Smart Structures and Systems, *Vol. 14, No. 4 (2014) 541-558*
DOI: http://dx.doi.org/10.12989/sss.2014.14.4.541

Design and investigation of a shape memory alloy actuated gripper

S. Krishna Chaitanya[1a] and K. Dhanalakshmi[*2]

[1]*Vignan's University, Vadlamudi 522213, India*
[2]*National Institute of Technology, Tiruchirappalli 620015, India*

(Received September 24, 2012, Revised July 24, 2013, Accepted October 3, 2013)

Abstract. This paper proposes a new design of shape memory alloy (SMA) wire actuated gripper for open mode operation. SMA can generate smooth muscle movements during actuation which make them potentially good contenders in designing grippers. The principle of the shape memory alloy gripper is to convert the linear displacement of the SMA wire actuator into the angular displacement of the gripping jaw. Steady state analysis is performed to design the wire diameter of the bias spring for a known SMA wire. The gripper is designed to open about an angle of 22.5° when actuated using pulsating electric current from a constant current source. The safe operating power range of the gripper is determined and verified theoretically. Experimental evaluation for the uncontrolled gripper showed a rotation of 19.97°. Forced cooling techniques were employed to speed up the cooling process. The gripper is simple and robust in design (single movable jaw), easy to fabricate, low cost, and exhibits wide handling capabilities like longer object handling time and handling wide sizes of objects with minimum utilization of power since power is required only to grasp and release operations.

Keywords: actuator; shape memory alloy (SMA); gripper; forced air cooling; response time

1. Introduction

Functionality of any gripping device is to perform pick and place tasks which are useful in vast applications such as in industrial automation, assembling parts, semiconductor industries, non-invasive medical surgeries, processing of biological objects and the like (Price 2007). Need for compact grippers paved the way to search for light weight and high performance actuators, which thereby led to the discovery of utilizing advanced, smart actuators in gripping devices. The aim of miniaturization is to develop actuators that yield high mechanical performance in a limited space. Use of smart materials like piezoelectric actuators and shape memory alloy actuators in designing engineering systems scaled down the overall size of the actuating elements and the system. Both piezoelectric and SMA actuators provide high force, but the strain rate for piezoelectric actuators is much lower than that for shape memory alloys, resulting in a lower stroke compared to SMA (Kornbluh *et al.* 1998). Apart from the above mentioned advantages shape memory alloys possess high strength, high power to weight ratio, good corrosion resistance,

∗Corresponding author, Associate Professor, E-mail: dhanlak@nitt.edu
[a] Assistant Professor, E-mail: chaitanyabright@gmail.com

http://www.techno-press.org/?journal=sss&subpage=8 ISSN: 1738-1584 (Print), 1738-1991 (Online)

offers large stable displacement, is non-magnetic, resistant to space radiations (caused by electrons, protons and heavy ions) and biocompatible and reliable for large cycles of operation without wear and tear.

There is a belief that shape memory alloys are slow (Kode and Cavusoglu 2007), but their speed of actuation can be increased by using short high current pulses, and by other forced cooling techniques such as convective or conductive cooling (Inderjit 2002, Koji 2004, Madden *et al.* 2004, Gorbet *et al.* 2009, Anupam *et al.* 2010).

Shape memory effect in shape memory alloy is caused due to solid state phase transformation between martensite (Less-ordered phase) and austenite (ordered phase). At low temperature the SMA attains a twinned martensite state; by applying force a permanent change is observed which is addressed as plastic deformation due to de-twinning. When the temperature is raised the SMA recovers its high temperature shape thus recovering entire plastic deformation i.e., reaching the austenite phase. The mechanical work derived from the shape recovery is very much exploited in the actuator field, especially in the miniature actuator where light weight technology is required. Shape memory alloy can attain a workable strain of 4-10% of its original length depending on the mode of operation (shape memory effect, superelasticity). In comparison with CuZnAl and CuAlNi, the nearly equi-atomic composition of nickel-titanium (named Nitinol) is the most successful SMA and best candidate with respect to its thermo-mechanical related performances and excellent biocompatibility (Huang 2002).

A survey of literature on various SMA actuated devices is done. Numerous actuators utilizing different forms (wire, spring and plate) of SMA elements are reviewed by Sreekumar *et al.* (2007), Adelaide *et al.* (2010) and Sun *et al.* (2012). Examination of various SMA actuated grippers indicates that very few reports are available on the open mode gripper design. A microgripper proposed by Kyung *et al.* (2008) has the gripping jaws designed by two flexible hinges to open. Though the gripper was fabricated at a macro scale, this design gave a small displacement of 120 µm. Filippo *et al.* (2004) investigated the drawbacks posed by different actuating elements in gripper design and presented the design of a gripper in which six SMA actuator wires were employed to be mechanically parallel and electrically series in connection, to close the gripper. This design employed long lengths of SMA wire for actuation and relatively difficult fabrication because of multiple SMA wires running on multiple pulleys. Zhong and Yeong (2006) used a small piece of SMA wire in mechanically parallel form to pull a sliding unit thereby closing the microgripper jaws. This design offered low displacement range of 100-500 µm. Zhong and Chan (2007) have presented a gripper that could be closed by the rotation of the movable jaw using a mechanically parallel SMA wire. Although the design is simple, the force exhibited by the gripper to hold the object is too low, ≈2.2N. Asua *et al.* (2009) devised an SMA wire-based gripping device consisting of two flexible stainless steel sheets as the gripper fingers (which also act as the biasing elements) which closes when a nitinol wire attached between them is contracted. This design again provides small displacement ranges. Koji Ikuta (1990) presented a miniature gripper in which two antagonistic SMA coil springs actuate two cantilever fingers. Low force and small displacements are the limitations of this gripping device. Mertmann and Hornbogen (1997) developed two different gripping systems using flexure hinges; one design was using two SMA helical springs in antagonistic arrangement and the other design used pseudo-elastic NiTiCu ribbon as actuator element. It is observed that the displacement achieved is small; moreover the fabrication cost is expensive since it uses EDM (Electric Discharge Machine) for structural fabrication. Shaoze *et al.* (2007) presented a gripper whose two fingers are driven by a pair of differential SMA actuator through a six-bar linkage to realize their opening and closing operation.

