Improving the Speed of Shape Memory Alloy Actuators by Faster Electrical Heating

Roy Featherstone[1] and Yee Harn Teh[2]

[1] Dept. Systems Engineering
Australian National University
Canberra ACT 0200, Australia
roy@syseng.anu.edu.au
http://www.syseng.anu.edu.au/~roy/

[2] Dept. Systems Engineering
Australian National University
yee.teh@rsise.anu.edu.au

Abstract. This paper describes a method for improving the speed of actuators based on shape memory alloys (SMA) by increasing the rate at which an SMA element can safely be heated. The method consists of measuring the electrical resistance of an SMA element, calculating a maximum safe heating current as a function of measured resistance, and ensuring that the actual heating current does not exceed this maximum value. In effect, resistance is being used as a form of temperature measurement, and the maximum safe heating current is designed to prevent overheating. This method has been incorporated into a two-stage relay controller that controls the motion of a pantograph robot actuated by two antagonistic pairs of SMA wires. Experimental results show a substantial increase in the maximum velocity attainable by this robot, without any change in the cooling regime, purely as a result of faster heating.

1 Introduction

Actuators based on shape memory alloys (SMA) have a variety of uses in robotics [4,7–9]. Their advantages include mechanical simplicity, high power-to-weight ratio, small size, and clean, silent, spark-free operation. On the other hand, they also possess some serious disadvantages, including inefficiency, hysteresis and slow speed.

A typical SMA-based actuator contains an element, comprising one or more wires, coils, or formed shapes of SMA material. These elements can be stretched easily when cool, but contract forcibly when hot. In robotic applications, they are typically arranged in antagonistic pairs. An element is usually heated by means of joule heating (i.e., passing an electrical current through the element), and cooled by means of heat transfer to the environment. The limiting factors on the speed of such an actuator are the heating and cooling rates of the SMA elements. The cooling rate can be increased by various means, including forced-air cooling, oil or water cooling, and using thinner SMA wires; but the heating rate can be increased simply by passing a larger current through the element.

In principle, an SMA element can be heated arbitrarily quickly by passing a sufficiently large current through it. However, currents beyond a certain magnitude have the capacity to overheat the SMA, causing permanent damage. Thus, any strategy for electrical heating of an SMA element must take steps to avoid overheating. The simplest strategy is to limit the heating current to a known safe value, such as can be found in an SMA data sheet. A better strategy is to monitor the state of the SMA, and apply a current that is safe for the SMA in its current state. If the SMA is cool, for example, then it is safe to apply a very large heating current for as long as the SMA remains below some threshold temperature.

One such method has been proposed by Kuribayashi [6]. His method involves:-

1. measuring the temperature of the SMA element directly by means of a miniature thermocouple attached to the SMA element;
2. allowing a large heating current whenever the temperature is below a threshold value; and
3. setting the heating current to zero whenever the temperature is above the threshold.

This heating strategy was incorporated into a simple motion control system, and experimental results showed a large improvement in actuator response times.

We present an alternative heating method in this paper, that uses a resistance measurement of the SMA instead of a direct temperature measurement [2]. The main advantage of the new method is that it dispenses with the need for a special sensor co-located with the SMA element. To demonstrate the practical benefit of this method, it was incorporated into a simple motion control system based on Grant's two-stage relay controller [3], and used to control the motions of a pantograph robot actuated by four SMA wires arranged in antagonistic pairs. Experimental results show that the new heating method was able to double the maximum speed of the actuators, compared with a heating regime in which the heating current is limited to the data-sheet value. This improvement was achieved without any change in the cooling regime, and can therefore be attributed entirely to faster heating.

In the rest of this paper, we describe the principle of operation of the new method, the experimental hardware used to test it, and experimental results from the motion controller showing the resulting improvement in speed.

