Modeling and Control of an Integrated Sensing Shape Memory Alloy Actuator

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Foreword

This report is the result of three months of research at the Mechanical Systems Control Laboratory of the University of California at Berkeley. This wonderful period has been a great experience on both a personal and a professional level. I would like to use this opportunity to thank the people who have in any way contributed to this work.

I would like to thank professor Tomizuka for giving me the opportunity to work in such a motivating research lab and for his feedback on the various research issues. Many thanks also to Evan Chang-Siu who I have been working with on a daily basis. Your enormous commitment, valuable input and solid advice has been of great importance in the course of this project.

Furthermore I would like to thank Brendan Till for both his theoretical and practical input, and Sumio Sugita for his assistance and advice every time difficulties were encountered. Also many thanks for dr. Gummin of the Miga Motor company, who was kind enough to provide SMA wires, actuators and sensors.

Finally I would like to thank the technical staff, who have given their support in electronics and the development of the test setup, and all other students of the MSC Lab: it was a pleasure working with you.
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Chapter 1

Introduction

The human body can be regarded as a highly sophisticated mechanical system with many degrees of freedom. The actuators of this system, skeletal muscle, are unsurpassed by other actuation methods in many areas such as flexibility, compactness and integrated sensing. Utilizing these properties could be useful for a wide variety of purposes but is particularly beneficial when synthetic actuators collaborate with human muscles such as in rehabilitation. Muscles achieve these beneficial properties because they consist of many flexible fibers, and one possible way to mimic this behavior is by using wires of a Shape Memory Alloy (SMA). A SMA has the ability to go through a deformation while remembering its initial shape, to which it will return upon heating.

In this report the preliminary research on SMA’s in the Mechanical System Control laboratory at the University of California at Berkeley is discussed. The ultimate goal is the development of a bio-inspired modular SMA actuator that can be used within a highly versatile platform for rehabilitation devices. First SMA and other modular actuators are compared with the properties of human muscle and specific properties of SMA materials are reviewed. In order to be able to emphasize research purely on SMA behavior a custom actuator has been built to discard phenomena such as friction present in the available standard actuators. Next to hardware also the used software will be discussed. Thereafter the supposed integrated sensing capabilities of the material will be investigated followed by the development of a mathematic model of a SMA actuator. Various controllers have been tuned and these have been tested on several robustness issues. The final chapters will discuss the measurements on efficiency that have been conducted as well as further issues and research possibilities.
Chapter 2

Modular actuators and Shape Memory Alloys

2.1 Modular actuators

Compared to known artificial actuation technologies, skeletal muscles have distinct advantages because of their high power-to-weight ratio, integrated sensing and high flexibility and durability. Muscles have a modular design of energy dense compliant fibers that allows muscle size, shape, mechanical properties and energetics to be varied by varying the number and combinations of their component modules according to need [12]. The fundamental mechanical unit of a muscle is the sarcomere, a tiny cylindrical array of motor proteins and their racks.

Sarcomeres in series make a myofibril, and many myofibrils in parallel make a muscle fiber [7]. Muscle fibers are long, flexible cylinders, ranging from about 10 to 100 microns in diameter and from millimeters to many centimeters in length. These fibers can in turn be used in different architectures, e.g., short fibers in parallel for strength and force, and long fibers for speed and range.

Mimicking this modularity would provide significant improvements over conventional actuator design. The current research investigates recreating this modularity with smart material component actuators and seeks a transformative, flexible, self-sensing and reconfigurable synthetic muscle package. The target application of this new package is rehabilitation therapy and restoration of movement, although the technology could be used in a wider variety of areas.

The platform as described would ideally meet or exceed human muscle characteristics, such as maximum stress, maximum velocity, maximum power per unit mass and the range of active force production. In Table 2.1 several component level actuators have been compared in order to come to a proper choice of technology. The compared methods are pneumatic components, electroactive polymer (EAP) components and shape memory alloy (SMA) components.

Pneumatic actuators function as a contractile element to produce force. The most popular pneumatic actuator is the design McKibben first developed in the 1950’s. It is an elastomer surrounded by a flexible but inextensible mesh that can be inflated by a pressure source to induce contraction. Although a pneumatic actuator has a high power-
Table 2.1: Properties of various actuation methods

<table>
<thead>
<tr>
<th></th>
<th>Human Muscle</th>
<th>SMA (NiTi)</th>
<th>EAP (IPMC)</th>
<th>Pneumatic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max Stress [MPa]</td>
<td>±0.35</td>
<td>&gt;200</td>
<td>0.1-3</td>
<td>Source Dependent</td>
</tr>
<tr>
<td>Power Density [W/kg]</td>
<td>50-100</td>
<td>&gt;1000</td>
<td>±10</td>
<td>Source Dependent</td>
</tr>
<tr>
<td>Bandwidth [Hz]</td>
<td>±2.4</td>
<td>±5</td>
<td>±30</td>
<td>Source Dependent</td>
</tr>
<tr>
<td>Fatigue Life</td>
<td>Long</td>
<td>Long</td>
<td>Long</td>
<td>Short</td>
</tr>
<tr>
<td>Strain</td>
<td>&gt;40%</td>
<td>±8%</td>
<td>&gt;10%</td>
<td>20-30%</td>
</tr>
<tr>
<td>Density [g/cm³]</td>
<td>±1.06</td>
<td>5-6</td>
<td>1-2.5</td>
<td>-</td>
</tr>
<tr>
<td>Self Sensing</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Efficiency</td>
<td>&gt;35%</td>
<td>1-2%</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

In table 2.1 the various candidate actuators are compared with the human muscle. In terms of the bulky peripherals and high pressure source, the pneumatic approach is not a contender of the two smart material approaches, which are both attractive based on their physical properties. The main reason why the focus of this project is on SMA is its superior power density compared to EAP. In the next section SMA will be explained in detail.

2.2 Shape Memory Alloys

The shape memory effect refers to the ability of certain materials to ‘remember’ a shape, even after rather severe deformations: once deformed at low temperatures (in their martensitic phase), these materials will stay deformed until heated, whereupon they will spontaneously return to their original, pre-deformation shape (in their parent or austenite phase). The basis for the shape memory effect is that the material can easily transform from martensite to austenite and vice-versa upon a temperature change. The martensic transformation in SMA’s is a displacive transformation: the atoms are cooperatively rearranged into a new, more stable crystal structure, but without changing the chemical nature of the matrix. The low-symmetry martensite is formed upon cooling of the material from the high-symmetry austenite phase.

Nearly all physical properties of austenite and martensite are different, and thus as one passes...
through the transformation point, a variety of significant property changes occur. One property that changes in a most significant way is the yield strength. Unlike austenite, the martensitic structure can deform by moving twin boundaries, i.e. boundaries between martensite plates. A key property of twin boundaries is that they are quite mobile because all of the bonds remain intact in the twinned structure. This leads to a low yield strength and completely reversible twinning process.