Difficulty in fabricating the six-bar linkage mechanism leads to complex fabrication of the gripper. Also antagonistic operation results in cyclic degradation resulting to plastic deformation observed as slack in the SMA wire thereby making it less reliable (Sofla *et al.* 2008). Kianzad *et al.* (2011a, b) devised a forceps using an antagonistic SMA structure which consists of two sets of SMA wires that are integrated to opposite sides of a rotating part; one set for opening the jaw, and another set for closing the jaw. This design presented dimensionally long gripper for the corresponding opening.

Study of the past led to develop a new design of SMA gripping mechanism. This work presents a SMA actuated gripper that attempts to adopt a simplest design thereby unleashing difficulties such as complex design, fabrication difficulties, high actuator cost and also small opening and low gripping force. The fundamental objectives of this work are to develop a gripper which features simple and flexible design, easy to fabricate, optimal utilization of SMA wire to achieve larger displacement and low power consumption. This work aims at the design of an opening mode gripper and investigates its characteristics. Forced air cooling techniques are employed to improve the performance of the gripper.

This paper projects the work in four sections. Starting with introduction in section 1, section 2 explains the proposed design, construction and working of the gripper section 3 presents the experimental evaluation and results. Finally section 4 concludes the paper.

2. Configuration and design of SMA actuated gripper

Any simple gripping device invariably possesses minimum two fingers in order to grasp the object. Looking into time-line of various SMA actuated gripping devices developed earlier it is observed that a single SMA actuator or antagonistic SMAs (Sofla *et al.* 2008) can perform two different modes of gripping operation: the closing mode and opening mode.

Closing mode

When driving/actuating element (SMA) is used to close the jaws of the gripping device, the bias element (be any form of spring) acts in counter to the actuating element thereby separating the gripping jaws. When the SMA is energised i.e., heated, the jaws of the gripper are closed and the object is held between the jaws. If the object handling time increases correspondingly the SMA overheats; this is an undesirable feature of this mode of operation. Short duration pulses can overcome the overheating, but in turn reduces the object handling time. Moreover overheating can be avoided by employing forced cooling techniques.

Opening mode

When the driving element opens the jaw the bias element accumulates potential energy which will act in counter to catch hold of the object when the SMA is de-energised. This mode provides much simpler and an effective way to hold objects for long durations. The SMA wire is used only to open the finger while the energy stored in the passive spring is utilized to hold the object; hence the problem of SMA getting overheated is avoided and consumes less power.

2.1 Gripper assembly and function

2.1.1 Construction

The upper jaw of the devised gripper is movable and, the lower gripping jaw is fixed to an acrylic base using standard epoxy adhesive “Araldite”. Providing one movable jaw instead of two simplifies the gripper design and enhances the grasping accuracy (Filippo *et al.* 2004). A stainless steel torsion spring is integrated between the jaws supported by a shaft in order to exert a restoring force to close the jaw. The preferable form of the SMA is the wire actuator in tension mode since SMA straight wire has maximum force density and good dynamic response compared to other forms of the element. Here a one-way SMA wire (Flexinol® manufactured by Dynalloy, Inc. with NiTi in the near equi-atomic ratio) is used as the actuating element. In order to maximize the pull force, SMA actuator wire is fixed at a right angle (using B2-Hook) to the rear end of the upper jaw and the other end is fixed to the base of the gripper. Small grooves are created on the gripping surfaces of both gripper jaws for the purpose of generating sufficient surface roughness and friction on the gripping surfaces, so that slippage of the object being gripped can be avoided. Fig. 1 shows the pictorial representation of the gripper.

2.1.2 Principle of operation and working

The principle of the gripper is to convert the linear displacement of the SMA wire actuator into the angular displacement of the gripping jaw. When SMA wire is actuated by joule heating the wire contracts and pulls the upper gripping jaw by exerting a compression force on the spring. The upper jaw rotates to open the gripper when the contraction force generated by the SMA wire (by Joule heating) exceeds the restoring force exhibited by the spring, thereby accumulating potential energy. During deactivation the SMA wire stretches with the help of the elastic recovery force exhibited by the bias spring thus aids the gripping jaws to grasp and hold the object. The design of the gripper based on its mechanism is presented in the following section.

2.2 Gripper design

The SMA actuated gripper requires suitable choice of components and their mechanical design. As reported earlier, the proposed gripper consists of single rotatable jaw operated in open mode. It is easier to design the spring for a selected configuration of the SMA wire dimension and for selected angle of rotation. Table 1 shows the specifications of a commercially available SMA used for the design.

