# Experiments on the Audio Frequency Response of Shape Memory Alloy Actuators


**Yee Harn Teh and Roy Featherstone**
Department of Information Engineering
Research School of Information Sciences and Engineering
The Australian National University
Canberra ACT 0200
{yee.teh,roy}@rsise.anu.edu.au



## Abstract

The small-signal frequency response of Shape Memory Alloy (SMA) actuator wire was investigated in this paper, as a prelude to developing an improved motion controller for robotic applications. A series of experiments were carried out, in which SMA wires were heated at frequencies of up to 2 kHz under a variety of different tensions and thermal histories. The wire was connected to a diaphragm, so that small motions of the wire would produce acoustic emissions, which were detected and measured using a sound meter. The results show that the wire can respond at frequencies as high as 1 kHz, which suggests that a high-bandwidth motion controller is feasible. Given the high frequencies used in this experiment, some attention was paid to demonstrating that the observed behaviour is attributable to the shape memory effect.


## 1 Introduction

Actuators based on Shape Memory Alloys (SMA) present an interesting alternative to conventional robotic actuators. However, SMA actuators are difficult to control. This paper presents work that is part of an ongoing project to develop better control systems for SMA actuators. We are investigating a control architecture comprising a fast inner loop closed around a force sensor, and a slower outer loop closed around a position sensor. The idea is for the inner loop to make the SMA actuator behave like an ideal force source. The purpose of the experiments presented in this paper is to measure the response speed of SMA actuators as a prelude to designing the inner force loop.

### 1.1 Shape Memory Alloys

The special property of SMA is that it can undergo significant plastic deformation when cool, but will return to its original shape when heated. In robotic applications, an SMA actuator is usually a wire that can be stretched easily when cool, but will contract forcibly to its original length when heated. The contraction can be harnessed to perform mechanical work.

The Shape Memory Effect (SME) is the result of a temperature-dependent phase transformation between a low-temperature (martensite) phase, in which the SMA can be easily deformed, and a high-temperature (austenite) phase. In effect, an SMA actuator converts heat energy to mechanical work. They are usually heated electrically.

Shape Memory Alloy actuators have various uses in robotics. They include active endoscopes [Ikuta *et al.*, 1988], robotic actuators [Mosley and Mavroidis, 2001; Reynaerts and Van Brussel, 1998] and micro-actuators [Shin *et al.*, 2004; Troisfontaine *et al.*, 1998; Yao *et al.*, 2004]. Their advantages, for instance, include mechanical simplicity and compactness, high force-to-weight ratio and silent, spark-free operation. They are known as direct-drive actuators because they do not require a gear box. SMAs also have several disadvantages, such as inefficiency, limited strain and they are generally considered to have low speed and accuracy.

### 1.2 Problem Statement

The problem of achieving fast, accurate controlled motion remains the topic of much research for SMA-based robotic actuators. Various attempts have been made to improve the speed of these actuators. These include Kuribayashi's temperature feedback mechanism [Kuribayashi, 1991], Grant's two-stage relay controller [Grant, 1999] and our previous work on the rapid heating mechanism [Featherstone and Teh, 2004]. Other research, such as [Shin *et al.*, 2004; Wellman *et al.*, 1998], have achieved high-frequency actuation of 40 Hz using thin-film SMAs in de-ionised water and 30 Hz using a water-cooled SMA wire tactile display respectively, at small-signal displacements of 3 mm or less.