The one-way shape memory effect (OWSM) can be described with reference to the cooling and heating curves in figure 2.2. Starting at a temperature below the martensite finish temperature ($M_f$) the specimen is in the martensitic phase. When it is deformed when the temperature is still below $M_f$ it remains deformed until it is heated. The shape recovery begins at the austenite start temperature ($A_s$) and is completed at the austenite finish temperature ($A_f$). Once the shape has recovered at $A_f$ there is no change in shape when the specimen is cooled to below $M_f$ again, and the SMA can only be re-activated by deforming the martensitic specimen once again. Because the specimen does not change shape upon cooling the effect is referred to as one-way shape memory effect. In contrast to OWSM the two-way shape memory effect (TWSM) will cause the specimen to change back to its low temperature shape upon cooling from above $A_f$ to below $M_f$ (figure 2.3). This changing of shape upon heating and cooling can be repeated indefinitely. In order to produce this two-way behavior, special thermo-chemical treatment is required, which is called training treatment. In this project only two-way SMA's are utilized.
Chapter 3

The experimental setup

The first step in the design of the platform is identifying the characteristics of SMA actuators. Furthermore a model must be developed as well as a suitable control algorithm. The experimental setup that is used for identifying these characteristics is discussed in this chapter, starting with the actuator itself.

3.1 MigaOne Shape Memory Alloy Actuator

The actuator initially used in this research is the MigaOne, the standard actuator from the Miga Motor Company. This contains five two-way Flexinol SMA wires which form a series-resistive electrical circuit. If a current is induced through these wires the resulting increase in temperature will cause the wires to contract. The contraction starts at around 75°C and is fully completed at 110°C. During contraction a force up to 22 N can be obtained. In order to fully return to its initial position the actuator should cool below 60°C. Since the MigaOne provides force only in one direction, a bias spring is attached to the actuator to prevent the wires from ‘bulging’ outward during cooling. The specifications of the actuator are given in Table 3.1. While a contraction time within 50 ms is feasible if sufficient current is provided, (passive) cooling and thus returning to its original position takes much longer. This process could however be accelerated by applying active cooling e.g. thermoelectrically (by a Peltier element), by a fan or by a fluid.

An analog driver is used to power the actuator using a MOSFET switch (metal-oxide-semiconductor field-effect transistor). When the actuator reaches its end-of-travel, the driver immediately cuts power.

<table>
<thead>
<tr>
<th>Stroke</th>
<th>9.5 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output force</td>
<td>Constant 11 N, peak 22 N</td>
</tr>
<tr>
<td>Actuation time</td>
<td>50 ms to position hold</td>
</tr>
<tr>
<td>Max actuation speed</td>
<td>200 mm/s</td>
</tr>
<tr>
<td>Weight</td>
<td>12.8 g</td>
</tr>
<tr>
<td>Dimensions</td>
<td>71×33×2.5 mm</td>
</tr>
<tr>
<td>Wire diameter</td>
<td>0.3 mm</td>
</tr>
<tr>
<td>Wire length</td>
<td>273 mm in 5 segments</td>
</tr>
<tr>
<td>Nominal resistance</td>
<td>3.8 Ω</td>
</tr>
</tbody>
</table>
preventing the device from overheating.

An Alps resistive sensor is used to measure the displacement of the actuator. To reduce measurement noise caused by the switching of the MOSFET, the signal is low pass filtered before it is fed into the analog input (AI). In order to measure the current running through the actuator a 6 A closed loop current transducer is installed. The supply voltage of the actuator is too high to measure directly. Therefore two resistors of 10 kΩ in series (the resistance of the actuator is approximately 4 Ω) are placed parallel to actuator. The voltage measured in between these two resistors is exactly half of the voltage across the actuator.

3.2 Friction and Abbe’s Principle

During preliminary measurements the system did not perform as expected: an offset seemed to occur in the measurements for the self-sensing characteristics (chapter 4), and tuning a PID controller (chapter 6.1) also posed problems because a step in position was measured when switching direction. This was not due to the feedback controller as was concluded after investigating the controller output. After reviewing the mechanical systems it was concluded that the position sensor was not placed correctly: because it was not placed in the line of movement according to Abbe’s principle (figure 3.2), a rotation of the actuator caused a significant measurement error. Because of the wear of the pins supporting the intermediate sections this effect would increase with time.

![Figure 3.2: Abbe’s Principle](image)

![Figure 3.3: The newly designed SMA actuator](image)

Furthermore the intermediate sections, or ‘bones’, are produced by etching because of low production volumes. This produces much sharper edges than other production methods like punching, which on their turn cause a significant amount of severely nonlinear friction. Although this friction could be modeled, it is beyond the scope of this research: when new modular actuators are designed the friction of the MigaOne is not relevant anymore. In order to overcome these issues a new design is made to characterize the SMA wire. This new actuator contains the same SMA wire, MOSFET switch and position sensor as the MigaOne, all set up in one line.

During the course of this research further modifications to this actuator have been made eventually leading to the actuator as shown in figure 3.3. A tuner has been added to assure the same amount of initial force is applied when changing wires. Also a force transducer has been added to allow the experiments regarding efficiency as discussed in chapter 8.
3.3 Real-time controller

Two different real-time controllers and Field Programmable Gate Arrays (FPGA) have been used. The initial controller was a NI cRIO-9004 embedded real-time controller. This is coupled to a NI 9401 8-channel, 100 ns bidirectional digital input module. This module can provide the Pulse Width Modulation (PWM) signal to control the MOSFET and thus the actuator. The displacement, current and force sensor and voltage across the SMA actuator are coupled to a NI 9215 4-channel analog input module. The FPGA of the cRIO runs at a frequency of 40 MHz. This is sufficient to provide the PWM signal and to measure at the exact right moments. The real-time controller is via ethernet connected to a host computer, which acts as the graphical user interface.

However, after a number of measurements and different configurations of FPGA, real-time controller and host computer, this hardware does not live up to the needs of the experiment. In the real-time program a loop frequency of 1 kHz is desired; in reality this number is far from reached and gaps up to 0.3 seconds appear in the measurement data, making it far too inaccurate for control purposes. The cRIO is usually used as a low-level real-time controller where most calculations are executed on the FPGA. The real-time loop thus runs at a relatively low frequency discarding the need for a fast CPU. In our case however it is also used for graphical purposes and more calculations since this is easier and faster to implement in the real-time program than on the FPGA, which only uses integers and needs to recompile after every change.

Therefore it is decided to switch to a FPGA PCI 7833R. This is built in a regular desktop pc dedicated to this purpose, which has a much faster processor than the cRIO. This real-time controller does reach the desired loop frequency of 1 kHz. Sensors and actuators are connected directly to the FPGA via a breakout box.

3.4 Software

The software used for control is NI LabVIEW. A ‘project’ with three programs has been developed to control the actuator and acquire the desired measurements. The program at the lowest level runs at the FPGA. It acquires the data from the breakout box as well as constructing and sending a PWM signal. The voltage at an analog input channel is acquired as an integer value between 0 and $2^{16} = 65536$ and sent directly to the realtime program. Not all sensors are sampled at the same moment: the position sensor picks up severe noise in the beginning of the duty cycle so this one is sampled near the end of a PWM period. Voltage and current on the other hand can only be measured during ‘on-time’ and should thus be sampled as quickly as possible to reduce the required minimum duty cycle as much as possible, taking into account the settling time (see section 4.1).