2 Principle of Operation

The shape memory effect is caused by a phase transition between two crystalline phases: a low-temperature phase called martensite, and a high-temperature phase called austenite. In a typical SMA, like nitinol, the two phases have different resistivities. This causes a phase-related change in resistance as an SMA element is heated or cooled. This phenomenon is well known, and has been used before as a means of estimating the martensite ratio for the purpose of servoing the phase transition directly [5].

Figure 1 shows a (simplified) plot of resistance versus temperature that would be typical of an alloy like nitinol. As the alloy is heated from cold, it begins to transform into the austenite phase at a temperature called the *austenite start* temperature, A_s, and the transformation is essentially complete at a temperature called the *austenite*

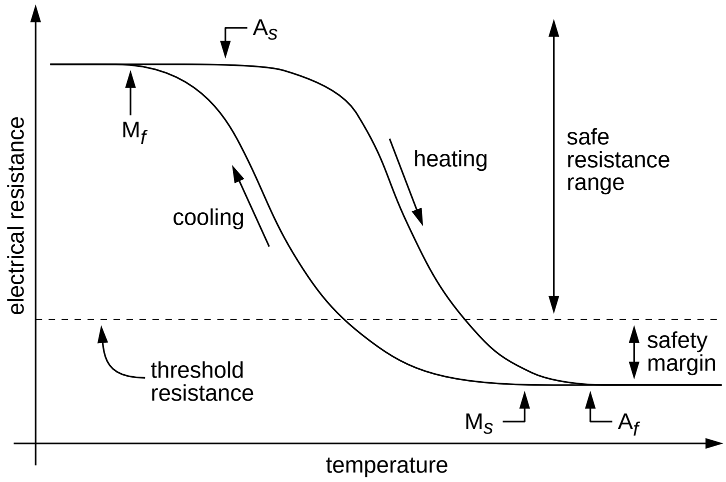


Fig. 1. Typical plot of resistance versus temperature for nitinol.

finish temperature, A_f. Likewise, as the hot alloy is cooled, it transforms back into the martensite phase between the martensite start and finish temperatures, M_s and M_f. These temperatures are lower than those for the heating curve, because of thermal hysteresis in the transformation. For an alloy like nitinol, the resistance changes by about 20%.

The presence of thermal hysteresis means that we cannot deduce the exact temperature from the resistance; but we can identify a threshold resistance, R_{thresh}, that marks the boundary between 'safe' resistances and 'possibly unsafe' resistances. This quantity is defined to be the resistance of the hot SMA element, plus a safety margin that accounts for resistance measurement errors and strain-induced resistance changes. If R_{thresh} applies to a batch of SMA elements, rather than an individual element, then the safety margin must also account for possible variations in hot resistance from one element to the next.

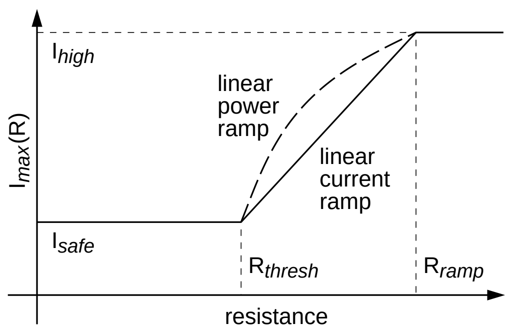


Fig. 2. Maximum safe current, $I_{max}(R)$, vs. SMA element resistance.

Given R_{thresh}, we can define a maximum safe heating current, $I_{max}(R)$, which is a function of the measured resistance of the SMA element, as shown in Figure 2. In this figure, I_{safe} is a current that can safely be applied to the element indefinitely without risk of overheating, but is sufficient to keep the temperature above A_f. Suitable values for I_{safe} can be found in data sheets for SMA actuator wires, e.g. [1]. I_{high} is the maximum value of the rapid-heating current. I_{high} will typically be determined by limits on the available power, e.g. the maximum voltage or current available from the power supply, or the current-handling capacity of the individual regulators supplying each SMA element. R_{ramp} is an optional additional resistance threshold on the safe side of R_{thresh}, and its purpose is to allow a smooth transition between I_{safe} and I_{high}. Two obvious possibilities are shown in the figure: a linear current ramp and a linear power ramp. If a ramp is not required, then I_{max} is a discontinuous function of SMA resistance, given by

$$I_{max}(R) = \begin{cases} I_{high} & \text{if } R \geq R_{thresh} \\ I_{safe} & \text{otherwise.} \end{cases} \tag{1}$$