Although prior research on control systems have improved the speed of SMA actuators, the problem of ac-

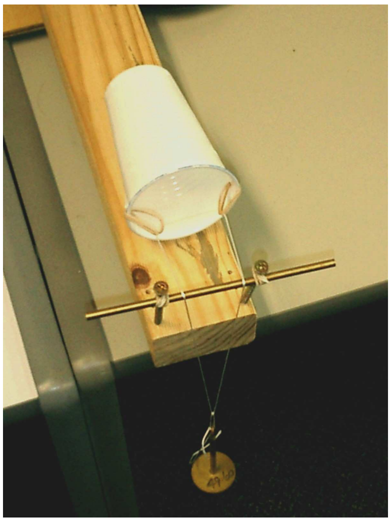


Figure 1: The loudspeaker setup

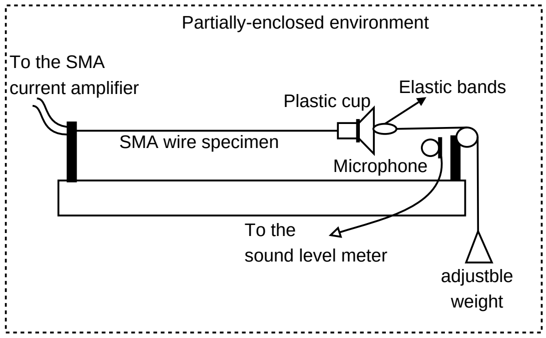



Figure 2: The schematic view of the loudspeaker setup

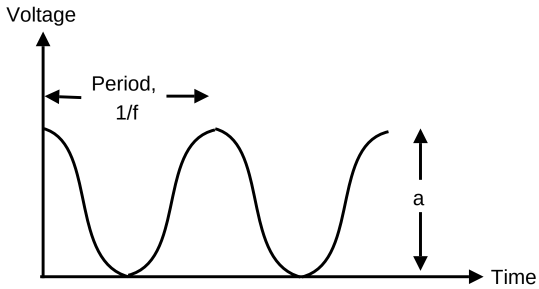



Figure 3: General input signal of the form $\frac{a}{2}\left(\sin\left(2\pi ft\right)+1\right)$

curacy still lingers. This is particularly evident in conditions where an external load affects the dynamics of the plant and causes limit cycles [Grant, 1999]. The modified proportional controller [Teh and Featherstone, 2004a; 2004b] has managed to reduce the limit cycles, but it is also apparent that the accuracy could be improved.

We therefore propose a control architecture in which a fast inner loop is closed around a force sensor. The question is, can this loop run fast enough to eliminate the observed limit cycles at 20-30 Hz? The aim of the experiments in this paper is to measure the response speed of SMA wires, which is a limiting factor on the speed of the inner loop.

### 1.3 Overview

We have constructed a simple loudspeaker setup actuated by an SMA wire. Using a sound level meter, we measure the loudspeaker sound output by passing a sine-wave current signal with frequencies up to 2000 Hz through the actuator. This allowed us to observe the delay between a change in electrical input and an observable response, which is audio sound amplified by the loudspeaker. One normal Flexinol SMA wire and an annealed Flexinol wire in a controlled environment were respectively tested under various conditions. Annealing the wire deteriorates the Shape Memory Effect. This allowed us to demonstrate that the observed behaviour depends on the Shape Memory Effect. This paper describes the experimental setup, the experimental procedures and the results from our experiments.

## 2 Experimental Setup

### 2.1 Experimental Hardware

The loudspeaker setup is shown in Figure 1 and schematically in Figure 2. The loudspeaker consists of a normal plastic drinking cup actuated by the SMA wire specimen. The cup basically functions as an acoustic amplifier. The tension on the SMA wire is supplied by an adjustable weight attached to the front of the cup. The cup is free to move and also free from friction, using a pair of elastic bands attached between the cup and the string of the adjustable weight as shown in Figure 2. The microphone of a db-307 sound level meter manufactured by Metrosonics is placed in front of the plastic cup to record and measure the sound level output in decibel (dB). The distance between the cup and the microphone is approximately 8 cm. The db-307 features a 95 dB dynamic range between 45 to 140 dB. It can compute instantaneous sound level, the maximum sound level as well as the average sound level for a duration of time. For our experiments, we used the average sound level for a duration of 10 seconds under each condition.

