f}\right)+1\right] && \text{for } M_f<T<M_s \qquad (2) \\ &\xi(T)=1 && \text{for } T<M_f \end{aligned}$$

where: M_s is the start temperature of martensitic, M_f is the finish temperature of martensitic.
For heating process

$$\begin{aligned} &\xi(T)=0 && \text{for } T>A_f \\ &\xi(T)=\frac{1}{2}\left[\cos\left(\pi\frac{T-A_s}{A_f-A_s}\right)+1\right] && \text{for } A_s<T<A_f \qquad (3) \\ &\xi(T)=1 && \text{for } T<A_s \end{aligned}$$

where: A_s is the start temperature of austenitic, A_f is the finish temperature of austenitic.

C. Mechanical Model of the SMA spring actuator

A helical spring is the most popular SMA shape for an actuator because it can produce more displacement than a straight SMA wire. Our actuators consist of two SMA springs. One spring extends and raises the pin when heated, while the other contracts when heated to return the pin to its original position. Thus, the position of pin is based on tension/compression of two springs while the end-point position defined by using a magnetic latch mechanism.
The force generated by the SMA spring is determined by the constitutive equation proposed by Majima et al [11]. which contains a relationship between the force and martensite fraction and ξ can be expressed as follows:

$$F = Ax + B\xi \qquad (4)$$

Here, the axial load is F and x is the displacement, A and B are constants defined as:

$$A = \frac{d^4 E}{8nD^3}, B = \frac{\pi d^3 \Omega}{8D} \qquad (5)$$

where E is the elastic modulus tensor, Ω is the coefficient tensor, d is the number of active coil spring SMA, d is the diameter of the SMA wire and D is the diameter of the coil spring SMA.
The displacement of the pin display is determined through solving the equation of motion. The differential equation based on Newton's equation can be written as:

$$m\ddot{x} = F_b - F_a - F_e \qquad (6)$$

where m is the mass of the pin actuator, $\ddot{x}$ is the acceleration of pin actuator, F_b is the lower SMA spring force, F_a is the upper SMA spring force and F_e is the force disturbance occurs due to magnetic force. F_a and F_b are determined by equation (4-5).

Properties	Value	Unit
Wire's diameter d	0.2	mm
Mean coil diameter D	2.825	mm
Active coil n	32	
Density ρ	0.645	g/cm^3
Specific heat C_p	0.32	J/g°C
Volume V	8.92	mm^3
Convection surface A	178.31	mm^2
Heat-transfer coefficient h	6	W/m^2°C
Transformation temperatures		

feedback signal which is the resistance obtained from the position sensor on each pin is fed back to the input modules as shown in Figure 6.

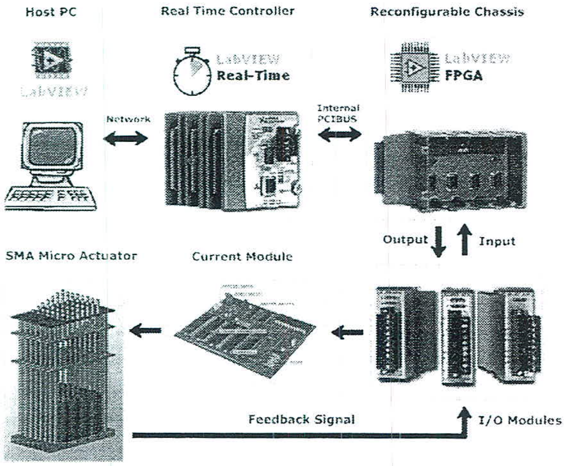

Figure 6: System overview

According to the principles described above, both the heat transfer model and the mechanical model can take the form of transfer functions. The combined model along with the heating power input into the system, and the output displacement are taken into consideration when we designed the controller. We simulated the position feedback control systems using MATLAB/SIMULINK as shown in Figure 7.

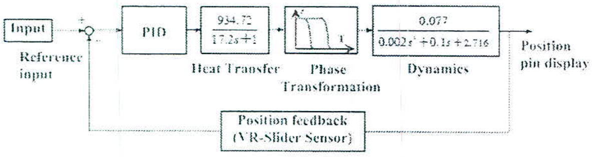

Figure 7: Simulation block diagram

IV. RESULTS

In this paper, we focus on the position control of the pin display. First, the simple PID control is applied to the combined model as presented in part II. The simulation was performed through Matlab/Simulink to display the displacement of the actuator after applying the PID controller. On the other hand, an experiment is performed in order to also observe the displacement of one pin display. The goal is to determine the optimum condition to control the motion of the pin includes the response time each pin takes to travel to the desired position. The experiment is divided into two parts the first part Figure 8-9 correspond to the pin displacement without the magnetic latch mechanism. The magnetic collar is added to the second part of the experiment in order to hold the position of the pin display, therefore that force has resulted in the motion and the displacement of the pin. The condition of the experiment and the simulation are shown in Table2 where K_P and K_D correspond to proportional and derivative gain.

