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Pulse width modulation-based temperature tracking for feedback control of a shape memory alloy actuator

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Abstract

This work presents a temperature-feedback approach to control the radius of curvature of an arc-shaped shape memory alloy (SMA) wire. The nonlinear properties of the SMA such as phase transformation and its dependence on temperature and stress make SMA actuators difficult to control. Tracking a desired trajectory is more challenging than controlling just the position of the SMA actuator since the desired path is continuously changing. Consequently, tracking the desired strain directly or tracking the parameters such as temperature and electrical resistance that are related to strain with a model is a challenging task. Temperature-feedback is an attractive approach when direct measurement of strain is not practical. Pulse width modulation (PWM) is an effective method for SMA actuation and it can be used along with a compensator to control the temperature of the SMA. Using the constitutive model of the SMA, the desired temperature profile can be obtained for a given strain trajectory. A PWM-based nonlinear PID controller with a feed-forward heat transfer model is proposed to use temperature-feedback for tracking a desired temperature trajectory. The proposed controller is used during the heating phase of the SMA actuator. The controller proves to be effective in tracking step-wise and continuous trajectories.

1 INTRODUCTION

The behavior and the properties of SMA depend on the temperature and the stress acting on it. Phase transformation, heat transfer and changes in stress and temperature of the SMA material are highly nonlinear. These nonlinear characteristics present difficulties in designing control systems to control the SMA actuators. Most of the work on SMA modeling and control has concentrated on straight annealed SMA wires and springs whereby the phase transformation results in linear motion. The general approach to controlling the SMA is to directly measure the position of the SMA actuator and use a bias spring or a linear actuator to apply forces on the SMA actuator during cooling to compensate for the hysteresis (Jayender et al., 2008; Liu et al., 2009; Song et al., 2003; Teh and Featherstone, 2008). Then, the strain and the force measurements are fed back to the control loop to generate control inputs using the proposed controllers. (See Sreekumar et al. (2007) and Elahinia et al. (2011) for a review of different linear and nonlinear control strategies). Tracking a desired trajectory is more difficult than controlling the position of the SMA actuator due to the nonlinear nature of the SMA. When SMA is used as an actuator in a compact device, actuating the SMA actuator(s) becomes a further challenge. Direct

measurement of strain and controlling the forces acting on the SMA become impractical. Electrical resistance of the SMA wire changes during phase transformation and it can be used as a feedback to control the position of the SMA actuator. This is an attractive approach since the electrical resistance is an internal parameter and its measurement does not require an additional sensor. However, SMA has a low resistance and most of the work that implement resistance feedback use 22–100 cm length SMA wires (Dickinson and Wen, 1998; Dutta and Ghorbel, 2005; Ma et al., 2004; Teh and Featherstone, 2008) or multiple SMA wires that are connected in series to increase resistance of the SMA wire (Ikuta et al., 1988). During phase transformation the resistance change of a 2.1 cm SMA wire that is annealed in our laboratory is approximately 0.02 Ω . Therefore, using a resistance feedback approach has poor resolution based on the existing hardware available in our laboratory. Temperature-feedback presents a powerful approach to control the strain in the SMA wire using the constitutive model of the SMA. The constitutive model describes the relationship between the stress, strain and the temperature of the SMA actuator (Brinson, 1993; Liang and Rogers, 1990; Tanaka, 1986). Temperature-feedback can be used with a PWM controller for SMA actuation. PWM is an efficient way to actuate the SMA (Ma and Song., 2003; Price et al., 2007) and can be used to control the temperature of the SMA wire along with a linear compensator such as PI, PD, or PID. SMA is a natural low pass filter and is not disturbed by the switching of the input power. PWM can be easily implemented using hardware or software and it is robust to external disturbances. PWM also enables multiple SMA actuation simultaneously using a single power supply (Ayvali et al., 2012; Ho and Desai, 2010). In our previous work, the relationship between the temperature of the SMA wire, strain and the external stress was modeled using the constitutive model of the SMA and it was demonstrated that the strain of the SMA wire can be indirectly measured using the constitutive model (Ayvali and Desai, 2012). This enables the use of temperature-feedback to control the strain in the SMA actuator. The constitutive model relates the desired strain trajectory to a desired temperature trajectory.

