Development of SMA Actuated Legged Robot

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Aamir Shaikh[1], Jawaid Daudpoto[2], D.K. Soother [3], M.A. Soomro[4]

[1,2, 3,4] *Institute of Information and Communication and Technologies, Mehran UET Jamshoro, Sindh Pakistan*

Abstract: This paper reports the development of a miniature shape memory alloy actuated legged robot. The solid model of the robot is developed using commercial software known as SolidWorks. The robot prototype was developed after simulating the model in the same software. The 6.3 cm long and 4.2 cm wide, four-legged robot is tested with SMA actuator wires of different diameter (0.10, 0.15, .31, 0.38 mm) manufactured by Dynalloy Inc, to analyze effects on cycle time and displacement of the robot. The prototype was tested with different voltages and actuation times. The maximum speed recorded was 1.1 mm/sec for 0.15 mm diameter SMA wire at 2.6 V.

Keywords: *SMA, Miniature Legged robot, Flexinol*

1. Introduction

Research in small-scale robotic systems is underpinned by the common goal of developing autonomous robotic machines for applications that require miniature sized robots [1]. Such robots are particularly used in medical, manufacturing, and search operations [2-3]. In search and rescue operations, a robot may encounter rough and bumpy surfaces. Legged robots are preferred over wheeled robots in such irregular and uneven terrains. Mobility and obstacle avoidance are some of the issues that have been focused by modern research on miniature robots [4]. Legged robots have various types of locomotion gaits from crawling [5] to jumping types [6]. The locomotion gait must be selected as per requirement. In designing a miniature legged robot, the size and mass of the robot need to be considerably reduced. The conventional actuators like DC and servo motors result in heavy robots. Miniature robots must use small-sized and light-weight actuators. Ionic polymer metal composites (IPMC) SMA facilitates these both requirements [7]. This paper presents the design and control of four-legged SMA robot. Foot length of the robot has been increased with the concept of lever action. Shape Memory Alloys (SMA) have the tendency to return to a memorized form/shape after being exposed to temperature stimulus. This property is known as shape memory effect (SME). SMAs are noiseless, eco-friendly, bio-compatible and have a high force-to-weight ratio. SMA wire actuator can contract up to 8 % of its length for a mere few cycles. For cyclic applications, the typical contraction is 3-5 % of length [8]. Spring and wire actuators are commonly used in robotics. This research uses SMA wire as an actuator due to its higher force output. The prototype reported in this paper uses 0.10, 0.15, 0.31 and 0.38 mm diameter Nickel-Titanium (Ni-Ti) wire actuators available under the commercial name of Flexinol.

SMA wire has been used as an actuator for legged robots in past. A climbing robot was made by Menon and Sitti [9]. The robot was based on Gecko and has a climbing speed of 0.3 cm/sec. A two-legged micro robot made using polyethylene plate [10], a hexapod with pulleys and pantograph mechanism for long step [11], a hexapod known as RoACH with unequal leg lengths [12], jumping robots [6] and Stiquito [5] have been reported in literature. Table 1 presents some of the specifications of the aforementioned robots.

2. Material and Methods

The body of the prototype is formed by frame and legs. Each leg is made up of upper and lower parts. The upper part is made from acrylic and lower part is made of steel pins, frame is made of plastic. Miniature crimps, pins, bolts, and nuts are used as connectors. The prototype is actuated by Ni-Ti actuator wires available under the commercial name of Flexinol. Flexinol wires, manufactured by Dynalloy Inc are shape memory alloys composed of nickel and titanium with a 50% / 50% ratio.