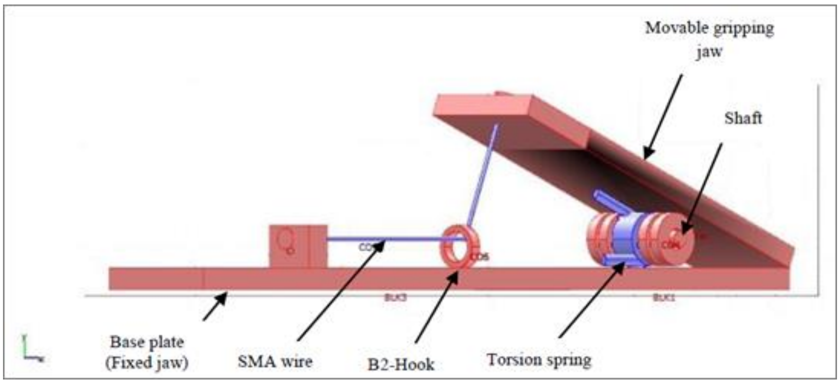


Fig. 1 CAD model of the SMA actuated gripper with torsion spring

Table 1 Dimensions and properties of the NiTiNOL wire actuator

Property	Unit	Variable	Value
Length	mm	l_s	140
Diameter	mm	d_S	0.25
Transition Temperature	^oC	T_t	90
Martensite Start Temperature	^oC	M_s	72
Martensite Finish Temperature	^oC	M_f	62
Austenite Start Temperature	^oC	A_s	88
Austenite Finish Temperature	^oC	A_f	98
Hysteresis	^oC	H_s	20
Young's modulus	GPa		
Martensite		E_M	28
Austenite		E_A	75
Density	kg/m^3	ρ_s	6450
Resistance	ohm/m	R_s	18.5
Approximate Current at room temperature	A	I_s	1.05
Contraction Time *	s	t_{cont}	1
Off Time	s	t_{off}	5.4
Maximum Pull Force	g	F_{max}	891

* Contraction time is directly related to the current input

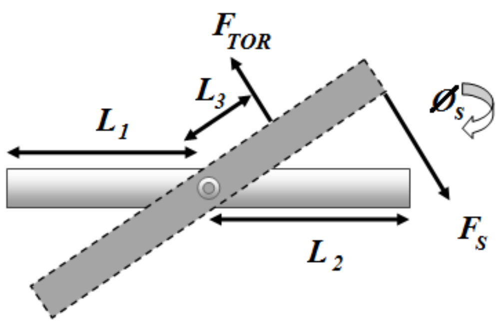


Fig. 2 Free body diagram of rotary upper gripping jaw under steady state

The performance of the gripper at steady state i.e., after the SMA wire is heated by the electrical current (at the end of maximum contraction time) is the basis for the design of the bias element and the length of the SMA wire actuator. When SMA wire is energised with a current of 1.05A for 1s it exhibits a maximum pull force of 8.7318N by contracting to 5% of its length. Having known the maximum pull force exhibited by SMA wire actuator the energy conservation on the gripper at steady state at time t=1s is established. The free body diagram of the moving jaw is shown in Fig. 2 indicating its initial (dotted representation) and steady state position (solid line representation) and the corresponding forces acting on it.

Here L_1 is thedistance from the centre of the shaft to the gripping end of the jaw (mm)

L_2 is the distance from the centre of the shaft to the rear end of the jaw where the SMA wire is fixed (mm)

L_3 is the leg length of the torsion spring (mm)

F_S is the force exerted by the SMA wire at steady state (N)

F_{TOR} is the force produced due to the accumulated potential in the torsion spring (N)

$\emptyset_S$ is the steady state angular rotation (rad).

When the SMA wire is actuated, the work done by the rotating jaw to reach its final steady state position is given by

$$W = F_S \times L_2 \phi_S \quad (1)$$

where W is the work done by the SMA wire on the gripping jaws (J).

The work performed by the SMA actuating element is accumulated in the form of potential energy in the torsion spring. The stored potential energy is

$$\Delta E = \frac{1}{2} K_S \phi_s^2 \quad (2)$$

where ΔE is the stored potential energy (J)

K_S is the spring rate of the torsion spring (Nm/rad)

According to the work-energy theorem, the work done is equal to change in energy. Therefore Eqs. (1) and (2) can be equated.

$$W = \Delta E \quad (3)$$

$$F_S \times L_2 \phi_S = \frac{1}{2} K_S \phi_S^2$$

$$K_S = \frac{2 F_S L_2}{\phi_S} \quad (4)$$

By replacing the spring constant of torsion spring with its general formula it is seen that

$$\frac{d^4 E_T}{10.8 DN} = \frac{2 F_S L_2}{\phi_S}$$

$$d = \sqrt[4]{\frac{21.6 F_S L_2 DN}{\phi_S E_T}} \quad (5)$$

where d is the wire diameter of the torsion spring (mm)

D is the mean diameter of the torsion spring (mm)

N is the number of turns

E_T is the Young's modulus of the torsion spring (GPa)

The above relation indicates that the wire diameter of the bias spring is inversely proportional to the fourth root of the angle of rotation. For the maximum force exerted by the SMA wire and, the geometry of the gripper and the torsion spring, the following parameters have been selected:

F_S = 8.7318 N, $\varnothing_S$= 22.5^0 (prefered angle), L_2 = 30 mm (geometry), D = 4.1 mm, N = 3, E_T = 200GPa (stainless steel)

Using the above values in Eq. (5), the wire diameter of the torsion spring is obtained to be d = 0.97 mm; this is the estimated diameter of the spring to obtain a rotation of 22.5°.

2.3 Gripping force

It is important to know the gripping force of the gripper for proper handling of objects. Operation of the gripper in open loop must be understood fully in terms of the maximum force exhibited by the gripping jaws for various power cycles inorder to prevent damage of objects handled, which helps in choosing the type of objects to be handled.

Present design consists of one fixed bottom jaw and the other upper movable jaw as seen from Fig. 1. Fig. 3 shows the free body diagram of the SMA gripper when handling an object.