Furthermore two PWM signals are constructed: the first one simply divides the FPGA frequency by the PWM frequency to get a number of ‘total ticks’ that one PWM period takes. The product of this number with the desired duty cycle is the number of ‘ticks’ that the PWM signal should be on and for the remainder of the period it should be off. The second PWM signal does the same for multiple actuators (chapter 9), i.e. it divides the total number of ticks by the number of connected actuators. The latest feature of the FPGA program is a timed stacked sequence of Interrupt Requests which provide a handshake with the realtime program to ensure that the desired loop frequency of that program is met. The FPGA has enough room to accommodate the control loop entirely but this would require recompiling after every structural change. This would slow down the process of doing experiments significantly and therefore the control loop is programmed in the real-time program.
The real-time controller runs the primary control loop at a loop frequency of 1 kHz. The data received from the FPGA is first converted to the voltage. Since the FPGA has a range of -10 V to 10 V the conversion factor is: \( \frac{20}{2^{16}} \). Since the voltage range is not exact a fine tuning is required. Subsequently the voltage is converted to position, current or force depending on their respective calibration data. The control loop is a standard SISO control loop with feedforward. It is possible to switch between controllers during operation. Initially the real-time program was also used to display results and to save data. In order to address the fact that the loop frequency at the cRIO did not reach 1 kHz these two tasks are transferred to a host program.

The communication between the host and the real-time program leads through a data library. The size of the variables in this library and the buffer size can be chosen according to need. In order to save data an empty array is initiated with a predetermined size since increasing the array when new data is received will slow the program down. If the record mode is enabled a loop with a shift register checks if new data is received and will put this on the allocated position in the array. As soon as the program is stopped the array will be saved regardless of the extent to which it is filled.
Chapter 4

Integrated sensing characteristics of the SMA actuator

One of the interesting features of SMA actuators is their high power to volume ratio. This could be maintained if the need for an additional displacement sensor is discarded and the actuator could determine its own displacement. During the change of crystallographic structure and shape of the SMA wire, the electrical resistance changes too. According to [11], the change in electrical resistance of the SMA wire could be used to measure the displacement. Especially at high SMA temperatures the correlation between displacement and resistance becomes almost linear.

4.1 Practical issues

One of the challenges when measuring the self-sensing characteristics of the SMA wire is coping with the use of PWM control. This makes the measurements more difficult because when only one power source is used, resistance measurements can only be conducted during ‘on-time’ of the PWM signal, since at ‘off-time’ there is no voltage across and thus no current through the SMA wire. Therefore a small duty cycle must be applied even when cooling. The dynamic characteristics of the electrical system were determined by connecting an oscilloscope to the setup. The (simulated) behavior displayed in figure 4.1 is characteristic for the setup, although it was slightly dependent on the supply voltage.

The time it takes the voltage across and the current through the SMA wire to reach steady state typically varied around 50 µs. At a PWM frequency of 1000 Hz this would imply a minimum duty cycle (DC) of 0.05 is required to do an accurate measurement. Preliminary measurements immediately showed the first practical objection to this strategy: the 0.05 DC causes a significant increase in cooling time at a supply voltage of 5 V. Using higher supply voltages means that more electrical energy is put into the system than is lost to the environment by natural convection, so the system does not cool down at all.

A quick-fix to this problem is decreasing the PWM frequency, in this case to 500 Hz, which is possible due to the relatively slow response of the actuator (the minimum actuation time of the actuator is 50 ms using a high supply voltage of 30 V). A different approach, proposed by Ikuta [6], is to have an additional current source apply a small current to the system at all times. A second precaution to ensure equal behavior during heating and cooling is to set the upper limit of the duty cycle to 0.8 such that during fast heating the voltage and current are not

![Figure 4.1: Dynamic behavior of voltage and current on PWM signal](Image)
constant and therefore do display dynamics. If the duty cycle is maintained at 1, the electronics will remain in steady state and will therefore lead to different results.

### 4.2 Experimental results

The self-sensing characteristics of the SMA wire are investigated using a closed loop response to sine and positive and negative step inputs. A proportional controller is used and a fan applies forced convection to ensure the system still cools down despite a minimum duty cycle. The supply voltage is 10 V. The first input is a sine wave with an amplitude and offset of 4 mm and a very low frequency of 0.05 Hz due to the limits in duty cycle. The results are shown in figures 4.4 and 4.5. The first thing that manifests itself is that at low temperatures and thus small displacement the linear relationship does not hold as was also concluded by Malukhin [11]. If self-sensing is to be used for this particular actuator, position should always remain above 1 mm. Furthermore hysteresis is visible in the position - resistance diagram. Reducing the amplitude as shown in figures 4.6 and 4.7 ensures that the position stays above 1 mm but the hysteresis is still visible.

As mentioned above similar experiments have been conducted using step inputs from 1 mm to 7 mm. These show similar behavior but give a little more insight. It appears that during heating the relationship between position and resistance is linear as can be seen in the red data in figure 4.9. Cooling however shows a relationship that is not as linear thus impairing self-sensing capabilities. A linear fit has been made to the data during heating and cooling and it is clearly visible that the slopes of the two fitted lines are not equal.

Not shown in these figures are the results of similar experiments using supply voltages of 5 V and 7.5 V. These presented comparable results in that the linear fits of the data during heating were equal for all three supply voltages. The same holds for the fits during cooling. Using a lower supply voltage
Figure 4.6: Change of resistance using a sine input with small amplitude

had a further disadvantage because measurement noise deteriorated the images somewhat. This noise is caused by the fact that absolute current and therefore the signal to noise ratio is lower.

Concluding an obvious relationship is visible between resistance and displacement. The extend to which resistance-feedback can be applied in practice however depends on the required accuracy because this is limited by the hysteresis that is present.
Chapter 5

Development of a nonlinear model of the SMA actuator

In order to use nonlinear control algorithms, a nonlinear model of the SMA actuator has to be developed. Keeping the desired modularity in mind, the model should be a numerically efficient and reliable representation of the actuator. Even when multiple SMA-wires are used the simulation should still run fast and accurate. The model presented below is based on the one developed by Elahinia [13] and consists of a dynamic/kinematic model, a wire constitutive model, a phase transformation model and a heat transfer model. These various parts are adapted for the used actuator and described in the sections below.

5.1 Kinematic-dynamic model

The dynamic model of the actuator is based on a standard second order mass-spring-damper system. The spring in the mass-spring-damper system is the linear bias spring present in the actuator and for the sake of numerical efficiency only viscous friction is modeled. Since these dynamics are not dominant in the total behavior this approximation is assumed not to affect results. The total dynamic model of the actuator can thus be described as:

\[ M_t \ddot{x} + c \dot{x} + kx = \sigma A \]  
(5.1)

where \( x \) is the position, \( M_t \) is the total displaced mass, \( c \) is the viscous friction coefficient, \( k \) is the linear spring constant, \( A \) is the cross-sectional area of the SMA wire and \( \sigma \) is the stress in the wire. The strain of the SMA wire and the displacement of the actuator are related kinematically as:

\[ \dot{\varepsilon} = - \frac{\dot{x}}{l_0} \]  
(5.2)

where \( \varepsilon \) is the strain and \( l_0 \) is the initial length of the SMA wire.