Table.1. A comparison of SMA legged robots

Robot name	**Actuator Type**	**Actuator diameter (mm)**	**Mass (g)**	**No. of legs**	**Speed (mm/s)**
Climbing robot [09]	Ni-Ti	0.1	10	4	3
Biped [10]	BMF250	0.25	2.8	2	0.5
Hexapod [11]	BMF150	0.15	100	6	5
Roach [12]	Ni-Ti	0.0375	2.4	6	30
Jumping Mobile robot [6]	MMF 150	0.15	70	4	35 mm /jump
Big Stiquito [5]	Ni-Ti	1	150	6	3.3

Main characteristics of SMA wires used are given in Table 2 [13]. The spring constant is calculated using a simple experimental setup shown in Figure 1.

The value of spring constant was calculated by measuring the extension in the spring after application of known load. (see Figure 1).

Corresponding author Email address*: aamirshaikh35@hotmail.com*

According to Hooke's law

$$F = -k\,.x \tag{1}$$

Table.2. Flexinol characteristics

Diameter (mm)	**Pull force (g)**	**Approximate current for 1 second contraction (mA)**	**Resistance (Ω/m)**	**Cooling time (s)**
0.10	143	200	126	0.9
0.15	321	410	55	1.7
0.31	1280	1500	12.2	6.8
0.38	2004	2250	8.3	8.8

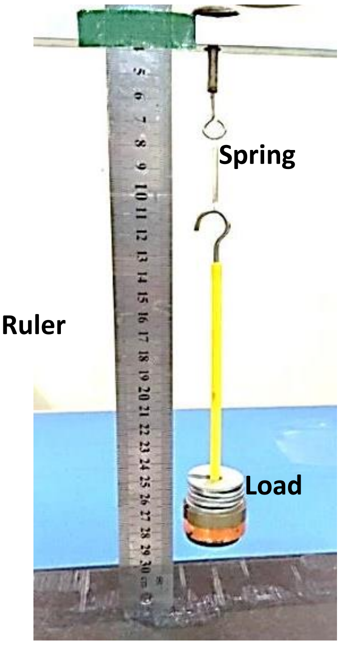

Figure.1. Measurement of extension in spring.

Where,

F = spring force (N)

k = spring constant (N/mm), and

x = spring extension (mm)

Negative sign indicates that spring force is opposite to the direction of spring extension.

Force in the spring is equal to external load. Hence,

$$F = Vertical\ load = -m\,g \tag{2}$$

Substituting value of F from Eq. (2) to Eq. (1)

$$k = \frac{mg}{x} \tag{3}$$

Equation (3) is used to calculate spring constant given in column 3 of Table 3.

Table.3. Spring constant calculations

Mass (g)	**Mean extension (mm)**	**Spring constant (N/m)**	**Mean spring constant (N/m)**
50	3.9	125	126
100	7.8	126	
150	11.6	127	

The robot prototype is controlled with an Arduino UNO prototyping board powered by a 9V battery. An integrated chip ULN 2003, which is an array of seven Darlington pairs was used to supply power from a DC power source.

3. Prototype Development

A commercially available solid modeling software known as Solid Works is used to design, assemble and simulate model. Although more legs would provide better stability, the robot was developed with four legs to keep the design simple. The dimensions of the robot are given in Figure 2(a). An actuation scheme (see Table 4) was developed. The actuation states mentioned in Table 4 are depicted in Figure 2(a to d). In state 1, actuators A and D, connected to Leg A & D, rotate simultaneously in the forward direction, legs B and C will be in static (OFF) position maintaining the stability of the robot. The model's frame is moved in the forward direction by the linear motor (state 2). Consecutively Leg B and C will rotate in the forward direction and Leg A and D will remain in static position (state 3). The model will move again in the forward direction (state 4).

The scheme is looped for continuous movement. This actuation scheme is developed with similar constraints that will affect the actual prototype by SMA such as cooling time. State 3 (Figure 2b and 2d) represent the actuation of SMA wires. State 2 and 4 (Figure 2c) represent the movement of the body in the forward direction that will occur during the cooling period of SMA wires. Figure 3(a) depicts the developed prototype. Dimensions of the prototype and the model are same. Each leg is installed with a SMA actuator wire.