Here F_L is the force exerted by the fixed gripping jaw (N)

F_U is the force exerted by the movable gripping jaw (N)

Performing momentum balance on the movable gripping jaw results in

$$F_S L_2 + F_U L_1 = F_{TOR} L_3 \tag{6}$$

$$F_U = (F_{TOR} L_3 - F_S L_2) / L_1 \tag{7}$$

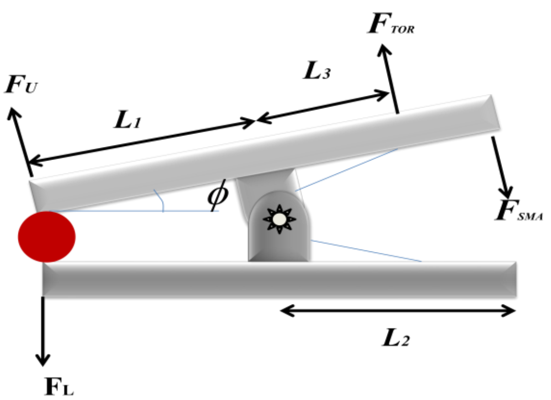


Fig. 3 Free body diagram of SMA gripper holding object

The force acting on the fixed lower gripping jaw is obtained by applying Newton's second law and is given by

` $$F_L = F_U \quad (8)$$

Therefore given F_S 'force exhibited by SMA wire' and F_{TOR} 'restoring force exhibited by torsional spring' (obtained from displacement of gripping jaw) it is possible to determine the maximum force exerted on the object.

2.4 SMA actuation

Though thermal actuation of SMA is possible, electrical actuation is attractive due to its invariable advantages like ease of use, fast actuation and good dynamic performance. To improve such operation the SMA must be heated (Joule effect) and cooled (forced convection) rapidly. A SMA actuator can be driven by a voltage-controlled or current-controlled operational mode. The stability behaviour of an open loop configuration of SMA with electrical actuation is analyzed.

For stable operation, the heat transfer into and from the SMA by Joule heating and convection, respectively, must be in equilibrium: $P_{el} = \dot{Q}_{conv}$ at a constant temperature. During actuation the electrical resistance R_{SMA} of SMA falls due to phase transition caused by increasing temperature.

- Under voltage-controlled mode of actuation, when SMA is heated with a constant voltage V it leads to an increasing current I = V /R_{SMA} and heating power P = V I. As a result, the temperature will increase furthermore. This has the same effect like a positive feedback and leads to an unstable operation. This phenomenon can be interpreted to be similar to thermal runaway in transistors.
- In current-controlled mode of actuation, when SMA is heated with a constant current I, the voltage V = R_{SMA} I decreases corresponding to the electrical resistance. This results in reduction in heating power P = VI and subsequent fall in temperature, which acts like a negative feedback and stabilizes the operation.

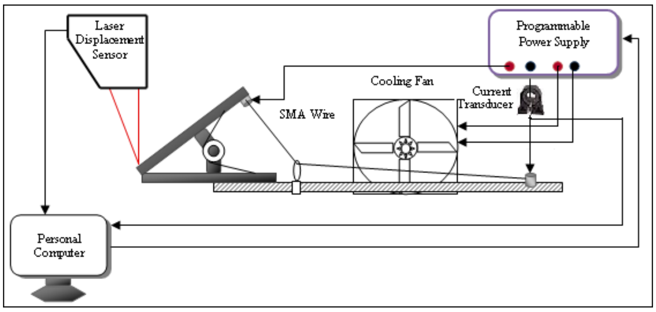
Similar behaviour can be seen during cooling. The above analysis shows that current-controlled mode is advantageous in stabilizing the operational behaviour. Hence the authors have preferred to adopt the current controlled mode of operation for the proposed SMA actuated gripper.

3. Experimental evaluation and results

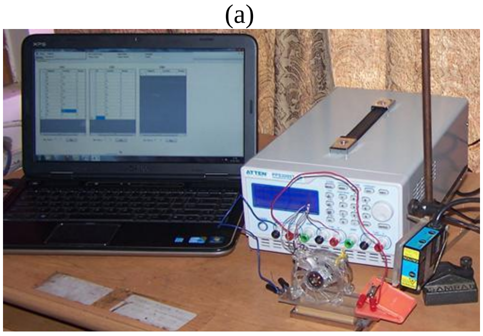
Primary testing was performed on the prototype of an SMA actuated gripper developed from a plastic clip with torsion spring. The power to SMA is supplied through Atten® Instruments programmable power supply (PPS3205T-3S) under a constant current mode of operation, a Hall-effect current transducer (LTS 6-NP) is used to measure the current, a load cell (FSH00107) is connected at the end of the SMA wire to measure the wire tension and Acuity laser displacement sensor (AR200) is employed to track the displacement of the movable finger. Two cooling fans are used for providing forced convective cooling of the SMA wire. The conceptual scheme and photograph of the experimental setup of the gripping system is shown in Fig. 4.

3.1 Sensor calibration

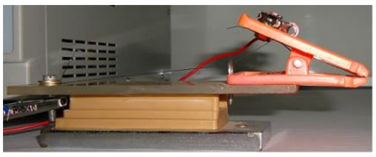
It is important to know the sensor's behaviour in order to rely on its response. So sensor calibration should be performed. Displacement is measured using a laser displacement sensor which has a linear relationship between the analog voltage and displacement. Initially the laser beam is focused on a flat surface and it is adjusted to zero, thereby reading 0V as output. The laser displacement sensor is calibrated with a known thickness of metal sheets ranging from 1 to 25 mm, and the corresponding analog output is measured using multimeter. In order to eliminate uncertainty errors, average readings are taken by performing the tests cyclically multiple times. Fig. 5 shows the linear relation between displacement and output voltage of the sensor, and the correlation coefficient R attained is 0.99984.