5.2 Wire constitutive model

The wire constitutive model, initially used in [10], shows the relationship between stress rate \( \dot{\sigma} \), strain rate \( \dot{\varepsilon} \) and temperature rate \( \dot{T} \). It states:

\[ \dot{\sigma} = D \dot{\varepsilon} + \theta_T \dot{T} + \Omega \dot{\xi} \]  
(5.3)

where \( D = (D_M + D_A)/2 \) is the (average) Young modulus, \( D_A \) is Austenite Young modulus, \( D_M \) is Martensite Young modulus, \( \theta_T \) is the thermal expansion factor, \( \Omega = -D \varepsilon_0 \) is phase transformation contribution factor, \( \varepsilon_0 \) the initial strain and \( \xi \) is the Martensite fraction.
5.3 SMA wire phase transformation model

The SMA wire displays hysteric behavior, enabling the need for different equations for heating and cooling. The reverse transformation from Martensite to Austenite caused by heating is described by:

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

(5.4)

On the other hand, cooling and thus the transformation from Austenite to Martensite are described by:

\[ \xi = \frac{1 - \xi_A}{2} (\cos(a_M(T - M_f) + b_M\sigma) + \frac{1 + \xi_A}{2}) \]  

(5.5)

In these equation, \( \xi \) is the Martensite fraction coefficient and \( \xi_M \) and \( \xi_A \) are the maximum and minimum Martensite fraction obtained during cooling and heating. The parameters \( a_A \) is defined as:

\[ a_A = \frac{\pi}{A_f - A_s} \]  

(5.6)

This ensures the argument of the cosine function stays between 0 and \( \pi \) if no external stress is applied and thus that the martensite fraction stays between 0 and 1. The same holds for \( a_M \). The remaining parameters \( b_A \) and \( b_M \) take into account that the phase transformation temperatures change when the wire is subject to stress. Taking the time derivative of equations 5.4 and 5.5 yields the state equations for heating and cooling:

\[ \dot{\xi} = -\frac{\xi_M}{2} \sin(a_A(T - A_s) + b_A\sigma)(a_A\dot{T} + b_A\dot{\sigma}) \]  

(5.7)

\[ \dot{\xi} = -\frac{1 - \xi_A}{2} \sin(a_M(T - M_f) + b_M\sigma)(a_M\dot{T} + b_M\dot{\sigma}) \]  

(5.8)

5.4 Heat transfer model

Assuming that the temperature is constant throughout the wire, the energy balance of the SMA wire is modeled as:

\[ mc_p \frac{dT}{dt} = \frac{V^2}{R} - hA_c(T - T_\infty) \]  

(5.9)

stating that the variation in temperature is caused by electrical heating and natural convection. In this equation \( m \) is the mass of the wire, \( c_p \) is the specific heat, \( V \) is the supply voltage, \( R \) is the resistance, and \( A_c \) is the circumferential area of the wire. In [13] the resistance of the SMA wire is assumed to be constant. However, if the resistance is measured in order to calculate the displacement \( x \), this measured value can easily be used instead of the constant value. The heat convection coefficient \( h \) is approximated by:

\[ h = h_0 + h_2T^2 \]  

(5.10)

If the actuator is cooled actively this approximation may have to be adapted in order to keep the heat transfer model accurate.

5.5 Improvement of numerical performance

As can be seen in figure 5.2 this model proves to be fairly accurate when comparing an open-loop simulation to a similar experiment. However, several numerical issues occur when implementing it in closed loop simulations. Although in some cases a solution can be obtained by substantially decreasing the stepsize for numerical integration, this is not desirable regarding simulation speed. Therefore a number of improvements are proposed to improve numerical efficiency.

The first issue that has to be tackled is the numerical loop containing \( \dot{\sigma} \) and \( \dot{\xi} \). It can be shown that the ‘loop-gain’ potentially exceeds 1, leading to numerical instability and thus poor convergence of
the solution. The solution is to substitute the phase transformation model into the wire constitution model, thus eliminating \( \dot{\xi} \). The resulting equations for heating and cooling respectively are:

\[
\dot{\sigma} = (1 + \Omega \frac{\xi_M}{2} b_A \sin(a_A(T - A_s) + b_A\sigma)^{-1}(D\dot{\varepsilon} + (\theta_T \frac{\xi_M}{2}a_A \sin(a_A(T - A_s) + b_A\sigma))\dot{T}) \quad (5.11)
\]

\[
\dot{\sigma} = (1 + \Omega \frac{1 - \xi_M}{2} b_M \sin(a_M(T - M_f) + b_M\sigma)^{-1}(D\dot{\varepsilon} + (\theta_T \frac{1 - \xi_M}{2}a_M \sin(a_M(T - M_f) + b_M\sigma))\dot{T}) \quad (5.12)
\]

The second improvement regards the sine function. The model is designed in such a way that the argument of the sine should always be between 0 and \( \pi \). The slope of the sine function however is 1 and -1 respectively at these boundaries, such that a saturation in argument will result in a sudden cut-off. This is numerically undesirable, so an approximation for the sine function is used in simulation in equations 5.11 and 5.12:

\[
\sin(\alpha) = 1.1 - 1.1 \tanh(1.1\alpha - 0.55\pi)^2 \quad (5.13)
\]

where \( \alpha \) is the argument of the sine function. The original cosine function (equations 5.4 and 5.5) and its approximation are plotted in figure 5.5.

### 5.6 Model parameters

The model parameters in table 5.1 are derived from the application sheets of the MigaOne and the Flexinol wire. The constants \( C_A \) and \( C_M \), which indirectly compensate for the change of the austenite and martensite start and finish temperatures under stress, are taken from Elahinia. The austenite start temperature and wire initial (maximum) strain are tuned for a better congruence of model and experimental results.

### 5.7 Model validation

The model as discussed in the previous sections is compared to the actual actuator by applying a step in the supply voltage to the open loop system and measuring the resulting displacement, using supply voltages of 5V, 7.5V and 10V. The experimental results are shown in figure 5.2, along with simulation results. In this figure the modified simulation represents the model where the numerical improvements as discussed in section 5.5 have been implemented.

It appears that the model represents the actuator very well. The biggest deviations occur at the beginning and the end of the transformation: in reality the transformation from martensite to austenite starts a little earlier and ends somewhat later than in the model. This is noteworthy since the the original model does not account for any transformation or displacement are present before the temperature reaches the austenite start temperature. In reality there is displacement immediately after applying a voltage and although it is not confirmed by measurements the assumption seems valid that this is below \( A_s \) since the temperature cannot change instantly from \( T_\infty \) to \( A_s \). After consulting a material scientist it is concluded that the reason for this behavior is presumably that the transition temperature which is mentioned in most literature is in fact a range, and the used resistive heating is far from uniform and thus introduces localized responses. More research is necessary however to take this into account in the mathematical model. The model which is numerically improved actually performs better than the original in this region since it already starts transforming before \( A_s \) is reached.
Table 5.1: Model parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d$</td>
<td>Wire diameter</td>
<td>$0.3 \times 10^{-3}$</td>
<td>m</td>
</tr>
<tr>
<td>$A$</td>
<td>Wire cross-sectional area</td>
<td>$\frac{\pi d^2}{4}$</td>
<td>m$^2$</td>
</tr>
<tr>
<td>$A_{circum}$</td>
<td>Wire circumferential area</td>
<td>$\pi d l_0$</td>
<td>m$^2$</td>
</tr>
<tr>
<td>$l_0$</td>
<td>Total wire length</td>
<td>$273 \times 10^{-3}$</td>
<td>m</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density of SMA wire</td>
<td>6500</td>
<td>kg/m$^3$</td>
</tr>
<tr>
<td>$m_{SMA}$</td>
<td>Total mass of SMA wires</td>
<td>$d A \rho$</td>
<td>kg</td>
</tr>
<tr>
<td>$D_A$</td>
<td>Austenite Young’s Modulus</td>
<td>$83 \times 10^9$</td>
<td>N/m$^2$</td>
</tr>
<tr>
<td>$D_M$</td>
<td>Martensite Young’s Modulus</td>
<td>$34 \times 10^9$</td>
<td>N/m$^2$</td>
</tr>
<tr>
<td>$A_s$</td>
<td>Austenite start temperature</td>
<td>75</td>
<td>°C</td>
</tr>
<tr>
<td>$M_s$</td>
<td>Martensite start temperature</td>
<td>95</td>
<td>°C</td>
</tr>
<tr>
<td>$M_f$</td>
<td>Martensite finish temperature</td>
<td>60</td>
<td>°C</td>
</tr>
<tr>
<td>$C_A$</td>
<td>Austenite stress correction factor</td>
<td>$10.3 \times 10^6$</td>
<td>N/(Km$^2$)</td>
</tr>
<tr>
<td>$C_M$</td>
<td>Martensite stress correction factor</td>
<td>$10.3 \times 10^6$</td>
<td>N/(Km$^2$)</td>
</tr>
<tr>
<td>$c_p$</td>
<td>Specific heat of SMA wire</td>
<td>0.8374</td>
<td>J/kg/°C</td>
</tr>
<tr>
<td>$h_0$</td>
<td>Heat convection constant coefficient</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$h_2$</td>
<td>Heat convection second order coefficient</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$T_\infty$</td>
<td>Ambient temperature</td>
<td>20</td>
<td>°C</td>
</tr>
<tr>
<td>$\theta_T$</td>
<td>Thermal expansion coefficient</td>
<td>$-8.8 \times 10^{-6}$</td>
<td>N/(Km$^2$)</td>
</tr>
<tr>
<td>$k$</td>
<td>Bias spring constant</td>
<td>250</td>
<td>N/m</td>
</tr>
<tr>
<td>$M_s$</td>
<td>Mass of one segment</td>
<td>0.004</td>
<td>kg</td>
</tr>
<tr>
<td>$\varepsilon_0$</td>
<td>Initial strain</td>
<td>0.040</td>
<td>-</td>
</tr>
<tr>
<td>$\sigma_0$</td>
<td>Initial stress</td>
<td>$6.3 \times 10^6$</td>
<td>N/m$^2$</td>
</tr>
<tr>
<td>$\xi_0$</td>
<td>Initial Martensite fraction</td>
<td>1</td>
<td>-</td>
</tr>
</tbody>
</table>