Model's actuation scheme (Table 4) is similar to the scheme of the prototype. In testing the prototype, it was observed that the legs with SMA were being lifted slightly, in upward direction, jeopardizing the stability of the robot. The legs of the robot were re-designed in a manner, that half of the distance will be covered in bringing the leg perpendicular to the frame of the body. This does not affect the speed of the robot however it stables the robot.

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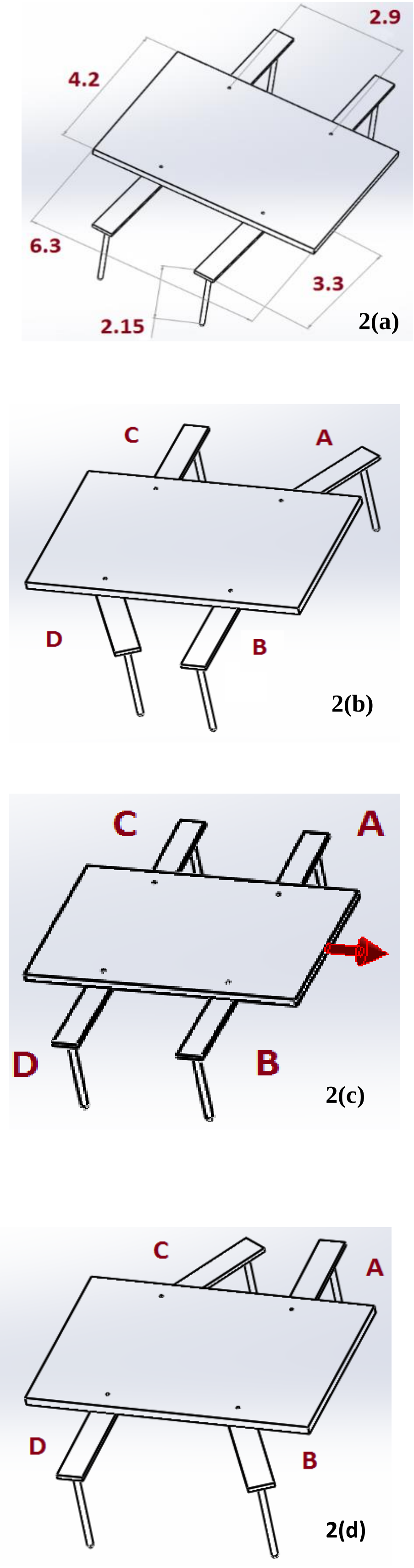

Figure.2. Design and States of the Model

Table.4. Actuation Scheme of Model

Actuator	State 1	State 2	State 3	State 4
A	ON	OFF	OFF	OFF
B	OFF	OFF	ON	OFF
C	OFF	OFF	ON	OFF
D	ON	OFF	OFF	OFF

The prototype legs are connected by (Ni-Ti) SMA wires. This mechanism is bias-type, which includes a spring, that will pull the leg to its original position in the OFF state. The design of lower part of the leg resists backward motion, that is forced by spring, compelling the body to move in the forward direction (Figure 3b). In this prototype SMA wire is attached behind the revolute joint, that results in greater foot-length. Similar robots have SMA wire attached away from the revolute joint, towards the lower part of the leg [5,12]. The length of each SMA wire is 10 cm.