Figure 3 illustrates the sine-wave voltage signal used to actuate the SMA wire. This sine-wave is of the form $\frac{a}{2}\left(\sin\left(2\pi ft\right)+1\right)$, where $a$ is the amplitude of the signal, $f$ the frequency in Hz, and $t$ the time in seconds. The signal is produced on a dSPACE DS1104 real-time con-

| Type of Wire | Operating Frequency (Hz) | | | |
|---|---|---|---|---|
| | 500 | 1000 | 1500 | 2000 |
| Normal Flexinol | 150 g | 50 g<br>100 g<br>150 g<br>200 g | 150 g | 150 g |
| Annealed Flexinol | 150 g | 50 g<br>100 g<br>150 g<br>200 g | 150 g | 150 g |

Table 1: Experimental parameters used for both the normal and annealed Flexinol SMA wire specimens.

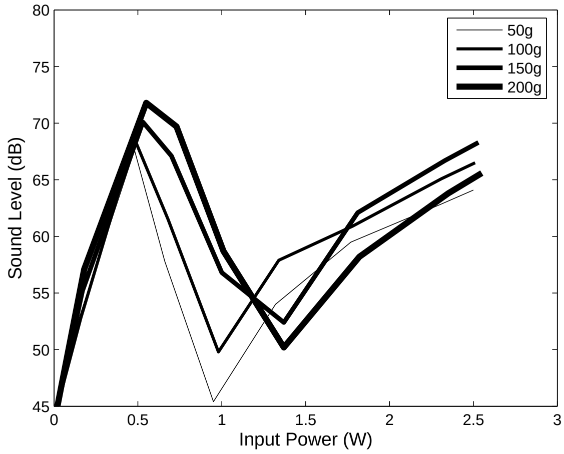
trol board, and sent to a custom-built voltage-to-current power amplifier that delivers the current to the SMA wire. The amplifier also serves as a data acquisition system working in conjunction with the dSPACE ControlDesk to measure the input power applied to heat the SMA wire. The heating power delivered to the wire is $P = I^2R$, where $I$ is the measured current through the SMA element and $R$ the measured electrical resistance of the SMA element.

The SMA wires used in these experiments are Flexinol[1], which are commercially produced NiTi alloy wires with highly repeatable motion under normal conditions. However, if the applied stress is too great or the temperature too high, some permanent strain will occur, thereby affecting its Shape Memory Effect. Two $100\mu$m-diameter, 60cm-long Flexinol wires, one normal, and the other annealed at 300°C for 15 hours in an oven such that its SME is damaged, are used to actuate the plastic cup respectively. This allows direct comparison between the sound level output from both wires.

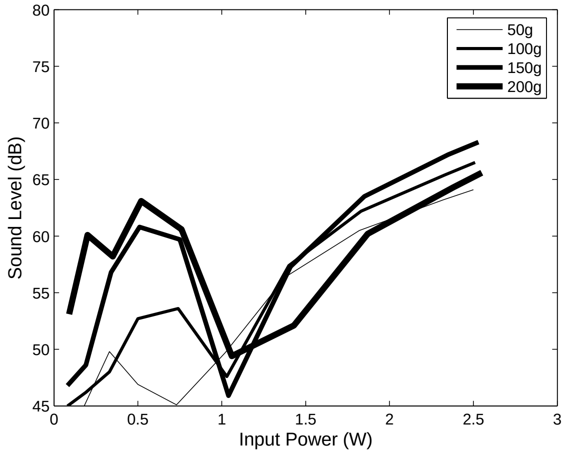
## 2.2 Experimental Procedure

The experiments were carried out under noise-minimised condition, in a partially-enclosed space to reduce the effect of air ventilation on the cooling regime of the SMA wires. A detailed list of test parameters for both Flexinol wires is provided in Table 1. Each set of experiments was conducted through the complete phase transformation process, which is the heating and cooling cycle. Starting at zero watts, readings were taken at progressively higher power levels, up to the maximum power for each experiment. This data is referred to below as the data obtained during a heating cycle. Further measurements are then made as the heating power is progressively reduced to zero. This data is referred to below as the data obtained during a cooling cycle. Each sound level reading is the average of 10 seconds of sound output, to reduce the effect of possible noise and sound output

[1]Flexinol wires are obtained from Dynalloy, Inc. (http://www.dynalloy.com)




(a)




(b)

Figure 4: Sound level output from the loudspeaker actuated by a normal Flexinol SMA wire using incremental loads of 50 g respectively to a sine-wave input of 1000 Hz during(a) the heating cycle and (b) the cooling cycle.

variations. The input power to the SMA wire was also measured. Between each reading, a 5-second delay was introduced so that any transient response of the sound output had been stabilised.

