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SMA Actuator Technology Application in Stewart Platform Construction

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Abstract: This research is a study of using a Shape Memory Alloy (SMA) as an actuator in a robotic application for a 6 Degrees of Freedom (DOF) Stewart Platform. Conventional actuators such as hydraulics, pneumatics and mechanical will be replaced by a new breed of technological advancement of SMA wires. The focused area of study is on a mini sized Stewart Platform which eliminates bulky conventional actuators. Hence, SMA will have the distinctive advantages over the other types of actuators. The mini Stewart Platform consists of a fixed base and a platform connected with specially designed SMA actuators along with a counter force spring. The support post for the platform uses a counter force spring material viz. sponges. Further study includes the design of a Pulse Width Modulation (PWM) technique power supply circuit for the controlling the current to increase the temperature of the heat sensitive wires. For the SMA wires, the cooling system serves as an important role to ensure the wires return back to its original length without any damage after they had been stretched out. Kinematic studies have been carried out to achieve required displacements of the platform.

Key words: Shape memory alloy (SMA), Stewart platform, pulse width modulation (PWM)

INTRODUCTION

Stewart Platform (ST) is a classic example of a mechanical design that is used for positioning and orientating the platform with respect to a fixed base. It is also known as parallel manipulator which has been in use since 1980, when high load carrying and precise positioning capability was needed. This study is important because it is a widely accepted design for a motion control device.

The paper involves, the design of a mini sized Stewart Platform, replacing conventional actuator with Shape Memory Alloy Actuator (SMA) actuators. Shape memory alloy is metal alloy made of Nickel and Titanium (Nitinol) which contracts when heated. The Nitinol wire has been used in many applications such as military technology, robotic application in surgery or space robot to stimulate motion and safety gadget like fire sprinkler (Kauffman and Mayo, 1993).

Traditional actuators such as electric motors, hydraulic pumps and pneumatic actuators necessitate the use of large and heavy supporting structures and are usually very noisy. Electric motors are heavy, revolve at very high revolutions and they require a reduction gear system to produce the needed torques that is compatible with the motion of most mechanical devices (Mavroidis, 2002). Hence, they are not suitable for the micro or mini sized Stewart Platform which is less than 20 cm of height and having limited base area.

To design the mini Stewart Platform with SMA actuators basic design software such as Solidworks and AutoCAD are employed. The design considered all available types of manufactured SMA wires products and qualities. Among them are different SMA wires tradenames such as Flexinol, Euroflex -GmbH, Bio Metal and Muscle Wires.

The design also involves the control system for the SMA wire which will monitor its contraction length and speed. This requires Oscillating Current (OC) circuit or Pulse Width Modulation (PWM) technique. PWM is the process of switching the electrical power to a device on and off at a given frequency, with varying on and off times. These on and off times are referred to as "duty cycle". This enables the user to operate the Stewart Platform with ease and avoid damaging the SMA wires.

Experimentations of the SMA wire performance were carried out to find important data such as speed of contraction, minimum and maximum weight that can be lifted and operating conditions. Fabrication and construction process of the mini Stewart Platform using the SMA wires actuators was based on analysis of the experimentation results.

DESIGN OF MINI STEWART PLATFORM

Kinematic mathematical model: The mathematical model is important to predict the motion or movement of the

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Stewart Platform. To predict the platform motion, the analytical method is used (Tsai, 1999).

Generally, ST has 6 spherical and 6 Prismatic joints resulting in a 6 Degree of Freedom (DOF). Although, the actuators have been replaced with SMA wires, they are still considered as prismatic joints for the limbs. Hence, the limbs connecting the base with the platform is type SPS or Spherical Joint-Prismatic Joint-Spherical Joint. The wires are considered as prismatic joint because the force acting on each limb is only directed along the longitudinal axis of the limb.