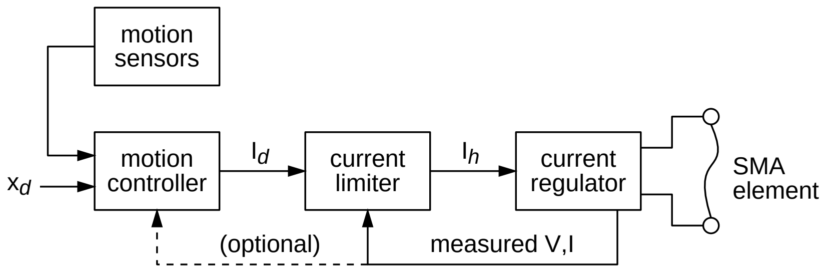
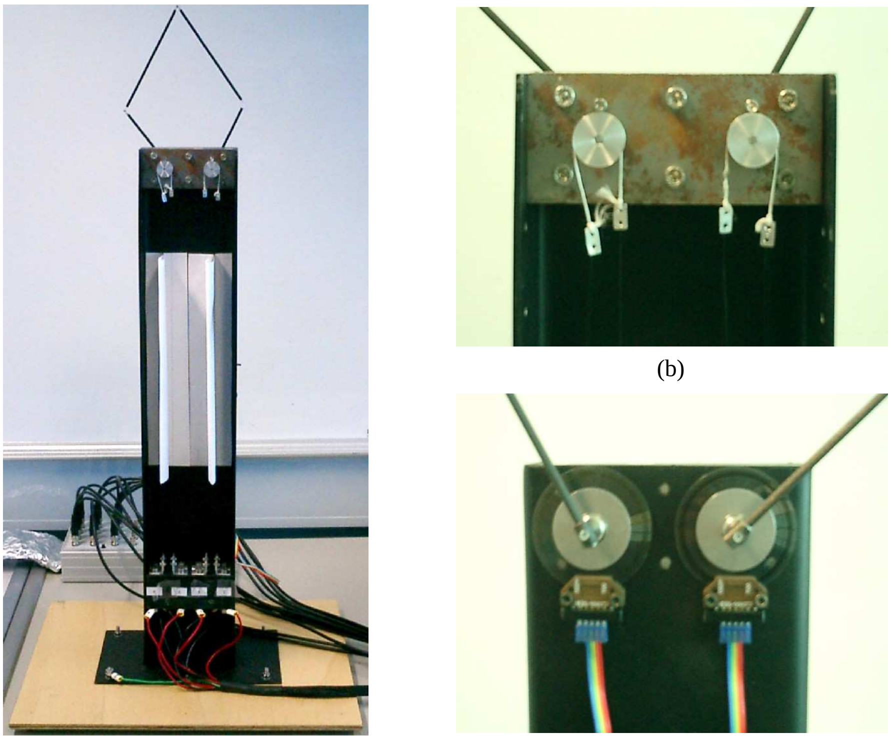


Fig. 3. Motion control system with current limiter.

Figure 3 shows one possible way to incorporate the rapid heating method into a motion control system. In this case, a motion controller receives a desired position input signal, x_d, and signals from one or more motion sensors. Based on this data, it calculates an output signal, I_d, that is interpreted as the desired heating current for a particular SMA element. This signal is input to a current limiter that calculates an actual heating current, I_h, according to the formula

$$I_h = \min(I_d, I_{max}(R_{meas}))\,. \tag{2}$$

This signal is then passed to a current regulator, which causes a current of I_h to pass through the SMA element. Measurements of the actual voltage across the SMA element, and the actual current passing through it, are passed back to the current limiter so that it can work out the resistance of the SMA element. These signals could also be passed back to the motion controller, if it has been designed to use them. Feedback of the actual SMA current is not necessary if the current regulator is sufficiently precise.