# 3 Results and Discussion

The two Flexinol wires have been tested under a variety of conditions as shown in Table 1.

## 3.1 Varying Wire Tensions

Firstly in Figure 4, we present the measured sound level output results using the normal Flexinol wire, at a constant input signal frequency of 1 kHz, during the heating cycle as shown in Figure 4 (a) and the cooling cycle in

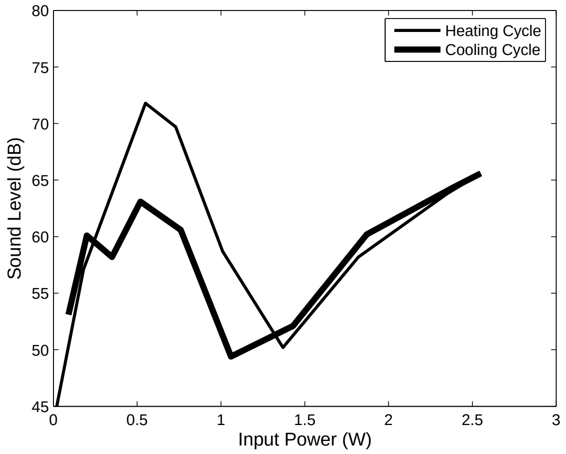
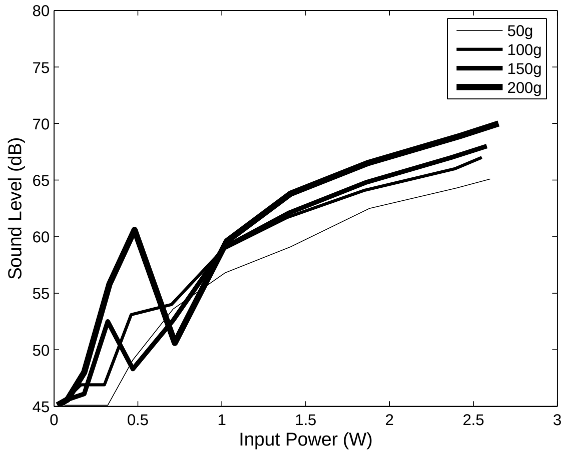



Figure 5: Sound level output from a normal Flexinol SMA wire using a 200 g load at 1000 Hz input signal.

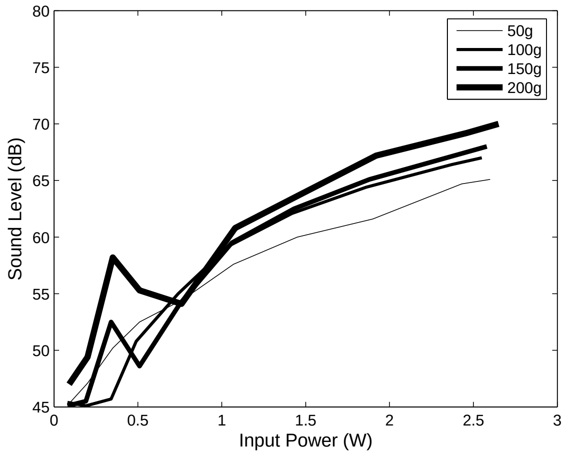
Figure 4 (b). The four plots in each graph correspond to the results of the wire at four different wire tensions using 50, 100, 150 and 200 g weights respectively. It should be noted that the loudspeaker was not as loud as the figures in the graphs suggest, because the microphone of the sound level meter was placed close to the cup. However, the sound output from the loudspeaker was still distinctly audible at 1 metre away.