In between the start and end of transformation the simulation approaches the experiment very well. In figure 5.3 the simulation is displayed in more detail. In this figure, also the stress $\sigma$ and martensite fraction $\xi$ are shown. These also vary much smoother with the numerical improvements.

5.8 Recommendations for improvement of the model

Although the open loop simulation of the actuator proves to be an accurate representation of the real behavior there is still room for improvement. Closed loop behavior yields different results as controllers designed using the simulation model will in practice not perform as expected. It is expected that this is caused by inaccuracies in the heat transfer model. If the wire is heated above the Austenite finish temperature, the discrepancies between model and reality will not be visible in the open loop experiment but will cause significant changes in closed loop behavior as the wire is cooled below the Martensite start temperature. In order to address this issue the temperature of the SMA should be measured. Attaching a thermocouple to the wire is not very trivial because of the small amounts of energy involved and the difficulty of connecting a thermocouple or any other thermometer to a thin wire. Furthermore there is no term in the heat transfer model that takes transformation energy into account. Simulations including this term did not lead to better results but here more information about the actual temperature may improve results too.

Next to temperature measurements, utilizing the force sensor that is used in chapter 8 might give new insights in the stress response. A further improvement would be to use nonlinear system identification technologies to get a better estimate of all parameters. If these improvements are implemented, the model should be suited for model-based control technologies and closed loop simulations.
Figure 5.2: Simulation and experimental results of step in supply voltage

Figure 5.3: Simulation and experimental results of 5V step in supply voltage
Chapter 6
Controller design

Since the SMA actuator is severely nonlinear, it seems that nonlinear control methodologies are more suited then conventional linear controllers. Besides the more or less standard requirements such as stability, tracking performance, disturbance rejection and noise attenuation, it is also desired to keep the controller relatively simple with the desired modularity in mind. In the paper by Elahinia [13] three Variable Structure Controllers (VSC) are proposed, which are discussed in this chapter. First of all however a PID controller is implemented to act as a benchmark for the nonlinear controllers. Furthermore additional modifications to the VSC controller as well as feedforward control are addressed.

6.1 PID Control

The first thing to choose is the supply voltage, where in theory a supply voltage up to 30 V should be feasible. A high supply voltage ensures the possibility to heat the wire fast, minimizing losses by natural convection. In practice, however, this advantage will be limited if the actuators are to be used in an antagonistic structure. In that case wires should not heat up faster than they can cool down, since this will only result in two wires counteracting each other. If heat is only lost by natural convection, approximately 5V should enable a heating rate similar to the cooling rate. With the possibility of active cooling in mind, an intermediate value of 10 V is chosen for the supply voltage. The PID controller is of the form:

\[ u = K_P e + K_I \int e dt + K_D \frac{de}{dt} \]  

(6.1)

where \( K_P \), \( K_I \) and \( K_D \) are proportional, integral and derivative control gains, respectively. The three control gains are tuned to get the system to track a step input of 8 mm and a sine input (0.1 Hz, amplitude of 3 mm) as accurate as possible. When using the step input, the rise time, overshoot and steady state error are assessed. The sine response is assessed by tracking error. Initially attempts were made to use the Ziegler-Nichols tuning method but this did not lead to satisfactory results. Manual tuning then led to \( K_P = 1000 \), \( K_I = 0.8 \) and \( K_D = 10 \).

One issue that has to be dealt with is integrator windup. As \( T_\infty \) is smaller than \( A_s \) and \( M_f \), and the wire can be heated above \( A_f \) and \( M_s \) time delays and thus integrator windup are introduced. Therefore the integral action is bounded. Furthermore a low-pass filter is applied to prevent the controller from amplifying sensor noise. The same filter is used in all controllers.
In figure 6.2 it is visible that the PID controller suffers from a significant amount of overshoot. This could be reduced either by increasing damping, leading to oscillation at steady state, or by decreasing gain leading to an increased rise time. Although settling time is quite slow the steady state error eventually converges to zero. The sine wave in figure 6.3 is tracked very well during heating but with cooling initially a larger error becomes apparent. This is due to the integral term that causes a little bit of positive control action immediately after the reference trajectory switches direction.

### 6.2 Simple Switch

The controller in the paper switches from a high voltage when the position error $e = r - x$ is positive to a low voltage when it is negative. In the present case the duty cycle $DC$ has to be controlled, meaning that it is set to 1 when the error is positive and then to 0 when it is negative. Hence, it is defined as:

$$DC = \begin{cases} 1 & \text{if } e > 0 \\ 0 & \text{if } e \leq 0 \end{cases}$$ (6.2)

In practice this is a proportional controller with an infinitely high gain that runs into saturation at $DC = 0$ and $DC = 1$. The usual drawback of this kind of controller is that chattering may occur at the sliding surface, $s = e = 0$ in this case.

In this case this behavior does not show as chattering but as a severe oscillation. As soon as the error is positive a substantial amount of energy is put into the system that leads to overshoot; then it cools down until the error becomes positive again and the process repeats itself. This property not only manifests itself at the step response and steady state but also when using a sine reference. Despite the fact that the simplicity of the controller is attractive, it is not satisfactory because of the inferior tracking performance.
6.3 Adding a Boundary Layer

The most common way to eliminate chattering when using VSC control is to introduce a boundary layer. This solution is also applied to eliminate the oscillation that occurs when using the controller as discussed in section 6.2. The switching law ensures that the system gets into the boundary layer quickly where a proportional controller takes over. It is defined as:

\[
DC = \begin{cases} 
1 & \text{if } e > \phi \\
Ke & \text{if } -\phi \leq e \leq \phi \\
0 & \text{if } e < -\phi
\end{cases}
\] (6.3)

The parameter \( \phi \), which is half the boundary layer thickness, should be chosen such that it just prevents the system from oscillating and keeps the steady state error introduced by the boundary layer at a minimum.