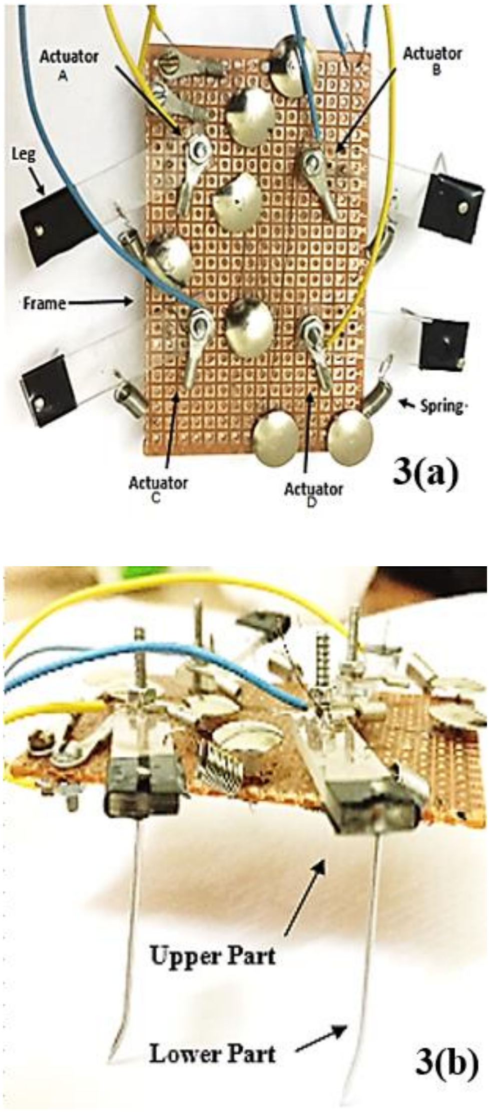

Figure.3. Top and Side View of Prototype

The contraction is 4 % of the total length i.e. 4 mm. SMA wire's contraction of 4mm will result in higher foot-length due to the lever ratio. The lever ratio of the leg is 4.5. Arduino prototyping board, ULN2003 integrated circuit, and a DC power supply were used to power SMA actuators attached to the robot (see Figure 4). Pins 8, 9, 11 and 12 were used to provide input signals to actuators A, B, C and D respectively. A program was written in Arduino Integrated Development Environment (IDE) to provide input signal to ULN2003 integrated chip as per actuation scheme given in Table 4. Two wires connected with Leg A and D were signaled through Arduino to pass the current for one second. The power was then turned "OFF" to allow the wire to cool down, moving the robot forwards. The other pair of Legs (N and C) was then powered to move the robot in the forward direction. The cooling time differed from the datasheet of flexinol, mostly because of the design of the robot and effect of surroundings (temperature and pressure) on system. The recorded time was programmed differently for 1 and 2 second actuation time.

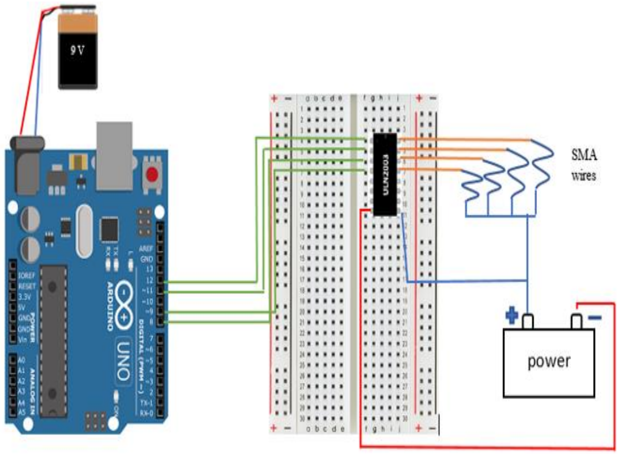

Figure.4. Schematic Diagram of control system

4. Results and Discussion

The robot had a smooth linear motion when tested on plain paper. The maximum speed, 1.1 mm/sec was recorded for 0.15 mm SMA wire at 2.6 v for 1 second actuation time. Speed of the robot is limited by cooling time consumed by SMA, energy lost by friction of SMA wire and legs sliding in forward direction. The performance of the robot can be improved by addressing these issues. The robot was separately tested with 4 SMA diameters wires on 5 different voltages. Range of actuation voltage is set by following calculation:

$$V = I.R$$

Where,
V = Voltage (V),
I = Current (A) for 1-second contraction of SMA wire,
R = Resistance (Ω/m) of SMA wire.