The motivation behind this work is towards controlling the strain of the SMA actuator with temperature-feedback to control the tip motion of the discretely actuated steerable cannula shown in Figure 1. The cannula is composed of straight segments connected by SMA actuators that generate local bending at discrete locations along its length. To control the position of the cannula, a combined image guided control and a model based temperature-feedback control is proposed. A preliminary PWM-based vision feedback controller was developed as the cannula will be eventually steered with image guidance in a MRI, CT, or ultrasound imaging environment (Ayvali et al., 2012). This work focuses primarily on the temperature-feedback aspect of the combined controller. When the image feedback from the imaging modality is not optimal, the controller can switch to the temperature-feedback controller. In this combined approach, the bending angle (strain) is measured by the imaging modality and the temperature is measured using the temperature sensor. When the strain and the temperature of the SMA actuator are known, the external stress acting on the SMA can be found using the constitutive model of the SMA. Therefore, temperature-feedback can also be used to sense the external forces acting on the cannula as the cannula is steered inside the soft tissue.

In trajectory planning, repeated switching between antagonistic actuators is not desirable since that increases the temperature of the two SMA actuators which in turn increases the elastic modulus. The elastic modulus of the high temperature austenite phase is 1.5–2 times higher than that in the martensite. Therefore, the actuated SMA wire also needs to overcome the high mechanical resistance of the unactuated SMA wire. This is not energy efficient and should be avoided. When one of the actuators is actuated the other one is naturally deformed. If the bending direction needs to be reversed, the controller switches to the antagonistic SMA actuator once the actuated SMA wire is cooled to the martensite phase. This approach increases the execution time of a joint trajectory. However, there is no need to model the hysteresis loop in this approach and this simplifies the control problem. Minimum number of switching between the actuators can be given as a constraint in trajectory planning and hence switching between the actuators can be minimized.

In this work, a PWM-based nonlinear PID controller with a feed-forward heat transfer model is proposed to utilize temperature-feedback for tracking a desired temperature trajectory. Constant gain controllers result in high errors as the temperature of the SMA wire increases. It is important to investigate the heat loss and the relation between the supplied power to the SMA wire and the corresponding maximum temperature that can be reached. The relation between the duty cycle of the PWM controller and the corresponding maximum temperature that can be achieved needs to be modeled to implement a feed-forward term that compensates for the heat loss.

This paper is divided into the following sections. In Section 2, the materials and methods are introduced which involve the arc-shaped SMA actuator, implementation of the PWM-based controller and the heat transfer model. The constitutive model of the SMA and the experimental setup are also explained in this section. In Section 3, experimental results of the controller are presented. Finally in Section 4, we make some concluding remarks.

2 MATERIALS AND METHODS

In this section, the details of the arc-shaped SMA are presented. The experimental setup used in strain measurements and the constitutive model which relates the temperature to the strain of the SMA are introduced next. As the temperature of the SMA wire increases, the heat loss also increases. Therefore, it is important to find the relationship between the temperature and the current supplied to the SMA actuator. Thermal modeling enables designing a feed-forward term to improve the performance of the controller. Finally, the details of the the PWM-based controller implementation are presented.

2.1 Arc-Shaped SMA

The SMA actuator is a 0.05334 cm diameter drawn nitinol (manufactured by Memry, Inc.) wire and has 2.1 cm length. The SMA wire is deformed into an arc shape and clamped down to a ceramic fixture during annealing. Heat treatment takes 40 minutes followed by quenching the SMA in a ice-water mixture. After the annealing process is completed, the SMA has one-way shape memory and upon heating the SMA above its transition temperature, the SMA can transform into the desired arc shape (see Figure 2). If we consider

an initially straight wire bent into the circular arc shape as shown in Figure 3, the relationship between strain and the arc radius can be derived as:

$$\phi\left(r+\frac{d}{2}\right)=\ell+\varepsilon\ell, \quad \phi=\frac{\ell}{r} \Rightarrow r=\frac{d}{2\varepsilon} \quad (1)$$

where, d , is the diameter of the SMA wire and ℓ is the length of the section of radius, r , and arc angle, ϕ . The original arc shape has 1.37 cm radius of curvature and straight configuration corresponds to 0.0195 (1.95%) strain.

