Proc. 2002 Australasian Conference on Robotics and Automation
Auckland, 27-29 November 2002

A Nitinol Wire Actuated Stewart Platform

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Abstract

The Stewart platform is well known parallel robotic mechanism often used as a flight simulator. Less well known applications involve robotics and machine tools. This paper deals with binary actuated robotic Stewart platforms that use Nitinol wire actuators that are switched on and off to control the position of the actuator. Binary control of the six actuators on a platform yields sixty four possible platform positions, and five stacked platforms yield more than a billion possible positions. The design of a simple basic two stage model is described in this paper.

1 Introduction

In recent years there has been considerable interest in the application of parallel robots because of their greater stiffness and accuracy when compared to the standard serial robots. However these desirable characteristics are obtained at the expense of a reduced workspace.

The 6 dof (degree of freedom) parallel mechanism known as a Stewart platform [Stewart 1965] was attributed to Stewart for use as a motion (flight) simulation platform, but it was originally developed as a tyre testing machine for the Dunlop Tyre Company [Gough 1962]. It was later used as a precision manipulator [McCallion and Pham 1979], as a milling machine [Rathbun 1985, Dunlop and Rathbun 1989], and as a singularity free antenna aiming mechanism [Dunlop and Jones 1998]. A schematic of the basic Stewart platform is shown in fig.1 [Merlet 2000].

Figure 1: A schematic view of the basic Stewart platform

The prismatic actuators used for the Stewart platform are usually continuous hydraulic or electrical linear servo actuators. The use of simple on off pneumatic actuators [Chirikjian 1994] to reduce the cost and complexity of robots looked promising for Stewart platform systems.

An open loop electrically operated actuator based on Nitinol wires has been developed to activate small Stewart platforms. This Nitinol wire system is described in detail in the next section. This is followed by a description of the actuator controller and some experimental results are presented along with some simulations. Finally the multistage Nitinol based Stewart platform is described.

2 Design of the Nitinol Wire Actuator

The Nitinol wire actuator is based on a 50% Nickel – Titanium alloy developed by the US Naval Ordinance Laboratory. These nitinol wires have been specially processed to have large stable amounts of memory strain for many cycles. They contract like muscles when heated above a critical temperature. This shape memory effect observed in nitinol is the result of a solid state transformation between two phases: austenite and martensite. This shape-memory phenomenon occurs in certain alloys where nickel-titanium is one of them. The material forms a crystal structure that is capable of undergoing a change from one crystal form to another at a temperature determined by the exact composition of the alloy. Austenite is the phase of the crystal that exists above the transformation temperature. It is high strength and not easily deformed. Consequently below the transformation temperature, martensite would exist. The alloy now can be deformed several percent by an uncommon deformation mechanism, which can be reversed when the material is heated and transforms. Martensite would undergo the reversible deformation fairly easily, so the memory strain can be put into the material at rather low stress levels.

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. Any of these can be used to follow the progress of the transformation, as is illustrated in fig 2 [Duerig et al, 1990]. The temperature, M_s, M_f, A_s, A_f, are indicated in the graph and refer to the temperature at which the transformation to martensite starts and finishes, and the temperature at which the reversion to austenite starts and finishes. Note that there is a hysteresis associated with martensitic transformations; in other words, the transformation temperatures differ upon heating and cooling. The hysteresis effect typically lies between 20 to 40 °C. The electrical resistance exhibits similar behaviour that is shown by the experimental results given in fig. 3 during the binary strain cycle.

To use the Nitinol wires as a prismatic actuator could involve using a constrained preloaded spring with the Nitinol wires up the middle. Termination of the spring constraints with ball joints and electrical terminations for the Nitinol wires results in a somewhat complicated structure, especially if many actuators are require. For example, an 8 stage stacked Stewart platform design would require 48 binary actuators to yield 256E12 positions for the final stage. Construction of such actuators is expensive and another approach is taken.