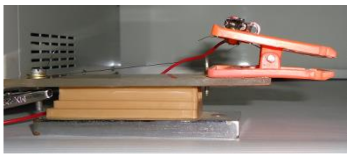
(a)



(b)



(i)



(ii)

(c)

Fig. 4 Set up to investigate the gripper characteristics (a) Schematic representation (b) Experimental setup (c) View of the gripper when (i) closed (ii) open

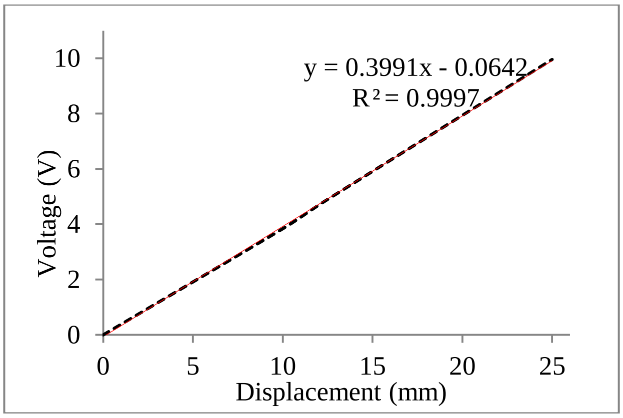


Fig. 5 Calibration curve of displacement sensor

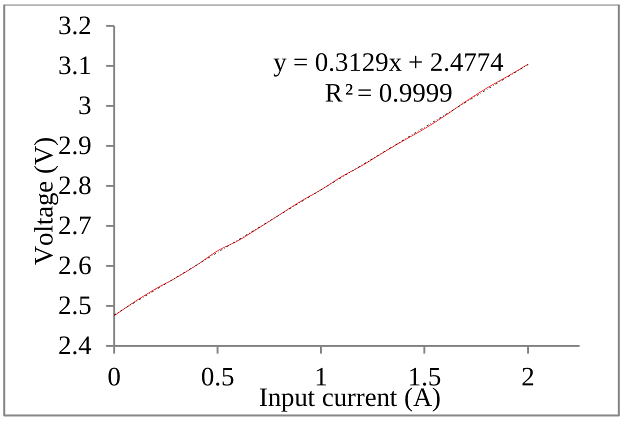


Fig. 6 Calibration curve of current sensor

Current measurement is conducted by a Hall-Effect current transducer which is also having a linear relationship between voltage and current. Series of current signals ranging from 0.1 to 2 A is passed from PPS and the corresponding output from the transducer is measured in terms of voltage using a multimeter. Uncertainty errors are eliminated by taking the average values upon repeating the test for multiple cycles. Fig. 6 shows the linear relation between current and output voltage measured from the transducer, the correlation coefficient R is 0.99994.

3.2 Investigation of the gripper characteristics

Experiments were performed to investigate the response of the gripper for the opening and closing operations at different power levels at a constant current mode of operation i.e., providing controlled current at different voltage levels. Fig. 7 represents the displacement response of the gripper when excited with controlled current pulses having programmed with amplitude 1.05A at different voltages ranging from 1 V to 10 V having duty cycle of 60% at the action period of 50s. The SMA wire responded for a minimum input voltage of 1.25 V but the response was improper due to insufficient current flow (0.501A) to properly heat the SMA wire. Proper response was observed for voltage ranging between 2 V and 2.5 V, to which corresponding current flow is 0.799A and 1.042A respectively. This range of current suits in particular, as they drive the SMA wire by properly heating to produce stable response. Similar response is observed for force as seen in Fig. 11; this figure shows the force response obtained for gripper excited with controlled current pulses at different voltages ranging from 1.25 V to 2.5 V having duty cycle of 50% at the action period of 40s. Beyond 2.5 V the actuator showed abnormal behaviour due to overheating resulting in deterioration of the actuator's cyclic performance. Theoretical verification showed that for 13.5 cm length of SMA wire (Ø 0.25 mm) require a safe operating voltage of 2.6 V. Above theoretical and practical analysis reveals that the SMA wire actuator could be operated between 2 V and 2.6 V.