Most of the research in SMA characterization and modeling are done on straight annealed SMA wires and springs. There is not much work done in modeling and control of SMA actuators that are annealed in an arbitrary shape. When a commercially available straight annealed SMA wire is used, its mechanical, electrical and thermal properties are available from the manufacturer. The drawn nitinol does not exhibit shape memory effect prior to the annealing. The mechanical, electrical and thermal properties of the SMA wire need to be determined after annealing. The uniaxial testing devices and experimental setup used in characterizing straight annealed SMA wires are not applicable when the SMA wire is annealed in an arbitrary shape. For example, measuring the elastic modulus in the austenite phase is not possible using the conventional tensile testing machine since the SMA wire does not move along a line and it moves in a plane as the temperature of the SMA increases. In our previous work a characterization procedure was presented to find the parameters of the SMA (Ayvali and Desai, 2012). Such an arc shape SMA can then be used in a robotic device to generate joint torques. The arc-shaped design expands the application areas for the SMA.

2.2 Experimental Setup

To measure the strain in the SMA, the experimental setup shown in Figure 4 is used. The apparatus consists of a rotary encoder and a pin attached a fixed distance, L , away from the center of the encoder. Initially, the SMA wire is at room temperature in the straight configuration. As the SMA wire transforms from the straight configuration to an arc shape, it pushes the pin. The rotation of the pin is recorded using the encoder. From the apparatus geometry, the relation between encoder reading and the radius of curvature can be found using Equation (2). The geometry of the setup is shown in Figure 5. The location of the encoder pin is shown as (x,y) . When the SMA wire is straight, the radius of curvature is infinite. Since the strain is computed using the radius of curvature of the SMA wire, the analysis starts from $\theta = 0^\circ$ (see Figure 6). There is a cable connected to the SMA wire and it is routed around a screw. The cable can be connected to a mass via the pulley to apply constant loading or it can be connected to the extension spring to apply variable loading.

$$(L\cos\theta+x)^2+(L\sin\theta+y-r)^2=r^2 \quad (2)$$

2.3 Constitutive Model

Stress, strain and temperature are the three variables that are used to describe the SMA behavior. Constitutive models are commonly developed for quasistatic loading assuming that the material is in thermodynamic equilibrium (Brinson, 1993; Liang and Rogers, 1990; Tanaka, 1986). Tanaka modeled the strain, ϵ , temperature, T , and martensite volume fraction, ξ , as the only state variables. The constitutive equation is given as (Tanaka, 1986):

$$\sigma - \sigma_o = E(\xi)(\epsilon - \epsilon_o) + \Omega(\xi)(\xi - \xi_o) + \Theta(\xi)(T - T_o) \quad (3)$$

where $E(\epsilon, \xi, T)$ represents the elastic modulus, $\Omega(\epsilon, \xi, T)$ is the phase transformation tensor and $\Theta(\epsilon, \xi, T)$ is thermal coefficient of expansion for the SMA material. The strain due to the thermal coefficient of expansion is neglected since it is much lower than the strain due to the phase transformation. The terms associated with subscript 'o' refer to the initial state of the material. The elastic modulus is defined as:

$$E(\xi) = E_A + \xi(E_M - E_A) \quad (4)$$

The phase transformation constant, Ω , can be expressed as (Liang and Rogers, 1990):

$$\Omega(\xi) = -\epsilon_L E(\xi) \quad (5)$$

where ϵ_L is the maximum recoverable strain. In our previous work (Ayvali and Desai, 2012), a cosine function developed by Liang and Rogers was used for the martensite volume fraction. During the martensite to austenite ($M \rightarrow A$) phase transformation, ξ , is given by (Liang and Rogers, 1990):

$$\xi = \frac{\xi_o}{2} \{ \cos [a_A(T - A_s) + b_A \sigma] + 1 \} \quad (6)$$

where a_A , b_A are constants defined by transformation temperatures and the stress influence coefficient. The experimental setup shown in Figure 4 was used to characterize the SMA wire. The details of the characterization of the SMA actuator and the cannula after everything is assembled can be found in Ayvali and Desai (2012).