The observation made from these results is that this is the Shape Memory Effect in action. If a normal metal wire is heated, the sound level output should increase steadily with the input power. This is because a normal metal undergoes thermal expansion when heated. The higher the input power, the hotter the wire becomes, leading to a larger temperature difference between the wire and the surrounding air. This results in a faster cooling rate, hence a larger temperature swing and motion in the wire. Thus, if the sound were due to normal thermal expansion, then the curve would show a steady rise in sound level with increasing input power. This was not observed in our experiments.

Focussing first on the curve using a 50 g weight during the heating cycle in Figure 4 (a), we observe that the sound level output increases steadily until it reaches a maximum of 68 dB at an input power of 0.5 W approximately. The sound level then drops to 45 dB at about 1 W. This drop in sound level occurs during the SMA phase transformation from the low-temperature phase to the high-temperature phase. This is evidence of SME. As input power is further increased, the SMA wire is still in its high-temperature phase. The increase in sound level from this point onwards is mainly due to thermal expansion of the SMA wire. The experiment ends at approximately 2.5 W input power, which corresponds to a




(a)




(b)

Figure 6: Sound level output from the loudspeaker actuated by an annealed Flexinol SMA wire (at 300°C for 15 hours) using incremental loads of 50 g respectively to a sine-wave input of 1000 Hz during (a) the heating cycle and (b) the cooling cycle.

heating current of 0.21 A. This heating current is slightly above the recommended data sheet heating current for Flexinol wires. This is to avoid overheating and damaging the normal Flexinol wire specimen for further tests.

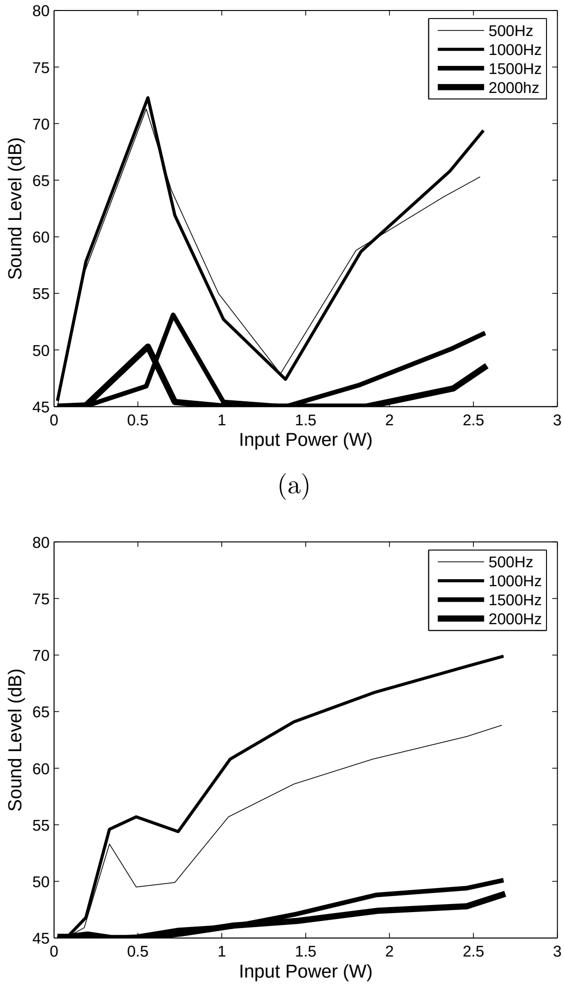
As wire tension is increased, the peak sound output is observed to have increased proportionally. The peak and the drop in sound level output also occur at progressively higher input power levels. This agrees with the well-known property of SMAs that higher stresses increase the phase transformation temperatures.