A thickness of \( \phi = 0.001 \) is tuned, eliminating the oscillatory behavior, but a significant amount of overshoot is still present as well as a small steady state error. The settling time has decreased considerably compared to the PID controller. Tracking of the sine input shows a small error during heating but during cooling better results are obtained than when using the PID controller.

6.4 Reducing Overshoot

Linear controllers address overshoot by adding damping. In the case of the VSC controller described above, results can be improved by modifying the sliding surface. In this case the sliding surface is:

\[ s = e + \lambda \dot{e} \] (6.4)

While maintaining the same controller shown in equation 6.3, a suitable value of \( \lambda \) has to be chosen to determine the amount of damping required.

Using \( \phi = 0.011 \) and \( \lambda = 0.0125 \) the overshoot is eliminated and the settling time is decreased significantly. The sine tracking error is approximately equal to that of the previous controller with a maximum of 0.103 mm. The steady state error is still present however and is addressed in section 6.5.

6.5 Elimination of the Steady State Error

Although the controller in section 6.4 performs well in terms of rise time, settling time and overshoot, there does exist a steady state error. Although this error is small an attempt is made to eliminate it completely. This is done by introducing an integral term to the sliding surface, thus resulting in:

\[ s = e + \lambda \dot{e} + \lambda I \int e \] (6.5)

Again anti integrator windup as described in section 6.1 must be implemented.

The parameters used for this controller are \( \phi = 0.011 \), \( \lambda = 0.0125 \) and \( \lambda = 0.00025 \). As expected, the steady state error has disappeared completely but this comes at the cost of a small amount of overshoot. Tracking of the sine input during heating has improved but during cooling performance has deteriorated. This has the same cause as in section 6.1, namely the remaining integral action.
Table 6.1: Performance of the various controllers

<table>
<thead>
<tr>
<th>Controller</th>
<th>Overshoot</th>
<th>Steady State Error</th>
<th>Maximum tracking error during heating</th>
<th>Maximum tracking error during cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>PID</td>
<td>0.757 mm</td>
<td>0.000 mm</td>
<td>0.061 mm</td>
<td>-0.097 mm</td>
</tr>
<tr>
<td>VSC1</td>
<td>0.745 mm</td>
<td>N.A.</td>
<td>-1.050 mm</td>
<td>-0.898 mm</td>
</tr>
<tr>
<td>VSC2</td>
<td>0.381 mm</td>
<td>0.046 mm</td>
<td>0.094 mm</td>
<td>-0.014 mm</td>
</tr>
<tr>
<td>VSC3</td>
<td>0.000 mm</td>
<td>0.046 mm</td>
<td>0.103 mm</td>
<td>-0.021 mm</td>
</tr>
<tr>
<td>VSC4</td>
<td>0.057 mm</td>
<td>0.000 mm</td>
<td>0.077 mm</td>
<td>-0.219 mm</td>
</tr>
<tr>
<td>PID with feedforward</td>
<td>0.814 mm</td>
<td>0.000 mm</td>
<td>0.061 mm</td>
<td>-0.097 mm</td>
</tr>
<tr>
<td>VSC1 with feedforward</td>
<td>0.717 mm</td>
<td>N.A.</td>
<td>-1.058 mm</td>
<td>-1.382 mm</td>
</tr>
<tr>
<td>VSC2 with feedforward</td>
<td>0.371 mm</td>
<td>0.010 mm</td>
<td>0.059 mm</td>
<td>-0.054 mm</td>
</tr>
<tr>
<td>VSC3 with feedforward</td>
<td>0.022 mm</td>
<td>0.010 mm</td>
<td>0.063 mm</td>
<td>0.035 mm</td>
</tr>
<tr>
<td>VSC4 with feedforward</td>
<td>0.130 mm</td>
<td>0.000 mm</td>
<td>0.057 mm</td>
<td>0.106 mm</td>
</tr>
</tbody>
</table>

6.6 Feedforward

A common way of improving tracking performance in motion systems is to apply a feedforward scheme. A standard feedforward scheme to compensate for coulomb friction, viscous friction and mass (acceleration) is not suited since the dynamics of the phase transformation are dominant over the mass-spring-damper dynamics. Therefore an alternative feedforward controller has to be designed.

In order to keep the actuator at a steady state position, a certain voltage has to be applied to balance the energy lost to the environment by (natural) convection. Having an accurate position feedforward controller is especially important to eliminate the steady state error if no integral action is present. In theory the required voltage can be determined from equation 5.9 and equals:

\[
V = \sqrt{RhA_{ci}(T - T_{\infty})}
\]  

(6.6)

In practice however this appears difficult to achieve because of model inaccuracies and hysteresis. A number of open loop experiments were performed to observe the voltage required to hold the actuator at a certain position. The result of this is plotted in figure 6.6. It can be observed that the hysteresis causes the plot to be somewhat scattered, but a linear fit shows a slope of 12, which is a first estimate of the gain of the position feedforward controller. Further tuning can be executed online when the system is in steady state.

Velocity feedforward is also tuned online using a constant velocity reference and thus a ramp position input. Only positive setpoints are used, since for negative velocities the feedforward gain should be set to 0. Best results for tuning of feedforward parameters can be obtained when using a low gain feedback controller. Acceleration feedforward has also been tried but did not lead to further improvements. The low mass of the moving part of the actuator is probably the reason for this. Eventually a position feedforward gain of 7 and a velocity feedforward gain of 20 are chosen.

Using a feedforward controller does not lead to substantial changes in the step responses of the PID, VSC1 (section 6.2) and VSC2 (section 6.3) controllers. The differences for the VSC3 (section 6.4) and VSC4 (section 6.5) is interesting however: feedforward control eliminates the steady state error that is present when using VSC3 completely while creating a little overshoot if integrator action is applied (VSC4).
When applying a sine reference input, the use of feedforward leads to significant improvement of performance: during heating the tracking error of VSC2 and VSC3 is reduced and during cooling VSC4 benefits significantly.

Based on the experiments under standard conditions, it seems that the VSC3 controller combined with a feedforward controller would yield the best results. It displays neither overshoot nor a steady state error and tracking of a sine wave is not surpassed by any of the other controllers. Nevertheless the use of feedforward does not attribute to disturbance rejection and robustness of the controller. Thus, before a final conclusion can be drawn, experiments have to be conducted to assess the behavior of the various controllers under different conditions. These robustness issues are discussed in the next chapter.
Chapter 7
Robustness

The controllers designed in chapter 6 are tuned for standard conditions, i.e. a 0.3 mm wire, cooling by natural convection, 10 V supply voltage and a PWM frequency of 500 Hz. A number of the standard conditions have been varied in order to assess the robustness of the various controllers, which have not been tuned for the specific circumstances. The resulting differences in performance are discussed in the subsequent sections. Emphasis will lie on the PID, VSC3 and VSC4 controllers, both with and without feedforward control. These two VSC controllers showed by far the best performance under standard conditions while the PID again represents the benchmark. The results for VSC1 and VSC2 have been omitted in order to reduce the number of graphs per plot and thus enhancing clarity. Again both step and sine signals are used as reference inputs. At the end of this chapter some general remarks on these robustness issues will be discussed.