(a) (b) (c)

Fig. 4. The experimental rig (a), and detailed views of the pulleys (b) and optical encoders (c).

3 Experimental Hardware

The experimental rig is shown in Figure 4(a), and schematically in Figure 5. It consists of a vertical metal C-beam, about 0.7m high, supporting two horizontal shafts at the top and eight anchor points at the bottom. Each shaft rotates freely on ball bearings, and carries a small pulley at the front and an optical encoder wheel at the rear, as shown in Figures 4(b) and 4(c). The two shafts terminate in small sockets, welded to the rear end of each shaft, which hold the ends of a pantograph linkage made from carbon tubes. The pantograph serves as a mechanical load.

A short chord is wrapped 1.5 times around each pulley, and is affixed to the pulley at its centre so that it cannot slip relative to the pulley. Each end of each chord terminates in an eyelet. Four Flexinol (tm) wires are strung between the eight anchor points and four eyelets, as shown in Figure 5, to form two antagonistic pairs of SMA elements. The wires are approximately 1m long and 0.1mm in diameter, and they are too thin to be visible in the photographs in Figure 4. The white objects half way up the column in Figure 4(a) are separators, made from paper, which prevent the wires from making physical (and therefore electrical) contact with their neighbours in the event they go slack.

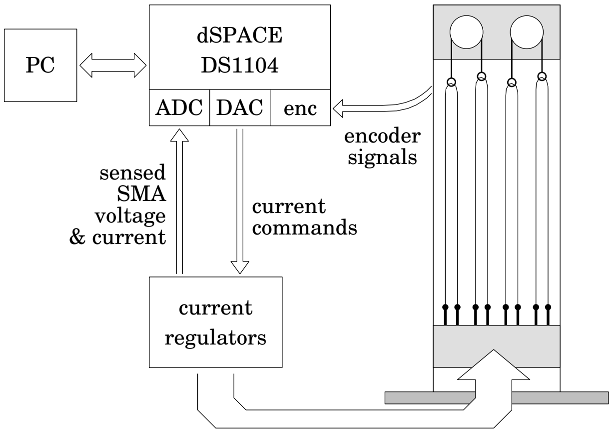


Fig. 5. Schematic diagram of experimental hardware.

Figure 5 shows a schematic of the complete experimental setup. All real-time computation and data capture functions are performed on a DS1104 board from dSPACE, which communicates with and is programmed from a PC. The four DAC outputs from the DS1104 are connected to four current regulators, which supply electrical power to the SMA wires. Each regulator is capable of delivering more than 0.65A (40W) to its load, which is more than enough to burn out the SMA wires. The actual voltage across each wire, and the actual current passing through it, are sensed at taps in the current regulator circuits, and the signals are passed back to the ADC inputs on the DS1104. The magnitudes of these signals are such that we have an effective resolution of 10.5 bits on the SMA voltage signals and 12 bits on the SMA current signals. However, all the signals are polluted with noise, especially the current signals, and we found it necessary to pass them through low-pass filters before we could get accurate resistance measurements.

The optical shaft encoders also connect directly to the DS1104. They have a resolution of 8192 counts per revolution, but the motion range of the pulleys is only slightly more than $90°$, so we have an effective resolution of 11 bits on shaft angle measurements.