Voltage Range is set by least and highest value (1.8 and 2.6 V) of column 4 from Table 5. Figures 5-6 show cycle time as a function of voltage. Cycle time is the total time, measured from actuation of legs at their neutral position to the legs returning to their neutral position.

Table.5. Actuation Voltage

Diameter (mm)	**Approximate current for 1-second contraction (A)**	**Resistance (Ω/m)**	**Voltage (V)**
0.10	0.200	12.6	2.52
0.15	0.410	5.5	2.25
0.31	1.500	1.22	1.83
0.38	2.250	0.83	1.86

Figure 5 presents results, when current was supplied for 1 second to one pair (A and D) of legs, followed by cooling at steady air, similarly for the other pair (B and C). Figure 6 presents result of 2 second actuation. Analyzing both figures.

1. Increasing voltage results in greater cycle time.
2. Cycle time is proportional to the diameter of SMA wire.
3. Cycle time of higher diameter SMA wires increases rapidly with increase of voltage compared to lower diameter wires.
4. Increment in actuation time results in higher cycle time.

Voltage is directly proportional to temperature concerning SMAs [9], Voltage increment raises temperature of SMA wire, augmenting the cycle time. Cooling time increases with increase in diameter of wire [13], for instance, cycle time of 0.38 mm is greater in comparison to others. Experimental results of Figure 5-6 suggest the use of low diameter SMA wire (0.10 or 0.15mm) for less cycle time

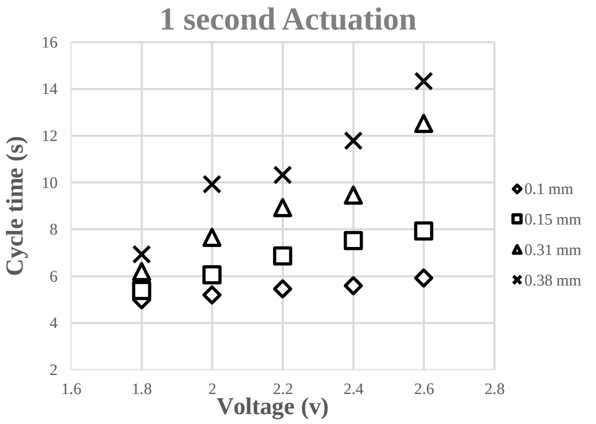

Figure.5. Cycle time of robot for 1 second actuation

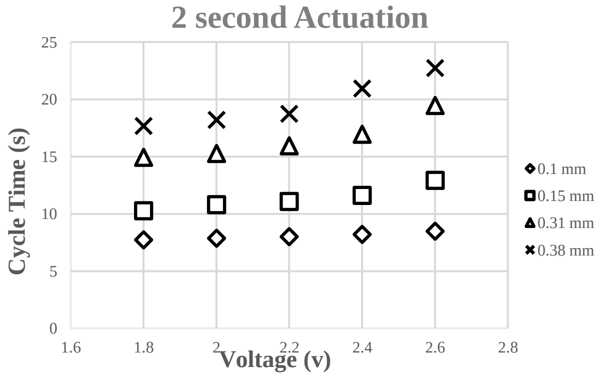

Figure.6. Cycle time of robot for 2 second actuation

The change in displacement due to SMA contraction, at different voltages and different actuation time was recorded. Figures 7-8 show linear displacement as a function of voltage. Analyzing both figures.

1. Voltage is directly related to the displacement of the robot.
2. In comparison, higher SMA Diameter wires have more deflection on the same voltage.
3. Increment in actuation time results in higher displacement.

SMA force and voltage are proportional to one another [9], increase in voltage increases force applied by SMA resulting in greater displacement. Resistance decreases with the increase in SMA diameter wire (Table 5), resulting in more deflection for higher SMA diameter wires. SMA actuation time is directly related with temperature of wire and temperature is proportional to displacement.