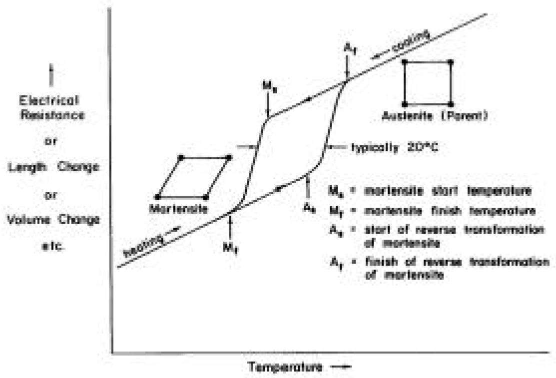


Figure 2: Temperature Dependence of Physical Properties

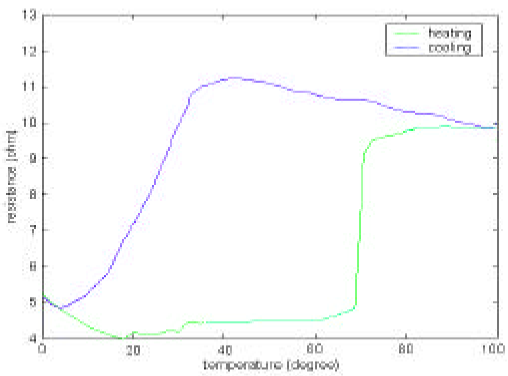


Figure 3: The Resistance- temperature characteristic of nitinol at constant weight 100.6g

The approach taken is to design a system that is suitable for rapid prototyping. The Nitinol wire is pre-tensioned using a bow that has ball joints at each end that connect to the two triangular stages (for a single stage Stewart platform one is the base and the other is the platform). This arrangement is shown in fig. 4. Note that the cups that hold the ball joints into the spherical cavities in the triangular stages are actually grown in situ during the rapid prototyping process. The bow is grown with a flat orientation during prototyping in order to develop full strength for flexing as it provides the forces needed to support the platform as well as to pre-tension the Nitinol wire which acts as a bowstring.

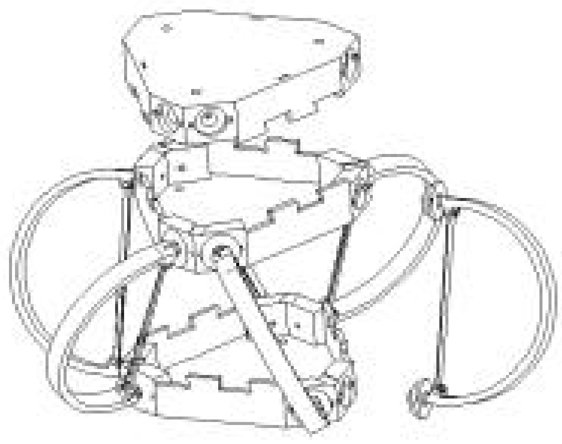


Figure 4: An exploded view of the single stage Stewart platform shape and shape memory alloy actuator.

3 Control of the Nitinol Wire Actuator

The electrical resistance of the Nitinol wire actuator is used to determine the operating temperature, and hence the strain. A graph of the mechanical strain as a function of electrical resistance in given in fig. 5. The strain (and resistance) of the Nitinol wire is controlled by means of a 4 state process as shown in the simulation of fig. 6.

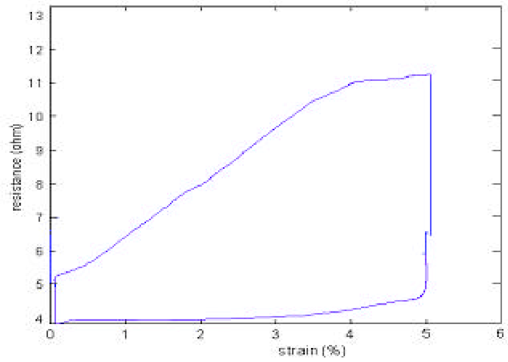


Figure 5: The Resistance- strain characteristic of nitinol at constant weight 100.6g

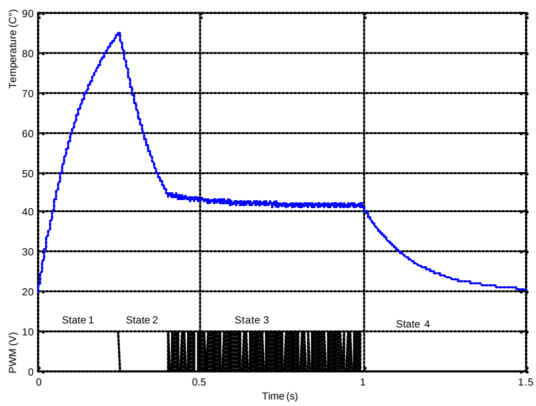


Figure 6: Four state control of a nitinol actuator.