4 Experimental Results

We have implemented a version of Grant's two-stage relay controller for antagonistic pairs of SMA elements [3], and incorporated the rapid-heating method into the controller, essentially as shown in Figure 3. The two-stage relay controller implements the following control law:

$$(I_{Fd}, I_{Rd}) = \begin{cases} (0, I_H) & \theta_{err} < -\phi \\ (0, I_L) & -\phi \le \theta_{err} < 0 \\ (I_L, 0) & 0 \le \theta_{err} < \phi \\ (I_H, 0) & \phi \le \theta_{err} \end{cases} \qquad (3)$$

where θ_{err} is the position error, I_{Fd} and I_{Rd} are the desired heating currents for the forward and reverse SMA elements, respectively, and I_H, I_L and ϕ are parameters of the controller. I_H is the current to apply when the position error is large; I_L is the current to apply when the position error is small; and ϕ defines the boundary between small and large position errors. The forward and reverse SMA elements pull in the positive and negative directions, respectively, as measured by the position sensor. The two desired heating currents, I_{Fd} and I_{Rd}, are sent to two current limiters, one for each SMA element, which calculate the actual heating currents to be sent to each element.

We have tested this controller under a variety of conditions. Overall, the rapid heating mechanism substantially improves the speed, but the tracking accuracy is poor because of large limit cycles. The two-level relay controller is known to suffer from large limit cycles [3], but the larger velocities produced by the rapid heating mechanism appear to exacerbate the problem.

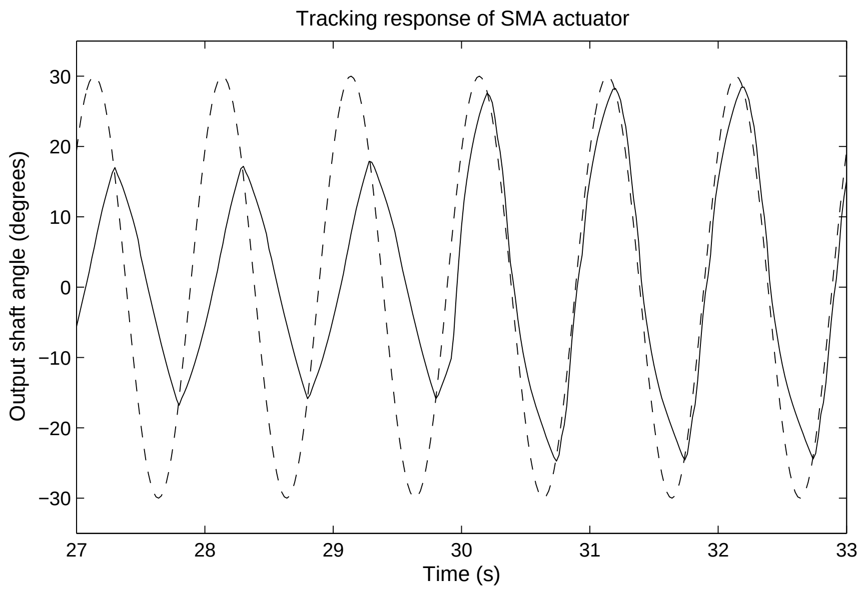


Fig. 6. Tracking response (solid line) of an antagonistically actuated pulley to a 1Hz sinusoidal position command (dashed line).

A representative example of improved tracking speed is shown in Figure 6. This graph shows the tracking response of a single antagonistic pair, under no-load conditions (i.e., without the pantograph), to a 1Hz sine wave input. (Limit cycles are much smaller under no-load conditions.) The 60° peak-to-peak magnitude of the sine wave corresponds to a 1.6% strain in the SMA wires.

The parameters used in this experiment were: $I_H = I_{high}$, $I_L = I_{safe}$ and $\phi = 3^\circ$ for the controller, and $I_{high} = 0.42\text{A}$, $I_{safe} = 0.18\text{A}$, $R_{thresh} = 105\Omega$

and $R_{ramp} = 118\Omega$ for the two current limiters. A linear power ramp was used for $I_{max}(R)$ between R_{thresh} and R_{ramp}.