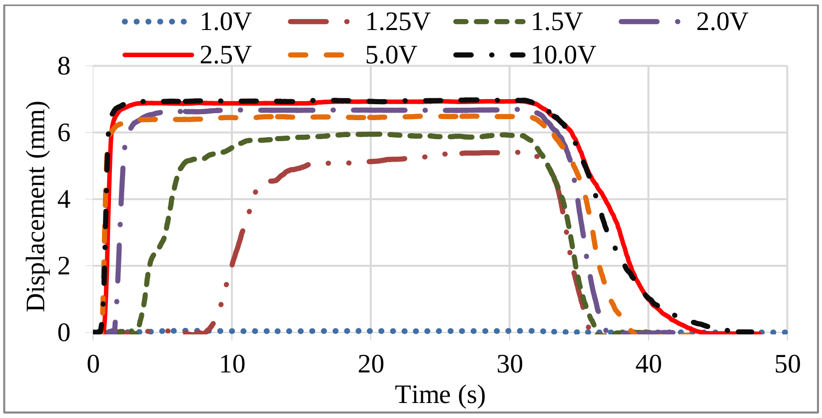


Fig. 7 Response of the gripper at different voltage levels

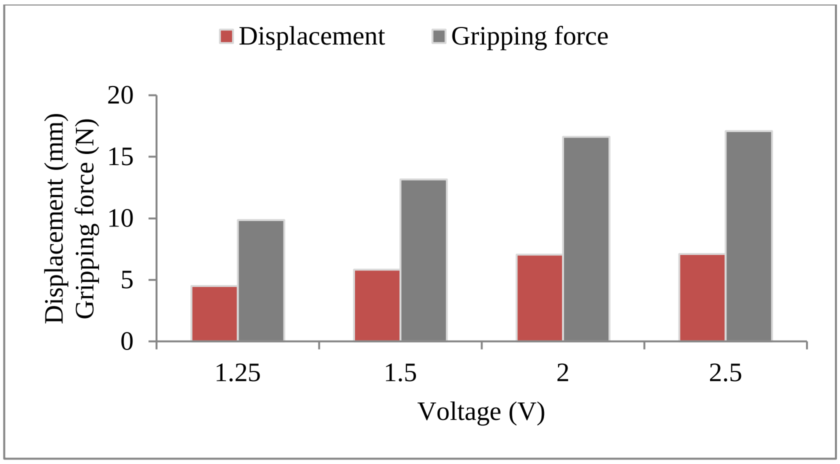


Fig. 8 Influence of driving current at various voltages

Fig. 8 shows the experimental results of displacement and force amplitudes of the electrically actuated SMA gripper under controlled current pulses at different voltages having duty cycle of 40% at the action period of 50s. The experimental results show that the electric voltage greatly influences the displacement amplitude of SMA actuator. The increase in electric voltage from 0-2V increases the current flow. Larger the current flow, larger the maximum force and displacement of the gripper. Further increase in electric voltage from 2 to 2.5 V drives the actuator into saturation state with only a slight incremental change in the maximum force exhibited by SMA wire; similar behaviour is observed in the maximum displacement attained by the gripper. Figs. 9 and 10 show the displacement of the gripper and the force response of SMA wire respectively. Fig. 11 shows the resultant force response of SMA gripper when exited with controlled current pulses at different voltage levels ranging from 1.25 V to 2.5 V having duty cycle of 50% at an action period of 20s.

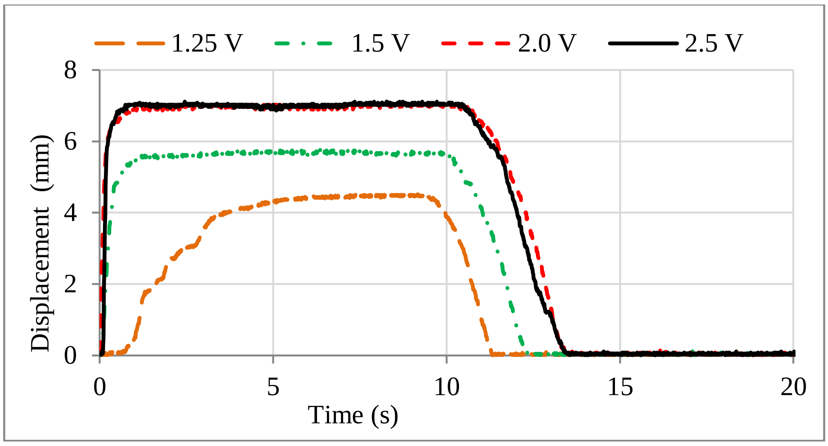


Fig. 9 Response of gripper at different voltage levels

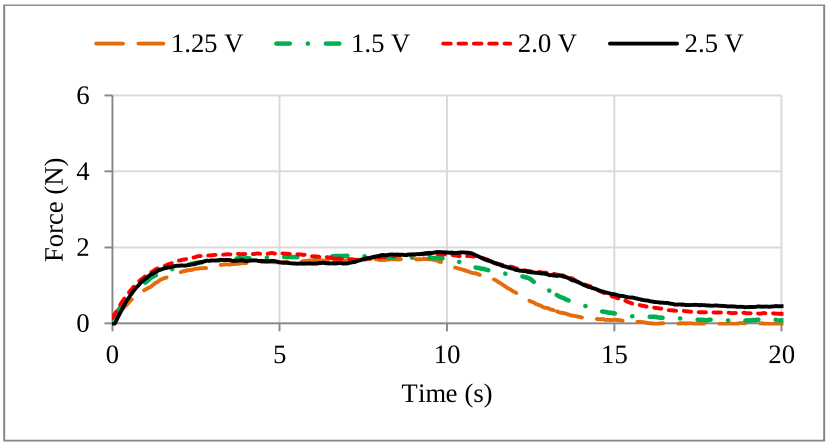


Fig. 10 Force response of SMA wire at different voltage levels

The following are understood from the experiment: The response of the gripper as shown in Fig. 12, the displacement increases linearly with increasing driving current and attains a steady displacement of 6.78 mm for the recommended voltage value at constant current mode. It takes some time for the SMA wire to be heated or cooled and to complete the phase change in the jaw opening or closing operation. The driving current applied is the main factor affecting the speed at which the SMA wire contracts and relaxes besides, the spring torque and the diameter of the SMA wire.