Martensite volume fraction determines the shape of the temperature-strain curve. The shape of the curve that describes the change in martensite volume fraction with temperature is independent of the SMA phase transformation phenomena and its dependence on stress. Depending on the SMA material used, this curve can be represented with a cosine expression or an exponential expression. Tanaka used an exponential function for the martensite volume fraction, ξ . During the phase transformation from the martensite phase to the austenite phase ($M \rightarrow A$), ξ is given by:

$$\xi = e^{a_A(A_s - T) + b_A \sigma} \quad (7)$$

Figure 7 shows that an exponential expression provides a better fit than the cosine expression for the martensite volume fraction as the wire is heated. Hence in this work, the

exponential expression for the martensite volume fraction will be used. The properties of the SMA actuator are given in Table 1.

2.4 Thermal Modeling

The heat transfer properties of the SMA need to be determined to find the relation between the current supplied to the SMA and the temperature of the SMA. Heat transfer equation of SMA is commonly defined in terms of input power to the SMA and it depends on the specific heat and the convection coefficient of the SMA (Amalraj et al., 2000; Dutta and Ghorbel, 2005; Jayender et al., 2008). Digital signal calorimetry (DSC) measurement is required to find the specific heat of the SMA. The convection heat transfer coefficient is commonly calculated using the empirical relationship for heat transfer over a horizontal or vertical cylinder based on the configuration of the SMA wire (A.Pathak et al., 2010; Prahlad and I. Chopra, 2003; Velazquez and Pissaloux, 2009). The shape of the SMA actuator changes during phase transformation and a fixed cylindrical geometry assumption cannot be used as in straight SMA wires. Bhattacharyya et al. (2002) and Senthilkumar et al. (2012) showed that temperature-current relation of SMA can be represented with an empirical relation:

$$T(t) = T_{\infty} + \frac{a_1}{a_2} IR(1 - e^{-a_2 t}) \quad (8)$$

where I is the current supplied to the SMA, R is the electrical resistance of the SMA, a_1 and a_2 are the parameters to be determined through experiments. The resistance change of the SMA actuator during phase transformation is less than 0.1Ω and it is assumed to be constant. The term $\frac{a_1}{a_2}$ is the time constant and $\frac{a_1}{a_2} IR$ represents the steady-state value. The temperature-current relationship depends on the SMA material used and the dimensions of the SMA actuator. Therefore, the constants a_1 and a_2 are also material dependent.

2.5 PWM-based Nonlinear PID Controller

PWM is implemented with a switching circuit. Sensoray 626 DAQ card generates a digital on/off signals to control the solid state relays (SSRs). The maximum turn on time of the SSR is $50\mu s$ and the maximum turn-off time is $300\mu s$. The discrete on/off control signal converts the continuous current into an equivalent PWM output signal. The heating time of the SMA wire, t , in a heating period, P , is computed using the desired control law – t/P is the duty cycle. During the interval t , the switch for the selected SMA wire is closed and current is supplied for t milliseconds. Once the interval is over, the switch is opened until the end of the period, P . The controller can switch to other SMA wires once the heating time of the actuated SMA wire is completed. Therefore, multiple SMA wires can be actuated in the same period.

Shameli et al. (2005) added a cubic term to PID and proposed using a $PID-P^3$ controller to reduce the settling time and overshoot of the SMA. For a small error, the cubic term vanishes and the controller works as a regular PID controller. Rahman et al. (2008) introduced a nonlinear PID (NPID) controller that has a quadratic and a cubic term. When the error is small, the cubic term tends to vanish but the quadratic term still produces a nonlinear control effort. As the temperature of the SMA wire increases, the steady-state

error increases due to increased heat loss and nonlinear dynamics of the SMA actuator. A NPID controller with a feed-forward term given by Equation (9) is used to calculate the required heating time of the SMA actuator. t_h is the feed-forward term and it represents the minimum heating time that is required to reach a desired temperature. The feed-forward term compensates for the heat loss. The integrator is adaptive and depends on the desired temperature of the SMA wire, T^d , to improve the steady-state response.

$$\Delta t = K_p e + K_D \dot{e} + K_I (T^d) \int e + K_T (e^2 + e^3) + \Delta t_h \quad (9)$$

In Equation (9) K_p , K_D , K_I and K_T are the coefficients of the PID controller and e is defined as the difference between the desired and the current temperature of the SMA wire. Figure 8 shows the block diagram of the controller. The blocks that are inside the dashed line are implemented in software. The PWM signal is implemented in the software. The algorithm runs on Windows XP at 500 Hz to obtain high resolution PWM signal.