These parameters were selected as follows. I_{high} is the current required to produce approximately 20W of joule heating in the SMA wires used. This is about half the power available from the current regulators, but many times more than the safe heating power. I_{safe} is taken directly from the data sheet for 0.1mm Flexinol wires [1]. ϕ was chosen to minimise limit cycle magnitude, and was determined empirically. R_{thresh} is the measured hot resistance of one of the SMA wires, plus a 4% safety margin to account for measurement errors, strain-induced variations in resistance, and variations in hot resistance from one wire to the next. (We did not measure the hot resistance of every individual wire.) R_{ramp} was set equal to the cold resistance of an unstretched SMA wire, for no particularly good reason. A lower value for R_{ramp} might have produced better results.

In separate experiments, we determined the largest measurement noise source to be the SMA current measurement, which exhibited an RMS noise of 1.4mA. This amounts to a 0.8% error at currents close to I_{safe} and a proportionately larger error at smaller currents. We removed some of this noise by passing both the SMA current signal and the SMA voltage signal through identical low-pass filters before using them. We also measured the effect of a full load (3 Newtons) on both the strain and resistance of a wire heated by I_{safe}, and found that it caused 0.2% strain and a 0.9% increase in resistance.

Figure 6 shows the tracking response both with and without the benefit of rapid heating. For the first 30 seconds, I_{high} is set equal to I_{safe}, which effectively disables the rapid-heating mechanism. During this period, the controller is unable to track the input signal accurately because the actuator moves too slowly. Then, on the 30 second mark, I_{high} is set to the value given above. This causes an immediate increase in maximum actuator velocity, although it is still not quite fast enough to track the whole of the sine wave accurately.

With the parameters used in this experiment, the rapid-heating mechanism increases the peak actuator velocity by a factor of 2, from approximately $90°/s$ to $180°/s$. Note that this speed-up is due entirely to faster heating. The cooling regime (ambient air cooling) does not change.

The tracking response shows a noticeable asymmetry after the rapid heating mechanism is enabled, and also a substantial reduction in the contraction rate of each wire as it gets shorter. The former is probably due either to one wire being slightly shorter than the other, or to the two eyelets not being exactly level when the pulley angle is zero. The latter suggests there may be some speed advantage, at the expense of motion range, in pre-straining the wires at installation.

Figure 7 shows the actual power delivered to the two SMA wires during this experiment, in the vicinity of the 30-second mark. The data in this graph comes from the SMA voltage and current measurements, which have been low-pass filtered as explained above. The spike in the centre corresponds to the moment when the rapid-heating mechanism is enabled. Prior to this moment, the tracking errors are large, and so the relay controller requests a current of I_H to be sent to each wire in

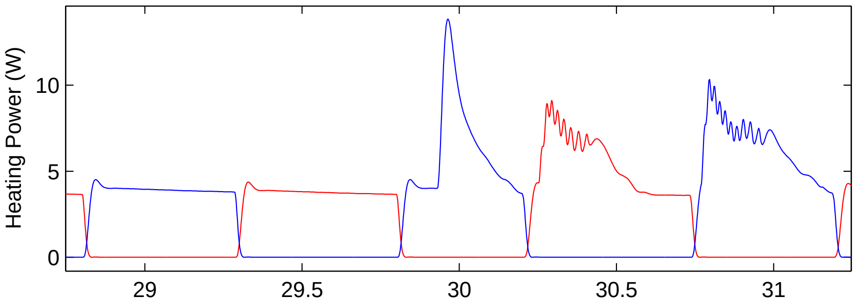


Fig. 7. Actual power delivered to the two actuator wires during the motion shown in Figure 6.

turn; but the actual current is limited to I_{safe} by the current limiter. Immediately after rapid heating is enabled, the tracking error is still large, so the relay controller continues to request I_H be sent to the contracting wire; but now the actual current is computed according to the resistance of the wire. Initially, the wire is relatively cool, and the heating power rises to 14W. The wire then heats very rapidly, but the heating power quickly decays to a safe level as the wire's resistance drops to R_{thresh}.