The geometry of the manipulator is shown in Fig. 1 and has Cartesian coordinate systems viz. frame A(x, y, z) and B(u, v, w) are attached to a fixed base and moving platform, respectively. The transformation from the moving platform to a fixed base can be described by position vector p of the centroid P and the rotation matrix ${}^AR_B$ of the moving platform. Let u, v, w be 3 unit vectors defined along the u, v, w axis of the moving coordinate system; then the rotation matrix can be written as:

$$ {}^AR_B = \begin{bmatrix} u_x & v_x & w_x \\ u_y & v_y & w_y \\ u_z & v_z & w_z \end{bmatrix} \tag{1} $$

Let $a_i = [a_{ix}+a_{iy}+a_{iz}]^T$ and $b_i = [b_{ix}+b_{iy}+b_{iz}]^T$ be the position vectors of A_i and B_i in the coordinates frame A and B, respectively. The vector loop equation for the ith limb of the manipulator is follows:

$$ \overline{A_iB_i} = p + {}^AR_B\ {}^Bb_i - a \tag{2} $$

Hence, the length of the ith limb is obtained by taking the dot product of the vector $\overline{A_iB_i}$ with itself.

$$ d_i = \sqrt{(p + {}^AR_B\ {}^Bb_i - a_i)^T\ (p + {}^AR_B\ {}^Bb_i - a_i)} \tag{3} $$

for i: 1, 2..

There will be two possible solutions for each limb. However, when the solutions of d become complex numbers, the location of the moving platform is not reachable. The derivation equations for Stewart Platform were obtained from Tsai (1999).

Figure 2 was a result of applying the inverse kinematic formula in Matlab. When the platform moved upward in z-axis, all the 6 limbs have the same value of elongation. However, when there is a rotation at x-axis or y-axis, the value of the limbs will differ whereby some will shorten and the opposite side will elongate to complement the movement.

Figure 3 shows the different length of each limb at certain time when the platform is at tilt or on rotation at certain axis. Hence, from there we can predict the

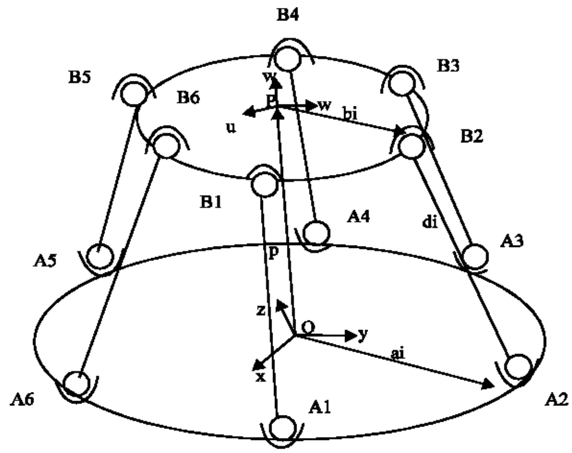


Fig. 1: Mathematical model of Stewart platform

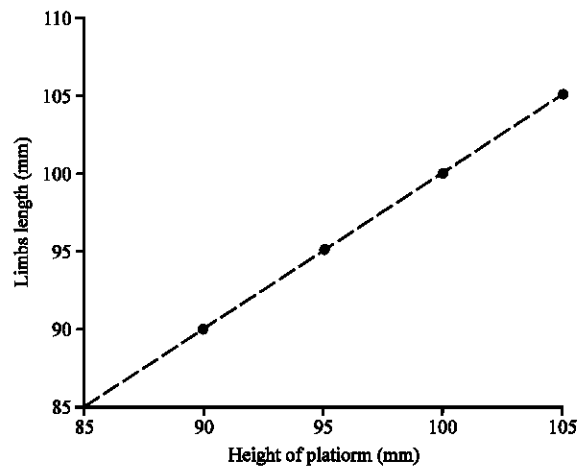


Fig. 2: Length of limbs vs. height of platform

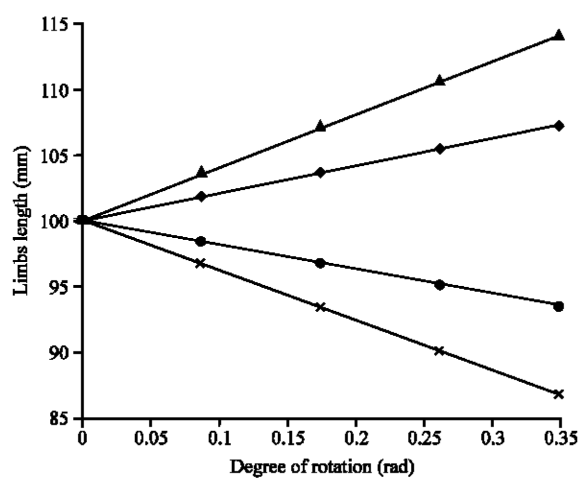


Fig. 3: Limb length vs. degree rotation at x-axis

characteristic and length of each limb when it is activated and design the platform better.