3 EXPERIMENTS AND RESULTS

3.1 Thermal Modeling

To model the relationship between the temperature and the current supplied to the SMA actuator, different current inputs are applied to the SMA wire. To ensure good thermal contact between the RTD sensor and the SMA wire, a thermally conductive paste (Omegatherm 201) is used. Figure 9 shows the temperature profiles obtained from the experiments. The parameter a_2 in Equation (8) was set to 0.047 and the steady-state temperature values obtained from the experiments were compared to the steady-state term in Equation (8). The parameter a_1 can be determined by a linear relation in I as:

$$a_1 = 49.1I + 18.6 \quad (10)$$

PWM has a high energy density. PWM results in a faster response and a higher steady-state temperature compared to continuously supplying the average current value. For instance, a 2A PWM signal with 50% duty cycle results in a faster response and a higher steady-state temperature compared to continuously supplying 1A. Figure 10 shows the temperature profiles for different period and heating time values for 2A current. Period values between 50ms – 500ms were tested. A smaller period value may lead to system instability and a high value may result in temperature drop when the current is off. The effect of period P can be neglected in this range and only the duty cycle $\frac{\Delta t}{P}$ is important. This implies that if more than one SMA wire needs to be actuated, a longer period can be selected to monitor all the wires in the same period. A relation similar to Equation (8) can be defined to obtain the temperature profile using PWM:

$$T(t) = T_\infty + \frac{a_1}{a_2} IR \left(\frac{\Delta t}{P} I \right) (1 - e^{-a_2 t}) \quad (11)$$

The difference between Equation (8) and (11) is the addition of the $(\frac{\Delta t}{P}I)$ term. Figure 11 shows the temperature profiles for different current inputs and heating times for $P=200\text{ms}$. Using $R=0.35\ \Omega$ and setting $a_2=0.047$ results in:

$$a_1 = 7.99e^{-5.417\frac{\Delta t}{P}I^2} + 3.413e^{-0.112\frac{\Delta t}{P}I^2} \quad (12)$$

A linear relationship can be obtained for a_1 as in Equation (10) if a constant current is used. Based on the open loop experiments in Figure 11, a relation between the PWM parameter $(\frac{\Delta t}{P}I^2)$ and the maximum temperature that can be reached is obtained. The maximum temperature increase that can be achieved is defined as $T = (T_{ss} - T_{\infty})$ where T_{∞} is the ambient temperature and T_{ss} is the steady state temperature. T_{ss} values for different PWM input parameters can be obtained from Figure 11. If PWM input parameter is plotted versus T , the trend is linear. Figure 12 shows the relation between the desired increase in temperature, T , and the PWM input parameter. The temperature change is used instead of the final steady-state temperature since the ambient temperature, T_{∞} , might be different for each experiment. The linear fit given by Equation (13) was obtained from Figure 12 and it is used to determine the minimum heating time, t_h , that is required to reach the desired temperature. For each sample of the desired temperature trajectory, T^d , T is calculated by replacing T_{ss} with T^d . Then, the corresponding t_h is obtained using Equation (13).

$$\left(\frac{\Delta t_h}{P}I^2\right) = 0.05515\Delta T - 0.16978 \quad (13)$$

3.2 PWM-based NPID Controller

The parameters of the controller were set to $K_p=55$, $K_D=45000$, $K_I=0.0001T^d$, $K_T=700$. The following conditions were implemented in the algorithm:

1. Until the temperature of the SMA actuator is within 1°C of the initial value of the temperature profile, the integral term $(K_I(T^d) \int e)$ is not used.
2. The minimum pulse width is limited by the heat transfer model: $t_{min} = t_h$
3. The maximum pulse width is limited to $t_{max} = t_{min} + 20$
4. Initially, the pulse width calculated using the heat transfer model is used to heat up the actuator until the temperature is within 2°C of the desired temperature: $t = t_h$ if $e > 2^\circ\text{C}$
5. The pulse width is set to 0.2 times the minimum pulse width if there is an overshoot (rather than turning the current off): $t = 0.2 t_h$ if $e < 0^\circ\text{C}$

Initially heating the SMA wire with a duty cycle calculated using Equation (13) prevents overheating. It also limits the strain rate. A high strain rate causes internal heating and increases the temperature of the SMA wire reducing the reliability of the constitutive model. The quasistatic loading rate can be assumed to be 0.0005 s^{-1} (Pralad and I. Chopra, 2003). To satisfy quasistatic loading 0.0195 strain (straight configuration to maximum curvature)

should be recovered in more than 39 seconds. This corresponds to approximately $1.6\text{ }^{\circ}\text{C s}^{-1}$. Note that the response time of the SMA actuator can be substantially increased. Fast response is not a crucial requirement for a surgical procedure and high strain rates corresponds to a quick deformation and tearing of the tissue. Hence, this is not desirable. If a faster response is required, the effect of strain rate on the temperature needs to be taken into account in the constitutive model (Prahlad and I. Chopra, 2003). The feed-forward term determines the minimum and the maximum heating times for a desired temperature. This is similar to variable structure control (Grant and Hayward, 1997). The desired temperature controls the sliding surface and the boundary layer is determined by t_h . When the initial value for the desired temperature profile is much higher than the temperature of the SMA wire, the integral term accumulates until the temperature of the wire reaches the desired value. This initial heating period results in overshoot due to large values in the integral term. Therefore, the integral term is not used until the temperature of the SMA actuator reaches the initial value of the temperature profile. The feed-forward term is used to guarantee that the temperature of the SMA actuator reaches within a close range of the desired temperature. When the desired temperature is updated, initially the error is large. Setting a limit to the maximum pulse width limits the initial rate of temperature increase. When the temperature of the SMA actuator exceeds the desired temperature, the current is not shut-off completely. Stopping the current flow results in sudden temperature drop and causes chattering in the control signal (Elahinia, 2001). The minimum current supplied to the SMA actuator should be low enough to let the SMA wire cool down but high enough to compensate for the heat loss and prevent sudden temperature drop. The limits for the minimum and maximum pulse width are defined as a function of t_h since heat loss increases with increasing temperature. The gains of the NPID controller are selected by trial and error.

To evaluate the performance of the controller a step-wise input was given as a reference. Figure 13 shows the performance of the controller in tracking the reference. The RMS steady-state error is 0.0551°C . The errors were calculated in the intervals between the time at which SMA actuator reached the desired temperature and the time a new command was sent. Tracking a continuous trajectory increases the complexity of the system, since the desired path is continuously changing. Tracking of continuous temperature profiles can be achieved by sampling the desired temperature trajectories. Figure 14 shows a 6th and a 7th order polynomial reference. The desired temperature is sampled at 2 second intervals. Phase transformation of SMA is a heat driven process and the response of the SMA actuator is slow. For 1°C increase, the response time of the SMA actuator is approximately 2 seconds. Using a higher sampling rate for the reference signal may be preferable, but it is not required. The RMS errors for the 6th and 7th order polynomial trajectories are 0.1472°C and 0.1262°C , respectively. The controller shows great performance and it can not only track step inputs but also continuous trajectories.

Two different experiments were carried out to evaluate the strain using the constitutive model. The experimental setup described in Section 2.2 was used and strain was calculated from the encoder readings. Figure 15 shows a step-wise reference temperature command and the temperature of the SMA actuator. Figure 16 shows the change in strain of the SMA actuator and the strain predicted by the constitutive model. A 7th order polynomial

temperature reference was also applied and Figure 17 shows the change of temperature. The change in strain of the SMA actuator is given in Figure 18. The RMS errors for the strain trajectories in Figure 16 and Figure 18 are 3.4479×10^{-4} and 2.3455×10^{-4} , respectively. A continuous temperature profile results in a smooth change in strain and this is essential for accurate trajectory tracking.