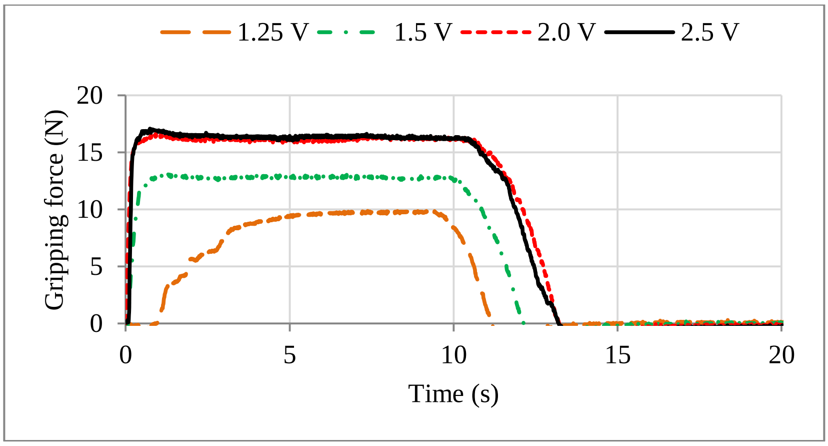


Fig. 11 Force response of SMA actuated gripper at different voltages

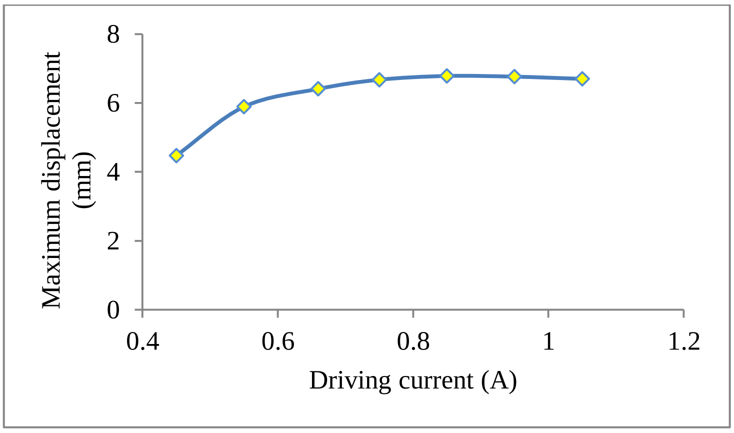


Fig. 12 Response of the gripper for increasing driving current

Fig. 13 shows opening time and closing time of the gripping jaws for increasing driving current. As shown in the figure, the opening time of the jaws decreased with increasing driving current. Hence, the wire was heated to start contraction in a shorter time. On the other hand, the closing time is much longer than the opening time, because it takes more time for the SMA wire to be cooled than to be heated as seen in Fig. 7 also. When the driving current is increased, the closing time of the jaws also increases. As the current increased, more heat was supplied to the wire. Therefore, it needed a longer time to dissipate heat generated by the increased current.

Fig. 14 shows the response of the gripper for a complete heating and cooling cycle, under a controlled current mode of operation by varying voltage ranging from 0 to 3 V, at increasing and decreasing steps of 0.1 V/s respectively. For a particular driving current, the minimum power to obtain a stable response and different heating and cooling paths are observed.

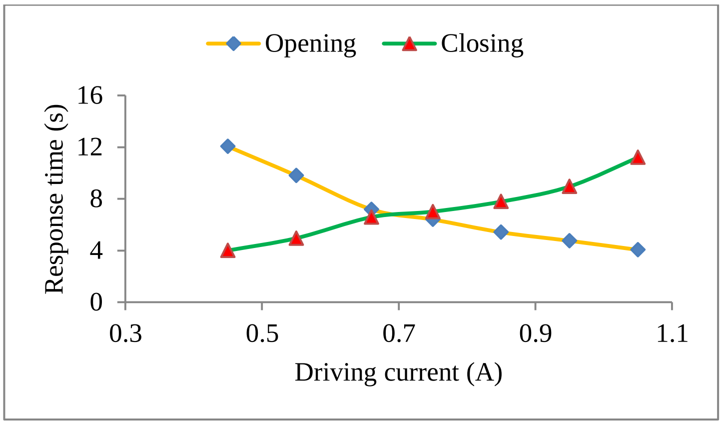


Fig. 13 Response time of the gripper for open and close operations

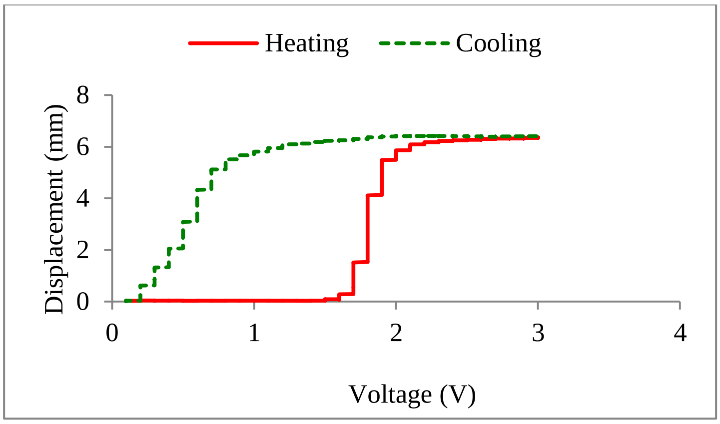


Fig. 14 Response of the gripper for one complete cycle

The performance of the SMA actuated gripper is obtained for step input current of amplitude 1.05A fed from a programmable power supply with 1s ON time under a current - controlled mode of operation. The laser displacement sensor senses the displacement *x* (mm) of the moving jaw. The rotation angle θ (degree) of the gripping jaw is obtained through the relation

$$\theta = 2 \times \sin^{-1}\left(\frac{x}{L_2}\right) \tag{9}$$

Fig. 15 shows the displacement and angular rotation of the gripper jaw corresponding to the step actuating current. At still air condition i.e., natural convective operation, the gripper exhibits a maximum displacement of 5.204 mm attaining a rotation of 19.97° when actuated for 1s and recovers to its initial position when the SMA cools. The cooling time of the SMA wire is 5.81s at a rate of change in displacement 1.25 mm/s at ambient temperature 28℃.

The larger cooling time is undesirable since it hinders the fast operation of the gripper. Hence better cooling is provided through forced air circulation by means of two fans, thereby the relaxing time reduces. The forced convective cooling brought down the cooling time to 3s from 5.81s, corresponding rate of change in displacement (speed of cooling) is improved from 1.25 to 1.67 mm/s (i.e., 33.6%) respectively. The continuous use of fans during both heating and cooling of the SMA wire reduced the cyclic rotational angle (displacement) between the gripping jaws to 13.67° (4.35 mm), thereby affecting the performance of the gripper. The above mentioned phenomenon is plotted from the experimental data obtained and shown in Fig. 16. To achieve desired performance it is required to overcome this limitation. Forced convective controlled cooling technique is adopted to address this shortcoming.