The rotation matrix below will change at different rotation at different axis. Hence, the rotation degree from 0 to 20° at x-axis results in different lengths is shown in Fig. 3. Meanwhile, rotation at y axis will also result in different limb length because it depends on their location at Fig. 1.

Nitinol wire selection: The correct selection of the Nitinol (NiTi) muscle wire is very important as it will affect the performance and control of the Stewart Platform. In this study, the Stewart Platform must have low activation temperature property which only needs low current supply to the wire. It must also possess a long lifetime cycle and low resistance. Other factors that also contribute to the wire selection are economical cost, delivery periods, wire diameter and maximum weight lifting capability. A specially manufactured alloy of nickel and titanium (NiTi), called Flexinol™ 150 LT type is selected as the most suitable wire to be used as the Stewart Platform actuator (http://www.musclewires.com/).

Design 3D modeling: The original design of the Stewart Platform limbs includes the return force from leaves sheet metal spring. This design is to shorten recovery time and accurately position the floating platform to its original coordinate location.

However, the SMA wires posses good recovery time performance, so, there is no need for a strong recovery force. Hence, a new option to replace the outside leaves sheet metal spring with a proper conventional spring in the middle of the platform or sponge spring is taken into consideration. It can be achieved by designing a centre post to support the spring. Final 3D Modelling of SMA Stewart Platform is presented in Fig. 4.

NITINOL WIRE ACTUATOR DESIGN

SMA actuators operate by means of a temperature-induced solid-solid phase transition, control performance hinges on the speed and accuracy of heating and cooling. At room temperature SMA wires are easily stretched by a small force.

However, when conducting an electric current, the wire heats and changes to a much harder form that returns to the "un-stretched" or initial shape-the wire shortens in length with a usable amount of force. It is the perfect example for SMA to have memory of its exact initial shape that is visible and controllable which differentiate them from other metal alloys.

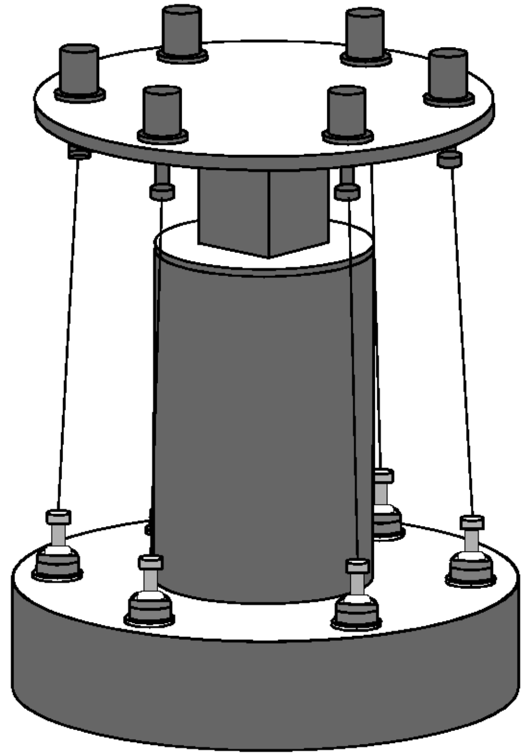


Fig. 4: Final 3D modelling of SMA Stewart platform

As an actuator, NiTi wire claims to be capable of up to 5% strain recovery. To verify the claim, an experiment was conducted using the Nitinol wire. The Flexinol 150 LT is a Nitinol wire 150 μm in diameter and can lift as much as 330 g. Nitinol also has the resistance properties which enable it to be actuated by joule heating. When an electric current is passes directly through the wire, it can generate enough heat to cause the phase transformation.

Low Temperature (LT) activation of Nitinol wire is at 70°C. It has a resistivity of 50 Ω m^{-1} which means at 100 mm the wire has 5 Ω of resistance. The recommended current is 400 mA. This current can be regulated through a direct current circuit using MOSFET components.

SMA performance experiment: The extension and the contraction of the SMA wires were conducted in a setup shown in Fig. 5. Several reading were taken in various percentage of initial length.