On subsequent cycles, the relay controller is able to track at least part of the sine wave. The small oscillations visible in the graph are caused by the relay controller hunting around the boundary between large and small position errors, so that its output oscillates between I_H and I_L. The frequency of oscillation is above the cut-off frequency of the voltage and current signal filters, so it appears greatly attenuated in the graph.

5 Conclusion and Future Work

This paper has described a method for rapid electrical heating of SMA elements without risk of overheating. It involves measuring the electrical resistance of an SMA element, calculating a safe upper limit to the heating current as a function of the measured resistance and element-specific resistance and current parameters, and ensuring that the actual heating current never exceeds the calculated upper limit. It improves upon the conceptually-similar method of Kuribayashi by dispensing with the need for special sensors (miniature thermocouples) co-located with the SMA elements; and it is the subject of a provisional patent application in Australia [2].

To demonstrate the effectiveness of this new method, it was incorporated into a motion control system based on Grant's two-stage relay controller, and applied to the task of controlling a pantograph linkage actuated by two antagonistic pairs of Flexinol (tm) wires. Experimental results for the tracking response of a single antagonistic pair under no-load conditions show that the rapid heating method doubles the peak actuator speed, compared with heating via the data-sheet value for safe heating current. This improvement is obtained purely by faster heating—the cooling regime does not change.

Although we have been successful in improving the speed of SMA-based actuators, the tracking accuracy is low (because of large limit cycles), and we suspect that the control system is over-stressing the SMA wires. (We have worn out several so far). We therefore intend to investigate alternatives to the two-stage relay controller, and to conduct fatigue tests on the wires. We are currently designing a new test rig that will include load cells for measuring the tension on each wire. We intend to investigate the use of load-cell data to implement force control systems and more accurate motion control systems.

References

1. Dynalloy, Inc., "Flexinol (tm) Technical Data," `http://www.dynalloy.com/-TechnicalData.html`, accessed May 2004.
2. R. Featherstone & Y. H. Teh, "A Shape Memory Alloy Actuator," Australian Provisional Patent Application no. 2004900618, 9^{th} Feb. 2004.
3. D. Grant, "Accurate and Rapid Control of Shape Memory Alloy Actuators," Ph.D. Thesis, Centre for Intelligent Machines, McGill University, TR-CIM-99-11, 1999.
4. S. Hirose, K. Ikuta & Y. Umetani, "A New Design Method of Servo-actuators Based on the Shape Memory Effect," in A. Morecki, G. Bianchi & K. Kędzior (Eds), *Theory and Practice of Robots and Manipulators*, MIT Press, Cambridge, MA, 1985, pp. 339–349.
5. K. Ikuta, M. Tsukamoto & S. Hirose, "Shape Memory Alloy Servo Actuator System with Electric Resistance Feedback and Application for Active Endoscope," *Proc. IEEE Int. Conf. Robotics & Automation*, Philadelphia, PA, pp. 427–430, 1988.
6. K. Kuribayashi, "Improvement of the Response of an SMA Actuator Using a Temperature Sensor," *Int. J. Robotics Research*, vol. 10, no. 1, pp. 13–20, 1991.
7. M. J. Mosley & C. Mavroidis, "Experimental Nonlinear Dynamics of a Shape Memory Alloy Wire Bundle Actuator," *Trans. ASME, J. Dynamic Systems, Measurement & Control*, vol. 123, no. 1, pp. 103–112, 2001.
8. D. Reynaerts & H. Van Brussel, "Design Aspects of Shape Memory Actuators," *Mechatronics*, vol. 8, pp. 635–656, 1998.
9. N. Troisfontaine, Ph. Bidaud & P. Dario, "Control Experiments on Two SMA Based Micro-actuators," in A. Casals & A. T. de Almeida (Eds), *Experimental Robotics V*, Springer, London, 1998, pp. 490–499.