7.1 Forced convection

By applying active cooling, the austenite to martensite transformation could be accelerated significantly. Nevertheless, variations in cooling should not upset the system. In this case a fan is used for forced convection to extract more heat from the SMA wire, possibly causing slower heating and a steady state error if integral action is absent or not sufficient.

In figures 7.1 and 7.2 it can be seen that the PID controller is least affected by applying forced cooling since results are quite similar to those shown in chapter 6. The system with VSC3 shows a steady state error with and without feedforward control implying that if the feedforward gain is not tuned for forced cooling it cannot eliminate the steady state error. The same holds for the integral action in VSC4 as can be seen in the steady state error that is present without feedforward control. If feedforward control is used in combination with the VSC4 controller, perfect steady state behavior can still be obtained.

Applying forced cooling improves tracking of a sine wave during cooling since the error of the PID and in particular the VSC4 controllers have decreased significantly. During heating however the VSC3 and VSC4 controllers show substantially increased tracking errors.

The PID controller is least affected by applying forced cooling but still shows a step response that behaves significantly worse than that of the VSC3 and VSC4 controllers. Tracking of a sine input on the other hand shows the best results when using the PID controller.

7.2 Supply voltage

Applying a higher supply voltage will result in faster heating but can cause instability and oscillations. On the other hand a lower supply voltage will lead to slower heating and possibly a steady state error. In that case the energy put into the system is insufficient to balance the heat loss to the environment. Therefore experiments have been conducted using supply voltages ranging from 5 V to 15 V.
The increase of rise time due to reducing the supply voltage is equal for all three controllers. Furthermore it leads to a decrease in overshoot using the PID controller, while using the VSC3 and VSC4 controllers introduces a steady state error comparable to the one in section 7.1. The VSC controllers also yield very bad sine responses, while tracking performance using the PID controller only slightly deteriorates due to more integral action.

Increasing the supply voltage to 15 V shows a totally different behavior. Minor overshoot is introduced when using the VSC controllers but this is still approximately a factor four less than using the PID controller. All three controllers show oscillation during heating and good tracking during cooling. When the supply voltage is increased, the necessity for the feedforward controller is decreased and may even degrade tracking performance due to improper tuning for these conditions. This can be seen in figure 7.6 during cooling.

7.3 Wire diameter

In this section the effect of various wire diameters is investigated. Besides the ‘standard’ 0.3 mm wire, 0.2 mm and 0.5 mm wires have also been used. The smaller wire diameter should lead to faster cooling because a higher surface to volume ratio [9]. The thicker wire can be expected to show the opposite behavior.

Using a 0.2 mm wire instead of a 0.3 mm one does not lead to significant changes in tracking performance and differences between the PID, VSC3 and VSC4 controllers with and without feedback are similar to those using a 0.3 mm wire.

Increasing the wire diameter to 0.5 mm does corrupt tracking performance. The variable structure controllers still perform an acceptable step response but the damping of the PID controller is clearly not sufficient. This manifests itself in a further increase of overshoot and oscillations. Moreover, the wire dynamics are too slow to cope with the 0.1 Hz sine wave, and an error is introduced during cooling. Also during heating the controllers do not perform very well and show heavy vibrations.
7.4 General remarks

As discussed in chapter 6 under standard conditions the step responses of the variable structure controllers perform better than that of the PID controller. Even when cooling, supply voltage or wire diameter are varied this remains the same. The VSC controllers always maximize gain outside the boundary layer and therefore high gain within the boundary layer is not required to get a fast response. This low gain within the boundary layer limits overshoot but comes at the cost of reduced tracking robustness. This poor tracking robustness manifests itself in tracking of a sine wave which deteriorates more severely when using a VSC controller under varying circumstances.

In case the controller is to be used with different supply voltages and wire diameters it is recommended to tune the gains for the lowest possible supply voltage and largest wire diameter. In section 7.2 it becomes apparent that tracking errors are significantly increased when decreasing supply voltage whereas an increase in voltage does lead to occasional oscillation but not to instability. Choosing a smaller wire diameter does not lead to substantial change in tracking performance while both bad tracking and heavy vibrations may be caused by choosing a larger wire diameter.

The effect of using multiple wires in parallel and thus increasing the force of the actuator has not been investigated thoroughly. Ideally this would not require a change in controller because the same voltage is supplied to all wires thereby leading to a similar response. In practice it appeared that attaching the wires to the actuator under the exact same pre-stress was difficult and led to different contractions. Other possible factors such as usage history and manufacturing variability could contribute to the difference as well. Therefore no relevant measurement data could be acquired. Further development of the actuator should resolve this issue and the hypothesis stated above can then be tested.

Some of the parameters varied above led to significant changes in response. In order to increase handling of these varying circumstances more advanced control algorithms could be used, examples of which are robust control, adaptive control and model based feedforward. The downside of this would be increased complexity of the controller.

Figure 7.3: Step response with 5 V supply voltage

Figure 7.4: Sine response with 5 V supply voltage
Figure 7.5: Step response with 15 V supply voltage

Figure 7.6: Sine response with 15 V supply voltage

Figure 7.7: Step response with a 0.2 mm wire

Figure 7.8: Sine response with a 0.2 mm wire
Figure 7.9: Step response with a 0.5 mm wire

Figure 7.10: Sine response with a 0.5 mm wire
Chapter 8

Efficiency

As observed in table 2.1 one of the drawbacks of SMA actuators is the low efficiency which also posts a limiting factor in the use of these actuators for rehabilitation. The actuator used in the experiments in previous chapters has an electrical resistance of approximately 4 Ω. The nominal supply voltage of 10 V leads to an instantaneous power consumption of \( P = V^2/R = 25 \text{ W} \) which is quite substantial for a small actuator with a stroke of approximately 1 cm. The maximum Carnot efficiency can be determined to be:

\[
\eta_{Carnot} = 1 - \frac{T_{cold}}{T_{hot}} = 1 - \frac{A_s}{A_f} = 1 - \frac{348}{383} = 9\%
\]

In practice an efficiency of about 4 % is expected but this must be verified experimentally.

The efficiency of the SMA actuator can be defined as:

\[
\eta = \frac{E_{out}}{E_{in}} = \frac{\text{mechanical work}_{out}}{\text{electrical energy}_{in}} = \frac{\int F ds}{\int P_{el} dt}
\]

In this equation \( F \) denotes force, \( s \) is displacement, \( P_{el} \) is electric power and \( t \) denotes time. In order to measure force a force transducer is installed on the actuator in series with the bias spring. The measured force is integrated directly over displacement instead of calculating mechanical power and integrating this over time. This eliminates the necessity for numerical differentiation which usually gives noisy results.