The objective of the experiment is to verify the pulling force of SMA wire and time on the activation and de-activation of the SMA wire. Since, the wire is heat sensitive, the first experiment used a dc power supply with a PWM technique and the second experiment used a direct dc power supply.

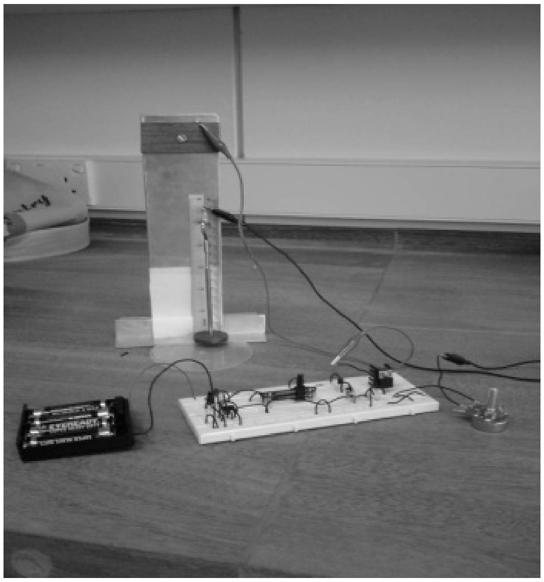


Fig. 5: SMA performance experiment set-up

Table 1: SMA wire performance with 200 g weights

Power supply	Volts (V)	Contraction percentage (%)	Time of contraction(sec)
DC	3	4	4
DC	6	4	4
DC	11	-	-
PWM	6	-	-
PWM	9	2.3	6
PWM	11	-	-

The results shown on Table 1 was based on the weight of 200 g attached to the wire. The contraction percentage and the time are recorded and compared.

Table 1 shows that higher contraction percentage can be obtained using DC power supply.

Figure 6 and 7 shows that varying the weights did not affect the time of SMA wire contraction in any trend. Due to small wire contraction, results in observation error in identifying the start and stop point of the contraction.

From both Fig. 6 and 7, it is observed that by using PWM, the contraction percentage was reduced to 2-3% only. It is because, PWM provided a better controlled current flow to prevent the SMA wire from being burned or damaged due to overheating or hot spots. However, this situation is noncritical as the objective was to ensure the wire is able to activate within specifications.

SMA actuator design: Several studies have been conducted to study the cooling system of the SMA actuators. For example, Odhner (2006) ASME has conducted a study on a feedback control of the temperature of Shape Memory Alloy (SMA) actuators without the use of dedicated temperature sensor.

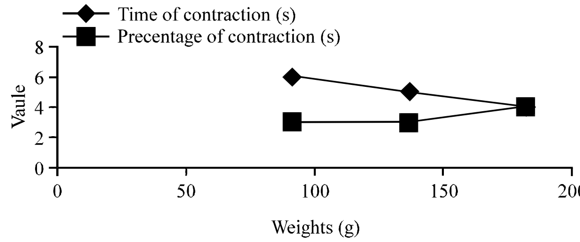


Fig. 6: The SMA wire performance without PWM

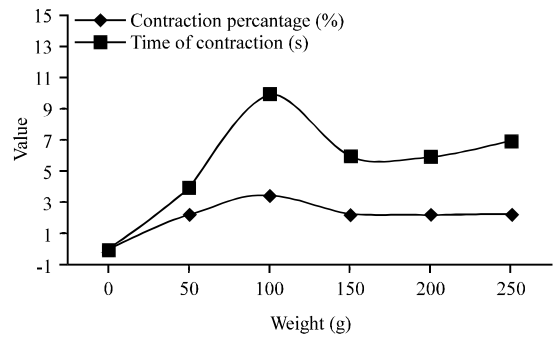


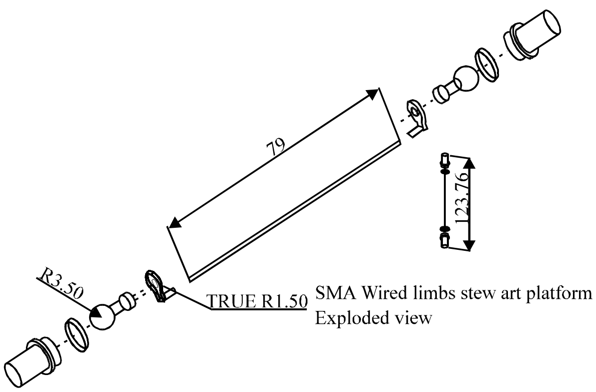
Fig. 7: The SMA wire performance with PWM

Another study presented by Mascaro and Asada (2003), where an SMA wire was embedded within a compliant vessel of flowing fluid, allowing for a higher bandwidth, while maintaining a high power to weight ratio. However, this study is neglecting additional cooling mechanism because the prototype will be operated in an air conditioned room. The SMA actuator wires are installed far from each other and the center platform to allow air flow for cooling mechanism.