The comparison between the simulation and the experimental results are shown in the following figures:

Figure	K_P	K_D	Condition
7	1.5	0	Without magnetic force
8	1.5	3.5	
9	1.5	0	With magnetic force
10	1.5	3.5	

Table2: The criterions used to perform each simulation and experiment.

The results show the step response of the pin display. The desired position of the pin is set at 25mm for Figure 8-9. We see from Figure8 that the steady state error and the overshoot are too large. The first 0.23 seconds of the closed-loop is due to the effect of phase transformation which takes place when the SMA spring is heated up.

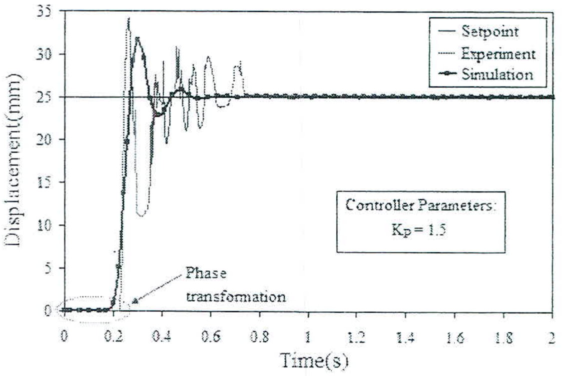

Figure 8: Step response of SMA actuator using the P controller.

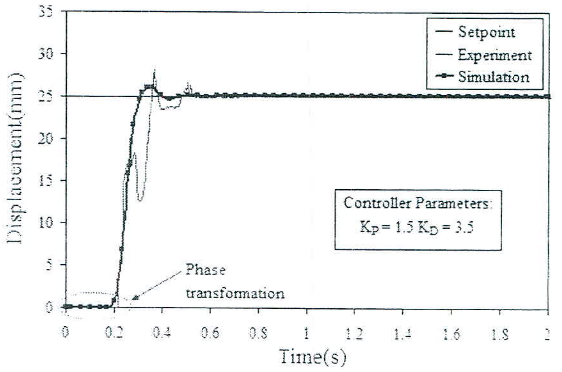

Figure 9: Step response of SMA actuator using the PD controller.

The results illustrated in Figure 9 shows the reduced steady state error after the PD controller is applied. At the same time, the overshoot decreases in comparison with P Control. The improvement is shown once K_D is applied. Without the magnetic latch mechanism, the pin takes approximately 0.56seconds to reach steady state position.

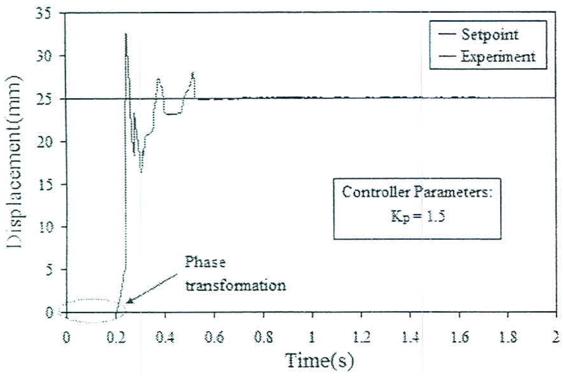

Figure 10: Step response of SMA actuator with magnetic latch mechanism

Figure 10 and 11 show the benefit of the magnetic latch mechanism which helps reducing the errors when the pin displaces (as compared to Figure 8-9) along with reducing the time it takes to reach steady state position. In this case, the desired position is set at 25mm. The PD control in Figure 11 eliminates overshoot but increase the rise time; however the steady state error is reduced to zero and the time response is transcendent to the case of the process without a magnetic force disturbance. The desired displacement set is 25 mm, and the device reaches steady state within a response time of 0.4 seconds.

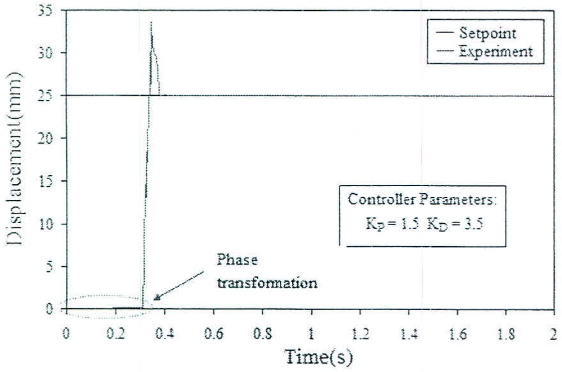

Figure 11: Step response of SMA actuator with magnetic latch mechanism using the PD controller.

V. CONCLUDING REMARKS AND FUTURE WORKS

The performance of 3D tactile display not only depends on the design of the SMA actuator, but also on controller design. We developed both position and position-derivative for this purpose. Simulation and experimental results indicate that the force disturbance from the magnetic latch mechanism and the PD controller has reduces the pin's position overshoot and steady-state error. The maximum displacement designed was 25mm and the device reaches steady state within a response time of 0.4 seconds. We are currently using the smaller diameter of the SMA wire to actuate the device. The response time has been significantly reduced.

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