During the cooling cycle in Figure 4 (b), similar trends are observed. However, the sound level outputs for each curve during the phase transformation are lower compared to the results obtained during the heating cycle. The cooling cycle is in fact conducted right after the heating cycle for each set of experiments. So if we plot, for example, the results of the normal Flexinol wire at 200 g weight for the complete heating and cooling cycle, we would obtain the curve shown in Figure 5. The results clearly show that the effect highly depends on the thermal history of the wire specimen. As the wire specimen is cooled, the cooling trend follows closely the heating curve until it reaches the phase transformation temperature. Due to hysteresis, the phase transformation temperature range during the cooling cycle is lower compared to the heating cycle. Thus we see that the rise in sound output during the cooling cycle is at a lower input power compared to the dip in the heating cycle. The peak in sound output which follows is also lower by about 10 dB.

Using an annealed Flexinol wire to actuate the loudspeaker, the following graphs are obtained in Figure 6. At 150 g and 200 g wire tensions, the heating trends, whereby there is initially an increase followed by a drop in sound output, and then a steady climb as input power increase, are similar to the heating cycle of a normal Flexinol wire in Figure 4. The important difference, however, is that the peak sound levels recorded during the phase transformation, are significantly lower compared to normal Flexinol wire actuation. This is evidence that we are observing the reduction in SME due to annealing. This feature is especially visible at lower wire tensions. At wire tensions of 50 g and 100 g in the heating cycle in Figure 6 (a), there are no peaks in sound output at the expected phase transformation range. Instead we observe a steady increase in sound output at progressively higher power levels. By annealing the actuator, we have reduced the SME such that it is barely observable under the conditions. Similar observations could be made for the cooling cycle shown in Figure 6 (b).

## 3.2 Varying Input Signal Frequencies

Next we present the results of heating a normal Flexinol wire at fixed wire tension with a 150 g weight with input signal frequencies of 500 Hz, 1000 Hz, 1500 Hz and 2000 Hz respectively. The results are plotted in Figure 7 (a). At frequencies of 500 Hz and 1000 Hz, the responses are very similar and follow the trend of a steady increase followed by a huge dip in sound output. The peak sound output for both frequencies are approximately 72 dB. However, the response decreases sharply at frequencies of 1500 Hz and above. Sound output continues to follow the trend but at a very low level. The peak sound output recorded using a frequency of 1500 Hz during the phase transformation is approximately 53 dB. The sound output was barely audible throughout the heating and cooling cycle.




(a)

(b)

Figure 7: Sound level output from the loudspeaker to sine-wave inputs of 500, 1000, 1500 and 2000 Hz respectively for (a) a normal Flexinol SMA wire, and (b) an annealed Flexinol SMA wire, during the heating cycle at a fixed load of 150 g.

When the annealed wire is tested, the sound level responses are worse. They are shown in Figure 7 (b). At input frequencies of 500 Hz and 1000 Hz, the initial peaks recorded are about 18 dB lower compared to the normal Flexinol when tested under the same conditions. The reduced SME has substantially affected the response of the wire. At 1500 Hz and 2000 Hz, the sound level meter barely detects any audible sound from the loudspeaker.

## 3.3 Repeatability of Experiments

During the experiments, we observed that, under constant conditions, the sound level output was highly variable. The volume of the sound output could change by as much as 15 dB under certain conditions. This variation in sound output was the reason why the sound level readings were taken as the average for a 10-second duration. This also indicates that an accurate plant model of the SMA wire is probably unobtainable.

We have also repeated the experiments several times, to get statistics on the variability of the results. The results recorded generally show the same trends as the graphs described in this paper, which agree with our Shape Memory Effect observation. However, different runs of the same experiment may differ by as much as 5 dB. This could be due to slightly varying states and thermal history of the SMA wire specimens, or the variable sound output effect as mentioned above.

## 4 Conclusion

The experiments of this paper have never been conducted previously, and the results are the first of their kind in investigating the audio frequency response of SMA actuators. Evidence strongly suggests that SMA actuators are capable of high speed actuation, although at very small displacements. This suggests that the delay between the change in input current and an observable response is very short. Using a loudspeaker, the displacements have been amplified sufficiently to produce detectable audio sound at frequencies of up to 2000 Hz.