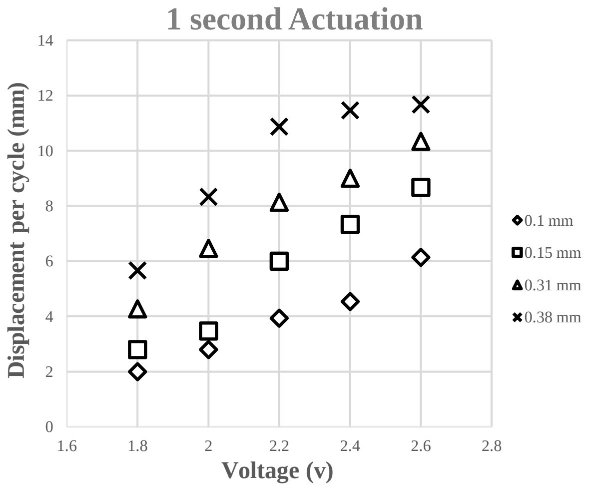

Figure.7. Displacement of the robot for 1 second actuation

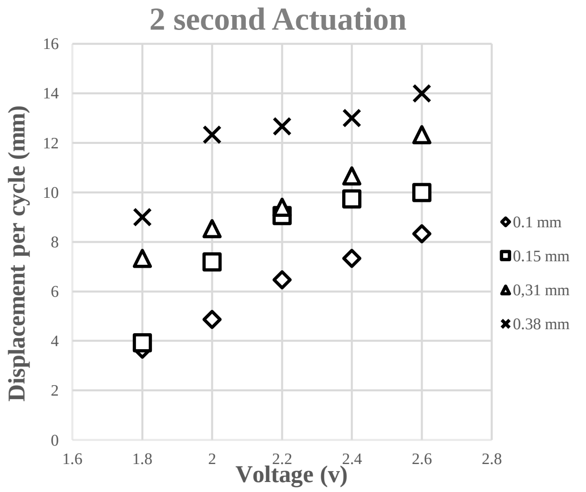

Figure.8. Displacement of the robot for 2 second actuation

5. Conclusion

This paper presents CAD design, simulation, electronic and mechanical design of a novel four-legged multi-pod that uses Shape memory Alloy as actuator. The size of the robot is 6.3 cm in length and 4.2 cm in width. The robot is tested with 4 different (0.10, 0.15, 0.31 and 0.38 mm) SMA actuator wires, having a length of 10cm. The maximum speed recorded was 1.1 mm/sec of 0.15 mm SMA wire at 2.6v for 1 second actuation time. As far as the knowledge of the author is concerned, a novelty in design is proposed here. The speed of the robot is increased without any major alterations by using the concept of lever ratio i.e. 4.5. The performance of the robot can be further increased by lifting of the legs instead of sliding or by introducing a cooling medium.

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About Authors

Aamir Shaikh received his B.E Mechanical degree from Mehran UET Jamshoro. He is currently working in SSGC as an Operation engineer. His interest lies in Shape Memory Alloys and miniature robots.

Jawaid Daudpoto received his Ph.D. in Mechanical Engineering from University of Leeds, U.K. He is IEEE Senior Member, Advisor to the IEEE RAS MUET Student Branch Chapter and In-charge of Mechatronics Lab at Department of Mechanical Engineering, Mehran University of Engineering and Technology, Jamshoro.

Dileep Kumar Soother has received his ME in Mechatronics Engineering and BE in Electronics Engineering. He is currently working as a Teaching assistant in Department of Mechatronic Engineering, Mehran University of Engineering and Technology, Jamshoro.

Mohammad Ali Soomro has a Masters in Mechatronics Engineering from Mehran UET Jamshoro. His interests lies in Shape memory Alloy and Soft robotics.