This state machine undergoes 4 transitions to the states: on, off, PWM (Pulse Width Modulation), and off. The transitions are determined by measurements of the electrical resistance of the Nitinol wire. The idea is to switch on the electric current until the Nitinol wire heats to above 80ºC and then the current is switched off until the wire cools to around 30ºC while still maintaining the same strain. PWM is then used to maintain the temperature at the knee of the hysteretic strain cycle. When the current is switched off, the wire cools and the strain returns to its original state.

The detailed circuitry for making these measurements is shown in fig. 7. The system is a modified Wheatstone bridge that operates whenever the heating switch is off. Once the switching transient has died away, the differential measurement provides a voltage proportional to the electrical resistance of the Nitinol wire, and proportional to the change of strain.

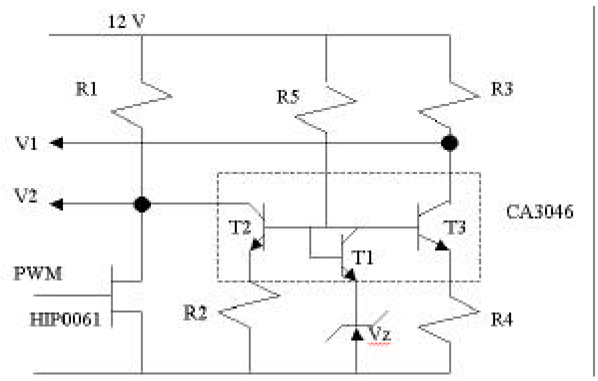


Figure 7: The PWM driver and resistance monitoring circuit

4 Optimisation of the cooling rate

The main problem with using Nitinol wire actuators is the time taken to cool the wire back to the ambient temperature state. As seen in fig. 6, the cooling from the high temperature state to just above the hysteresis knee (at around 40°C) occurs at approximately constant strain so this cooling time is removed from consideration, and it remains to cool the wire to ambient as quickly as possible.

The approach taken is to increase the number of wires so as to keep the same total cross sectional area while increasing the surface area. For example, using 4 Nitinol wires of 75µm diameter instead of 150µm retains the strength but increases the cooling surface by 2 times, and thus halves the cooling time. Placing the 4 lengths in series results in a resistance 16 times larger, but the current requirement is reduced. Essentially, the power requirement is doubled to maintain the same temperature, but since the heat capacity is unchanged, the transients power requirements to establish the strain remain unchanged. Maintaining the hysteresis knee temperature requires double the power, but since the system is only 20°C above ambient by using PWM, the actual power is still reduced compared to the standard method of maintaining the wire at the maximum temperature around 60°C above ambient. Thus while the power may be doubled, the PWM technique allows the power to be reduced by three times, and the result is only 2/3 the normal power use is required, and the switch off times are approximately halved

For this reason a fine continuous wire but with windings of three loops around two small diameters Teflon rod is needed. A loop number of three is particularly chosen for the purpose of equalising strain. A schematic view is shown in fig 8.

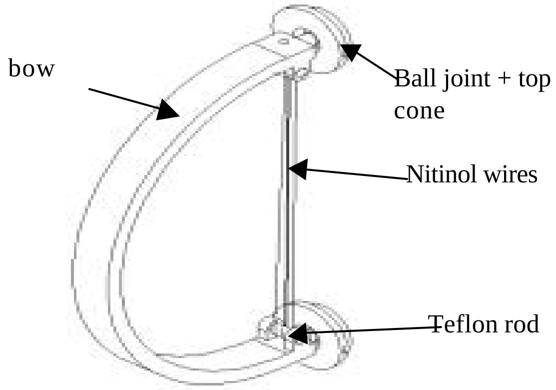


Figure 8: A schematic view of an ABS bow spring with nitinol wire wound as a bowstring.

5 Experimental results

To apply SMA wire actuators repeatable behaviours is very important. The applications mentioned above are driven by electric current and controlled electric resistance feedback. To measure the thermal cyclic behaviour of SMA wire actuators, it is necessary to heat cycle the SMA wire many times while measuring the response. A thermal cycling test was developed or this purpose and used electrical resistance monitoring. A schematic diagram of the test equipment is shown in fig 9.