4 CONCLUSION

Various control strategies have been proposed to control the strain or displacement of the SMA actuators. However, controlling the strain rate or the strain trajectory is challenging. When only the position control of the SMA actuator is required, the rate of deformation or the strain trajectory between the two desired set positions can be ignored. If SMA actuator is used in an application that requires trajectory planning, this trajectory corresponds to a strain trajectory. In this work, a temperature-feedback based controller is presented to control the strain of an SMA wire that is annealed in an arc shape using a model-based approach. An empirical model was developed to model the relationship between the temperature of the SMA actuator and the heating time of the PWM controller. This relation was used as the feed-forward term to compensate for the heat loss and to reduce the steady-state error at high temperatures. A nonlinear PID controller with an adaptive integrator and a feed-forward term was implemented. The controller was tested to track step-wise as well as continuous trajectories. The results show that the proposed controller is effective in tracking complex temperature trajectories which enables using temperature-feedback with the constitutive model of the SMA to control the strain of the SMA actuator. The constitutive model of the SMA relates a desired strain trajectory to a corresponding temperature trajectory. Through experiments it was shown that the strain predicted by the model matches with the experimental results. By controlling the temperature of the SMA actuator the change in radius of curvature (thus the strain) can be controlled. Using the proposed controller a desired temperature trajectory can be executed by sampling the temperature values from the desired temperature trajectory. Continuous temperature trajectories can be approximated and smooth strain trajectories can be obtained when the strain rate is limited. In this application, the controller switches to the antagonistic SMA actuator once the actuated SMA wire cools down to the martensite phase. Therefore, the controller is used for the heating phase. This may be a limitation for applications that require fast switching between actuators without waiting for the actuated SMA actuator to cool down to the martensite phase.

Based on the successful implementation of the PWM-based NPID temperature controller, the direction for the future work is towards modeling the heat transfer for different ambient conditions. The feed-forward term determines the minimum and maximum heating time for a desired temperature. The heating time required to reach a desired temperature depends on the ambient conditions. Therefore, the feed-forward term given by Equation (13) needs to be determined for soft-tissue and the heat transfer needs to be modeled when the cannula is assembled.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.

Discretely actuated steerable cannula; each joint has 1 DOF and there are two antagonistic SMA actuators at each joint.

Figure 2.
Phase transformation of SMA

Figure 3.
Relation between strain and arc radius

Figure 4.

1. Rotary encoder 2. SMA fixer 3. Main frame 4. Pulley 5. Extension plate 6. Pin 7. SMA 8. Resistance Temperature Detector (RTD) sensor 9. Extension spring 10. Force sensor

Figure 5.
Geometry of the experimental setup

Figure 6.
Strain vs. temperature

Figure 7.

Change of strain with temperature for Tanaka's model that uses an exponential expression for the martensite volume fraction and Liang-Rogers model that uses a cosine expression for the martensite volume fraction

Figure 8.
The block diagram of the proposed controller

Figure 9.

Temperature profiles for different current inputs. Solid lines represent the temperature profiles obtained using the empirical model.

Figure 10.
Comparison of different pulse widths and duty cycles

Figure 11.

Temperature profiles were obtained for different pulse width and current values for $P=200\text{ms}$. Solid lines represent the temperature profiles obtained using the empirical model.

Figure 12.

Change of the desired temperature increase with the PWM input parameter

Figure 13.
Step-wise temperature references and the temperature change of the SMA

Figure 14.

Continuous polynomial references and the temperature change of the SMA

Figure 15.
Step-wise reference temperature and the change in temperature of the SMA

Figure 16.

The change in strain in the SMA and the strain predicted by the model for a step-wise temperature reference

Figure 17.

A continuous temperature reference and the change in temperature of the SMA

Figure 18.

The change in strain of the SMA and the strain predicted by the model for a continuous temperature reference

Table 1

Material and physical properties of the SMA

Parameter	Value
E_A	104.31 GPa
E_M	48.69 GPa
C_a	30 MPa/°C
A_s	39.5°C
A_f	64.5°C
d	0.05334 cm
r	1.37 cm
ℓ	2.1 cm