The methods of measuring voltage and current needs some further explanation since the measurements in chapter 4 are measuring instantaneous values during 'on-time'. They do not represent the respective continuous or effective values. In order to calculate the electrical power and energy the dynamics, as displayed earlier in figure 4.1, are ignored in order to assume perfect square waves for both voltage and current. The total energy of one pulse can then be calculated using:

\[
E_{pulse} = VI[\text{pulsewidth}] = VI \frac{DC}{F_{PWM}}
\]

This leads to the following expression for \( P_{el} \):

\[
P_{el} = V IDC
\]

It can be expected that faster excitation leads to a better efficiency because less heat will be lost to the environment. Therefore a step response should have a better efficiency than a ramp response and the step response should be more efficient with higher supply voltages. Also keeping the actuator at steady state should lead to zero efficiency because of the lack of displacement. The effect of varying the supply voltage is investigated by applying a step from 1 mm to 7 mm. Furthermore ramps over the same displacement with different time intervals are tested, using a constant 10 V supply voltage. Results from one step and one ramp experiment are plotted in figures 8.1 and 8.2.
The resulting efficiencies can be found in tables 8.1 and 8.2. It can be seen that both hypotheses stated above are supported but the calculated efficiencies are even lower than expected. Moreover controlling the actuator at intermediate positions will lead to even lower efficiencies. If these actuators are to be used in rehabilitation great improvements have to be made in this area.
Chapter 9

Modularity and further issues

9.1 Multiplexing

If one of the demands of the actuator is modularity, it should be easy to add and remove actuators from the total system mechanically, electrically as well as in the software. Also, if the number of actuators increases, the number of required analog inputs (AI’s) and digital outputs (DO’s) increases as well. In order to minimize the number of required AI’s and DO’s a control strategy has been developed to use only one PWM signal to control multiple actuators. This PWM signal can then be directed to the various actuators using a 16 channel multiplexer, a device that selects one of the connected outputs to direct the input signal to. Using \( n \) DO’s a total of \( 2^n \) different addresses can be obtained. A similar strategy is possible for the measurements where the same address can be used for a second multiplexer. In table 9.1 a few examples are calculated for the number of required AI’s and DO’s, showing that this strategy gets more advantageous when the number of actuators increases.

<table>
<thead>
<tr>
<th>Number of actuators</th>
<th>2</th>
<th>4</th>
<th>8</th>
<th>16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of AI’s without multiplexing</td>
<td>2</td>
<td>4</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>Number of AI’s with multiplexing</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Number of DO’s without multiplexing</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Number of DO’s with multiplexing</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>

During one cycle the system sweeps through all actuators so that every actuator gets a maximum duty cycle of \( 1/n \). Here it also becomes apparent what the limits of this system are: if for a given frequency the number of actuators gets too high only a very limited ‘on-time’ is available for each actuator, thus limiting performance. Furthermore if it takes a longer time between subsequent power pulses to a single actuator vibrations may occur. The effect of increasing the number of actuators on the same PWM signal is discussed below.

9.2 Experimental results

In figures 9.1, 9.2 and 9.3 the effect of adding actuators to a single PWM signal on a step response is investigated. The exact same controllers are used as in previous chapters. Trivially the step response time will increase since the total amount of available energy has to be divided over a larger number of actuators. As can be seen in figure 9.1 this rise time becomes approximately nine seconds using a 10 V supply voltage. This performance is unacceptable since now heating instead of cooling has become the limiting factor. Increasing the supply voltage to 15 V already decreases the response time dramatically where the use of 20 V brings the response time back to approximately one second. The
higher supply voltage does cause overshoot and a high frequency oscillation manifests itself. These issues can be addressed by re-tuning the controllers with the supply voltage set at 20 V.

Besides the number of actuators, another factor that affects control is the frequency at which the actuators are swept. Choosing the frequency too high will exhibit slow response since both voltage and current will not reach steady state. A frequency which is too low will result in oscillations of the actuators. To get an impression of the suitable range of frequency experiments with 1, 8 and 16 actuators are conducted in the range of 100 Hz to 4000 Hz.

As observed in figure 9.5 oscillations indeed occur when choosing a low cycling frequency. The benefit of increasing cycling frequency is the substantial decrease of response time. Therefore both supply voltage and cycling frequency should be varied to ensure a balance between a suitable response time and low oscillation. Originally we hypothesized that the increase of the cycling frequency is limited by an increase of response time. However, figures 9.4 and 9.5 show that this increase is limited by the occurring vibrations. Oscillation is more likely to occur when using more actuators. For example, oscillations are not detected with one actuator at a frequency of 4000 Hz. However, eight actuators do show oscillations at this frequency and sixteen actuators already show oscillations at 3000 Hz.

A cycling frequency of 2000 Hz seems to give the best compromise between response time and suppression of vibrations when using a supply voltage of 10 V. If a faster response is required the supply voltage should be increased and tuning of the cycling frequency should be executed for the increased voltage.
9.3 Actuator Matrix Driver

The multiplexer as described above dramatically reduces the number of required AI’s and DIO’s for large numbers of actuators but it does not reduce the number of lead wires which is equal to the number of actuators and a ground wire. In a miniature device the space available for even these lead wires may be limited. Mukherjee [14] proposes the Actuator Matrix Driver concept in which the SMA elements are connected in the form of a matrix. Any of the SMA wires can be selected by choosing one of the columns and one of the rows of the matrix, and the total number of lead wires equals the sum of the number of rows and the number of columns. In the example by Mukherjee five segments with three SMA elements are used and the total number of lead wires is thus reduced from 16, in a conventional setup, to 8, in a matrix setup.

A combination of multiplexing and the actuator matrix driver would minimize the required resources for actuation of multiple actuators. The way this technology can be brought into practice however depends on the intended application and therefore further research on this topic has not been performed yet.

Figure 9.4: Step responses when using varying cycling frequencies and number of actuators

Figure 9.5: Detail per number of actuators
9.4 Further issues

As is examined in the previous chapter the low efficiency poses a limit on the use of SMA actuators in rehabilitation in spite of their attractive features as discussed in section 2.2. However this does not mean that the technology cannot be used in other areas. In the medical field much research has been done in using SMA as micro active catheters [4] and active endoscopes [6]. Here the extremely small required volume is the main reason for the choice of SMA actuators. According to Langelaar [9], using SMA actuators on a micro scale has another advantage. The cooling time of SMA wires limits the dynamic response when no active cooling is applied, but on micro scale the surface to volume ratio increases and natural cooling is much faster.

Research has also been done on modular actuators. Grant [5] has developed an actuator that can achieve higher strains to overcome one of the drawbacks of SMA’s. Vivek [17] has designed a binary manipulator which has the advantage of not using energy when hold stationary. This technology should prevent efficiency from decreasing further than the results shown in chapter 8. Furthermore displacement sensing is not necessary since the actuators can only achieve two states.

During this research a number of different actuator configurations have been discussed with 2 and 3 degrees of freedom per actuator. Either antagonistic structures or bias springs can be used to actively control movement in two directions. Also, combining SMA with other actuators or passive elements make for interesting possibilities such as variable stiffness devices. These ideas can be incorporated into many bio-inspired robots or artificial grippers.
Chapter 10

Conclusion

This project started off with the ultimate goal of developing a bio-inspired modular actuator suited for rehabilitation properties. In the course of the preliminary research however the apparently low efficiency and high power requirements seemed to pose a limit on the use of SMA in this field of application. This hypothesis was confirmed by the efficiency measurements.

Nevertheless valuable knowledge about shape memory alloys has been acquired. A relationship between electrical resistance and displacement was established and could be used for integrated sensing depending on the required accuracy. A mathematical model of a SMA actuator has been developed which showed surprisingly accurate results despite the fact that no temperature measurements have been done yet. Doing so will lead to further improvements of the model enabling to use it for closed loop simulations and model based control algorithms.

Furthermore variable structure controllers have been implemented and their performance was compared to that of a PID controller. A VSC control showed much better step response performance than PID control and if tuned properly showed comparable performance when tracking a smooth reference signals.

As rehabilitation is found not to be the prime application area of SMA’s, other possible applications for SMA actuators have been discussed. Compliant and semi-active applications appear to be interesting for the use of SMA and further research should be done in this area. On the short term however emphasis will lie on further developments of the mathematical model.
Bibliography