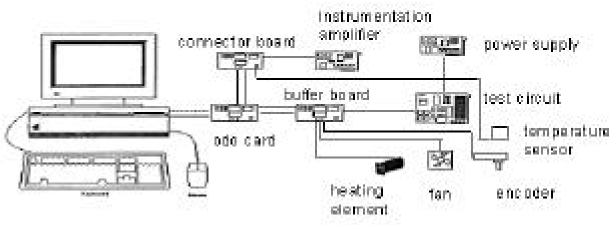


Figure 9: Experimental set up of heat cycle test

The specimen was a Nitinol SMA wire of 75µm diameter. It is wound about two ceramic rods and tensioned with 1N. Six strands of wire were used for the experiment and the whole apparatus placed in a thermo blanket lined polystyrene isolation box. The operation temperature inside the box was set with a heating element and a small fan placed near to the wire. The SMA wires were heated while monitoring the temperature within the polystyrene box, and then after reaching the maximum temperature, the SMA wire slowly cooled as the isolation box lost heat. The whole experiment continuously ran for 18 hours and underwent up to 10 cycles. Experimental results were shown in fig 10 and 11.

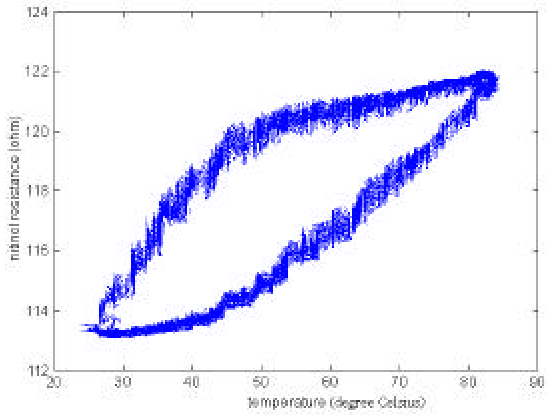


Figure10: The resistance--temperature characteristics of nitinol wire biased by a constant load of 100.6g

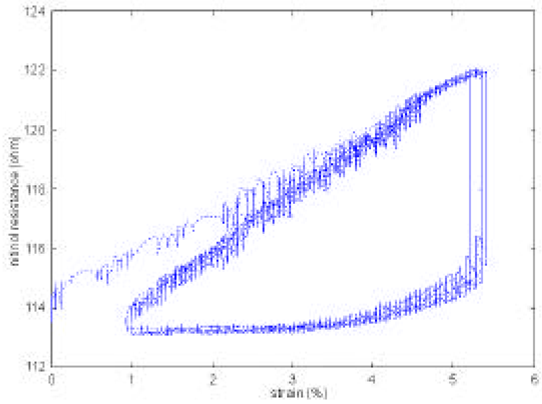


Figure 11: The resistance-strain of nitinol wire biased by a constant load of 100.6g

Although there is some noise in the results, the major trends can be clearly in both graphs. Fig 11 shows that the SMA wire electrical resistance and strain exhibit a relationship that has long-term stability. Thus the SMA wire can be used as a highly reliable actuator in a wide range of applications.

6 Cyclic Behaviour Training

Tobushi [et al. 1992] reported experimental results on an SMA coil that showed that not all the strain was recovered when the Nitinol wire underwent a cyclic strain variation. However he concluded that introducing training before it is employed in an application could reduce the rate of reduction of recoverable elongation. This phenomenon is investigated for the SMA wires.

The apparatus was the same as that used to measure resistance – strain variations with temperature except the force was provided by a low stiffness spring. If the spring was replaced by a dead weight, the SMA wire would eventually recover the strain without introducing too much stress. The SMA wire was then heated by pulsing an electric current through the wire and then allowing it to cool for a few seconds, and the heating cycle repeated 1000 times.

The relation between the irrecoverable elongation Δl_p of the SMA and the number of cycles N is shown in figure 12. The irrecoverable elongation Δl_p is represented by

$$\Delta l_p = (L - L_o)/L_o$$

where L denotes the axial length of the SMA wire under 70 % PWM and L_o denotes the shape-memorized initial length. In figure 12, the blue curve is the result in the cases subject to the training of N = 10^3 and show the relation between Δl_p, which was calculated by using L at N = 10^3 as L_o in the above equation and the number of cycles (N-10^3).