The actuator consists of 79 mm of SMA wire. The wire was fixed into metal crimps on both ends. The crimps were screwed to plastic spheres that act as spherical connector to the actuator or the Stewart Platform limbs as shown in Fig. 8.

Spherical connectors were then carefully enclosed into its cover or casing which were fixed to the base and floating platform. Total length of the assembly is 123.76 mm. All connectors except the crimps are made of insulating products such as plastic to avoid heat loss when current flows in the system.

Actuator control: While many robot builders use a microcontroller to generate the required PWM signals, the 555 timer can be used to build PWM circuit that is easier to construct The 555 timer in the PWM circuit is configured as an astable oscillator. This means that once power is applied, the 555 will oscillate without any external trigger.



Parts	Description	Size
1	Spherical connec for made of hard plastic (act as insulation to the SMA wire limbs)	
2	The round end crimp made of soft metal to act as eletrical conductor for SMA wire connection to the PMM circuit	End hole = 3.5 mm dia. inner connector dia. = 1.5 mm
3	Both end of the connectors body will attached to the fixed and float platform each	

Fig. 8: SMA actuator limb assembly

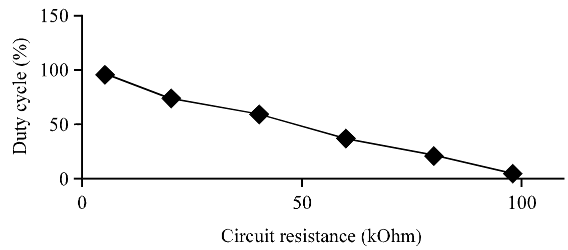


Fig. 9: Results for PWM duty cycle with variable

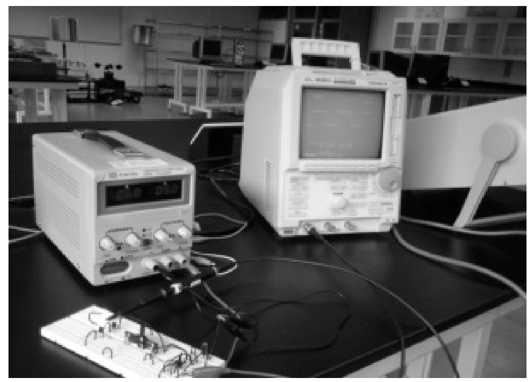


Fig. 10: PWM performance verification experiment

The PWM signal is still digital because, at any given instant of time, the full DC supply is either fully on or fully off. The voltage or current source is supplied to the analog load by means of a repeating series of on and off pulses. The on-time is the time during which the DC supply is applied to the load and the off-time is the period during which supply is switched off.

Based on the experiment setup shown in Fig. 10, PWM has proven to be the most reliable control circuit for the Stewart Platform SMA wire limbs. From Fig. 9, it shows that the PWM Duty Cycle is decreasing as the PWM circuit resistance is increased. The linear trend of the graph proves that the PWM is able to provide control for the SMA wire with variable duty cycle.

At lower resistance, the PWM circuit will provide a higher duty cycle current to the connected SMA wire. As a result the SMA wire would contract at a higher percentage of maximum 4% because of high duty cycle current.

Circuit resistance: The results of real time experiment and LTSpice software shows detailed similarities of the peak current across the Nitinol wire, the changes and percentage of the duty cycle at different circuit resistance, and the peak voltage of the circuit. To control Nitinol wire, the potentiometer is changed to lower resistance for higher duty cycle. In simple words, the lower resistance in potentiometer, the higher duty cycle can be obtained from the PWM circuit. It is proven that our PWM circuit is working correctly and ready to be applied with the Nitinol wire.