The curves plotted using the normal Flexinol specimen show that we are observing the Shape Memory Effect in action. This observation is supported by the results obtained from experiments of applying higher tensions to the SMA actuators. The results for the annealed SMA wire show that the sound output has been reduced at input powers corresponding to the phase transformation process. This is evidence that we are seeing the deterioration of the SME.

Based on these results, we believe that it is feasible to attempt small-signal force control at frequencies of up to several hundred Hertz. This is well above the observed limit cycle frequencies in [Teh and Featherstone, 2004b], therefore it is also feasible to use force control to improve stability and extend SMA actuation to hybrid motion and force control. A new test rig with force sensors is currently being constructed and we plan to implement force and hybrid control of SMA actuators.

## References


[Featherstone and Teh, 2004] Roy Featherstone and Yee Harn Teh. Improving the speed of shape memory alloy actuators by faster electrical heating. In *Proceedings of the Ninth International Symposium on Experimental Robotics*, Paper ID 128, Singapore, June 2004.

[Grant, 1999] Danny Grant. Accurate and rapid control of shape memory alloy actuators. PhD Thesis TR-CIM-99-11, Centre for Intelligent Machines, McGill University, 1999.

[Ikuta *et al.*, 1988] Koji Ikuta, Masahiro Tsukamoto and Shigeo Hirose. Shape memory alloy servo actuator system with electric resistance feedback and application for active endoscope. In *Proceedings of the IEEE International Conference on Robotics and Automation*, pages 427-430, Philadelphia, PA, April 1988.

[Kuribayashi, 1991] Katsutoshi Kuribayashi. Improvement of the response of an SMA actuator using a temperature sensor. *The International Journal of Robotics Research*, Vol.10, No. 1, February 1991.

[Mosley and Mavroidis, 2001] Michael J. Mosley and Constantinos Mavroidis. Experimental nonlinear dynamics of a shape memory alloy wire bundle actuator. *Journal of Dynamic Systems, Measurement, and Control*, 123(1):103-112, 2001.

[Reynaerts and Van Brussel, 1998] Dominiek Reynaerts and Hendrik Van Brussel. Design aspects of shape memory actuators. *Mechatronics*, 8:635-656, 1998.

[Shin *et al.*, 2004] Daniel D. Shin, Kotekar P. Mohanchandra and Gregory P. Carman. High frequency actuation of thin film NiTi. *Sensors and Actuators A*, 111, pages 166-171, 2004.

[Teh and Featherstone, 2004a] Yee Harn Teh and Roy Featherstone. A new control system for fast motion control of SMA actuator wires. Submitted to *The First International Conference on Shape Memory and Related Technologies*, Paper ID 34, Singapore, November 2004.

[Teh and Featherstone, 2004b] Yee Harn Teh and Roy Featherstone. Experiments on the performance of a 2-DOF pantograph robot actuated by SMA wires. In *Proceedings of the Australasian Conference on Robotics and Automation*, Canberra, December 2004.

[Troisfontaine *et al.*, 1998] N. Troisfontaine, Ph. Bidaud and P. Dario. Control experiments on two SMA based micro-actuators. In A. Casals & A. T. de Almeida (Eds.), *Experimental Robotics V*, pages 490-499. Springer, London, 1998.

[Wellman *et al.*, 1998] Parris S. Wellman, William J. Peine, Gregg Favalora and Robert D. Howe. Mechanical design and control of a high-bandwidth shape memory alloy tactile display. In A. Casals & A. T. de Almeida (Eds.), *Experimental Robotics V*, pages 56-66. Springer, London, 1998.

[Yao *et al.*, 2004] Qin Yao, Sheng Jin and Pei-Sun Ma. The micro trolley based on SMA and its control system. *Journal of Intelligent and Robotic Systems*, 39:199-208, 2004.