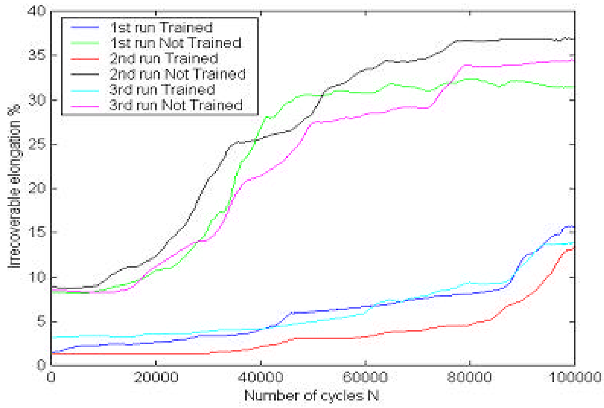


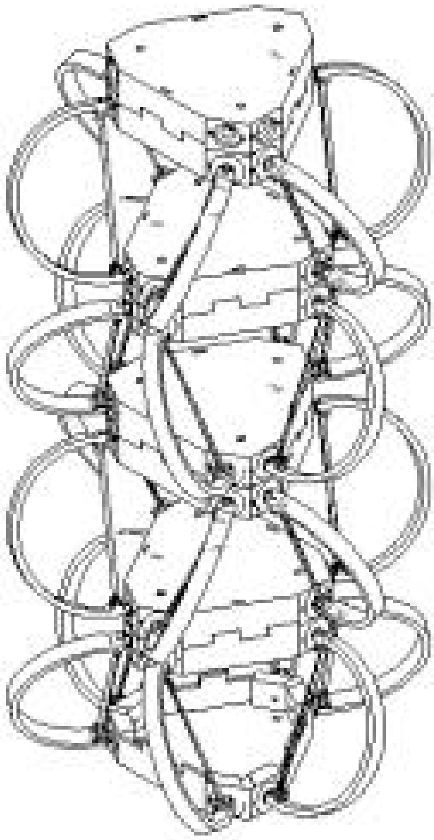
Figure 12: Changes in irrecoverable elongation as a function of the repletion cycles

As observed in fig 12, Δl_p decreases with an increase in N. If the SMA wire is subjected to the training, Δl_p becomes small. After 10^5 cycles of testing, the tremendous reduction in the change of Δl_p is caused by the training. Thus if a trained SMA wire is used in an application, then the irrecoverable elongation effect can be avoided.

7 Multistage Nitinol based Stewart platform

The basic arrangement for the multistage nitinol based Stewart platform mechanism consisting of a number of single stage Stewart platforms is shown in Fig 13. Each end piece of the Stewart platform is connected by 6 parallel bows that are preload to give a spacing of 80 mm at ambient temperature. The Stewart platform is designed specifically as an equilateral triangular box shape. The internal space is used for holding the circuit board, but also provides protection. The length of the triangular box is about 100 mm, and the height when the box closed is about 40 mm. Slots are available at each corner of the box for the connection of the nitinol wire to the circuit board.

Each nitinol actuator has 2 states, so a stage of 6 nitinol actuators with six degrees of freedom has a total of 64 combinations of movement. Hence the multi-stage mechanism should be capable of performing quite complex movements. With the ball joint provided at the end of the bow, rotation of the bow is possible, but this does not affect the attitude of the platform, and can be elastically constrained if desired. With this configuration the nitinol actuators produce a large working envelope and



avoid the danger of pile-up between each nitinol wire.

Figure 13: A multistage nitinol based Stewart platform mechanism

With 4 microcontrollers, and 8 Stewart platform stages, 2^{48} poses are possible, and distributed uniformly over 6 degrees of freedom, there are 2^8 or 256 possibilities for each of the 6 dof of the end platform. The main benefit of the design is that the mechanism can perform complex motions. It can alter its shape over its whole length, and with this mobility, it would be able to penetrate inside environments containing much chaotic piping such inside sewers, nuclear reactors etc, and undertake visual examination of difficult to access areas.

8 Conclusions

A method to utilize binary state SMA actuators in the control of a Stewart platform is presented in this paper. The nitinol actuated Stewart platform mechanism is suitable for construction by rapid prototyping. Moreover the experimental results show repeatability after some initial training (or conditioning) so the SMA wire shows promise as a useful actuator, which was one of the aims of this research. The main draw back is likely to be the fatigue and degradation of shape memory effect with the long use of the SMA actuator. However the degradation is reduced by training or preconditioning the unit, and SMA nitinol material has fatigue life of about 10^7 cycles. Further investigation will focus on the development of the controllers which specifically address the system nonlinearities.

Acknowledgements

The authors would like to acknowledge the technical support of Mr Andy Cree, and Mr Rodney Elliot, scientific officers in the Mechanical Engineering Department of University of Canterbury, New Zealand.

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