Construction of a SMA Stewart platform

The floating platform: The platform was made of Ply-Wood which is hard and light to reduce the loads applied to the SMA wire limbs. The size is 100 mm diameter with thickness of 25 mm. Six 4 mm diameter holes were drilled at 60 degree angles each. Six 4 mm diameter plastic spherical connector were inserted to the holes and secured with adhesive bonding.

SMA Actuator: To ensure the SMA wires receive sufficient heat, heat loss through the connection must be avoided. The most economic and practical solution is by using plastic material which is not an electrical conductor.

Figure 8 shows the individual spherical connector made of plastic components. Soldering or welding the SMA wire can damage its crystal structure, hence, they are avoided instead SMA wires are crimped mechanically. Care must be taken to avoid breaking of the SMA wires.

Stewart platform: Figure 11 is the side view and top view of the SMA actuated Stewart Platform. To make the design safe, the centre post consists of a hard and rigid cylindrical profile to ensure the platform does not move.

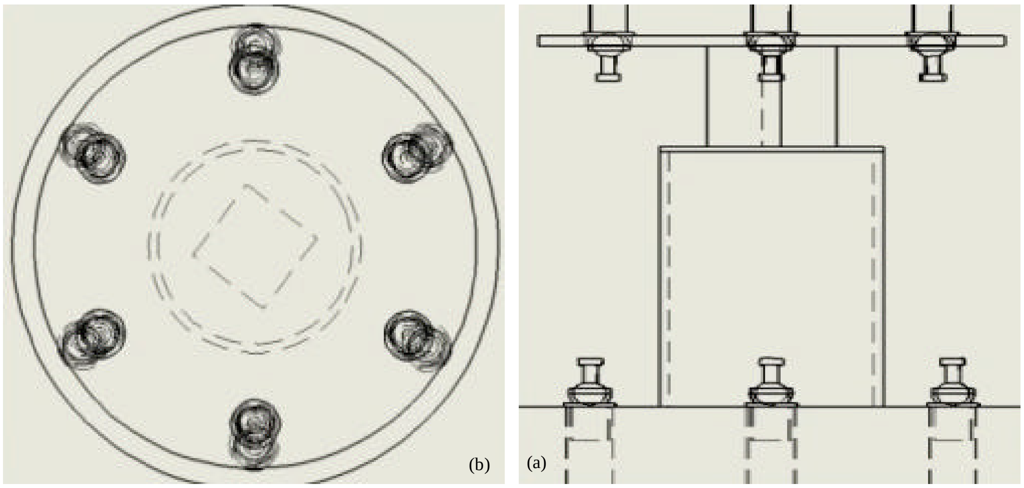


Fig. 11: Side and top view of the main body of the Stewart platform

A model prototype was successfully fabricated. The finished prototype was a fully working prototype according to its design. Figure 14 shows the completed prototype of the SMA wired Stewart Platform.

Figure 12 describes the working principle of SMA wired Stewart Platform. A 9V battery is used to supply Direct Current (DC) to the PWM circuit.

Pulse width modulator: There are 6 PWM circuits used in this prototype. Each limb of the platform is activated using their independent PWM circuits. Therefore, the platform tilting angle can be controlled systematically by varying the resistance in the PWM circuit. Direct current from a 9V alkaline battery is used to power all the 6 units of the PWM circuit.

Figure 13 is the full prototype model of the SMA actuated Stewart Platform connected with its PWM circuit controller powered by 9V alkaline battery.

Platform motion: The Main objective of the actuator is to be able to control the tilt angle of the floating platform. By adjusting the PWM resistance, users can control the contraction percentage of the SMA wire or the limb contraction. When a single limb contracts or shortens to a certain value, the opposite limb will slightly elongate to compliment the other side. This is when the floating platform tilts to a certain degree.

The platform is designed to move freely in 3 dimensions. The SMA wire will shorten hence moves the floating platform. When current is switched off, the wire will cool down and elongate to an initial length. The center post has been fixed with a sponge to help shorten

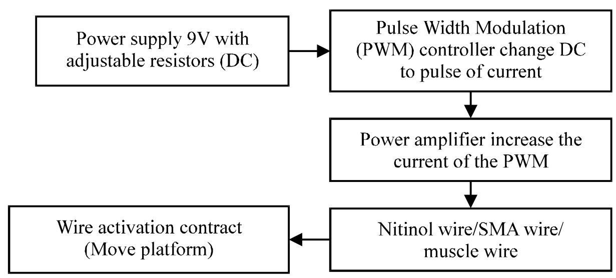


Fig. 12: Stewart platform working principles

Fig. 13: Stewart platform and PWM control box

recovery time after current is switched off. Figure 14 shows the movement by the floating platform. Analysis includes the contraction length by varying the resistance

Fig. 14: Stewart platform 3 dimensional movement

Table 2: Data of platform performance

Resistance (kOhm)	Initial wire (cm)	Final wire (cm)	Wire contract (cm)	Contraction Percentage (%)
0	6.9	6.62	0.28	4.06
20	6.9	6.64	0.26	3.77
40	6.9	6.65	0.25	3.62
60	6.9	6.70	0.20	2.90
80	6.9	6.75	0.15	2.17
100	6.9	6.80	0.10	1.45

in PWM circuit that results in different duty cycle to each SMA limb.

Based on data in Table 2 which was obtained from the Stewart Platform experiment which shows resistance increasing up to 100 k Ohm resulting in decreasing of SMA wire contraction. Hence, the wire performance can be controlled and complied with the requirement for an actuator. Controlled actuator is essential for a precise and accurate position manipulator like the Stewart Platform. It is important for the newly designed Stewart Platform to have both control and strength attributes in order for it to be used in industry applications. In this study, the SMA wire has successfully been controlled, using PWM.

The limbs are limited to only 0.28 cm or 2.8 mm contraction length when at 0 Ohm PWM resistance as shown in Fig. 15. This limit is because of the property of SMA itself. For example;

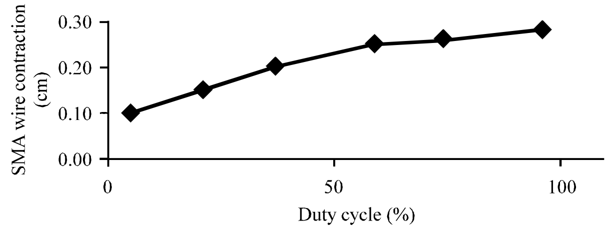


Fig. 15: SMA wire relationship with duty cycle

- At zero ohm resistance, contraction percentage is 4.05%
- Contraction length = Total length of wire x contraction percentage
- So, at 69 mm SMA wire;
- Contraction length = 69 mm×4.05% = 2.8 mm
- If, at 150 mm SMA wire;
- Contraction length = 150 mm×4.05% = 6 mm

If the limbs are to use longer SMA wire, they will contract more. For example, if the SMA wire used is 150 mm total length it will contract up to 6 mm. However, a special method might be needed to store additional wire because the Stewart Platform height is fixed to 110 mm. In order to have more contraction of the limbs, an alternative design of the limb must be included with additional excess wire storage.

A cooling experiment was not conducted because the experiment was conducted in an air conditioned environment at 25 degree Celsius. During the experiment, the SMA wires were able to recover within 10 sec. Nevertheless, cooling mechanism was also considered in the Stewart Platform design. To guarantee a maximum natural cooling effect, the SMA wire was exposed to the air conditioned environment.

CONCLUSION

The basic design and working prototype of the platform was completed with slight improvement and adjustments in relation with the construction materials available.

As a result, it was proven that the SMA wire has the potential to become an alternative actuator to other conventional actuators in the market. This is due to its ability to control contraction and expansion linearly with the use of a Pulse Width Modulation (PWM) technique. Its performances are excellent in the activating period (time in seconds) and the weight or force it can lift.

A lot of research and commercial work has been conducted on SMAs but only a few truly investigate the application of SMAs in an aggressive and robust control environment (Teh, 2003).

The study has to continue in order to increase its potential to be commercialized as an alternative actuator for many other applications.

RECOMMENDATION

The next phase is to design and calculate the most suitable spring to replace the sponge which had been used in the prototype. Further improvements can be incorporated using microprocessors. The Design of the Stewart Platform requires deep understanding of the geometry of the manipulator, positional analysis, calculation for inverse kinematic and Jacobian inverse matrix. Further research should also include the dynamics of the parallel manipulator to obtain the velocity and acceleration analysis and the dynamics of the moving platform.

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