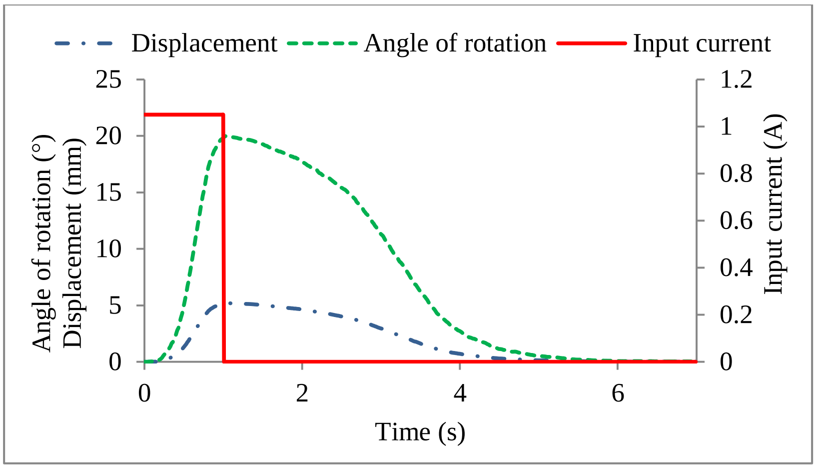
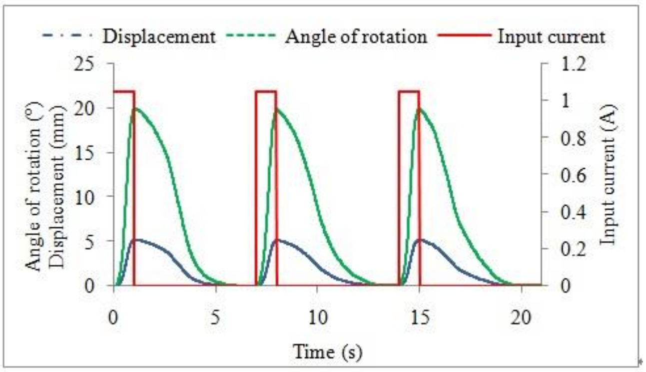
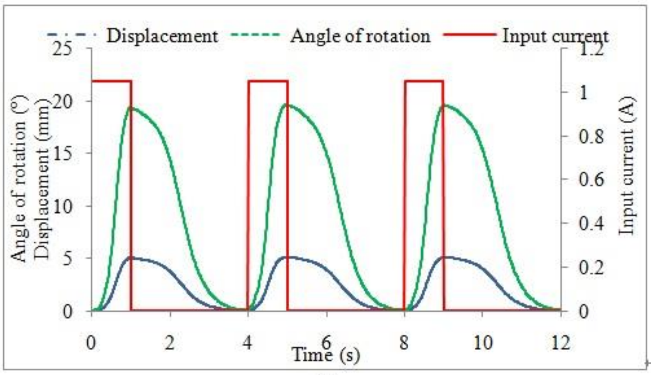


Fig. 15 Step response of the gripper



(a)



(b)

Fig. 16 Separation of the movable jaw when the SMA wire is actuated (a) in still air (b) under forced air

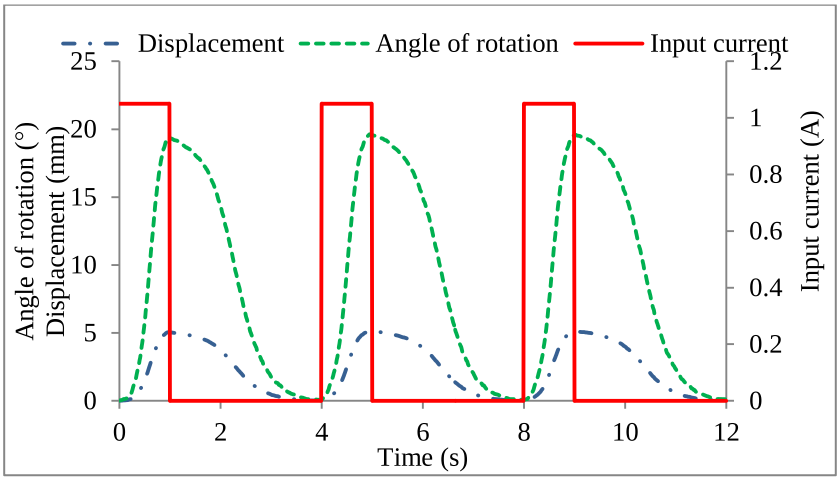


Fig. 17 Separation of the movable jaw of the gripper when the SMA wire is actuated under controlled forced air

The continuous forced air cooling technique i.e., uncontrolled cooling reduces the cooling time and hence aids in fast actuation of the device; in addition reduces the displacement which is due to improper heating of SMA wire thereby not completely transforming beyond the austenite finish temperature. This drawback can be overcome by programming the two cooling fans to be switched ON only during the cooling phase of SMA. The improved response on employing programmable forced convective cooling obtained experimentally is shown in Fig. 17. It is observed that the reduction in displacement during continuous forced convective cooling is recovered by applying controlled cooling. The rotational angle (maximum displacement) of gripping finger attained is 19.63° (5.11 mm). Reduction in cycle time due to introduction of forced cooling has enhanced fast gripping operation. It is observed that during forced cooling the time taken for 1 cycle of operation is reduced by 41.26%. Though such results may be well known it is interesting to observe that the convective cooling rate is improved considerably for controlled cooling in comparison to continuous forced cooling; the rate of change in displacement is seen to be 2.28 mm/s for the former whereas it is 1.67 mm/s with the later, and 1.25 mm/s under natural convection. This improvement can be related to Newton's law of cooling $Q = hA(t_s\text{-}t_f)$, which is caused because of creating large temperature differences created between the surface of SMA (t_s) and the surrounding medium (t_f) during controlled forced convective cooling.

4. Conclusions

A new design of the SMA wire actuated gripper which has an easy to fabricate shape and structure is proposed to offer wide handling capabilities. Design of the bias spring is made through steady state analysis for a particular dimension of the SMA wire actuator. A model of the gripper is developed and its basic functional characteristic under varied driving current, power levels and cooling conditions of the SMA are experimentally investigated. The response time and hysteretic behaviour of the device are obtained in the study, which provides a scope for further improved design. The gripper has attained an angular rotation (maximum displacement) of 19.97° (5.204 mm) for an input step current of 1.05A passed through the SMA wire actuator against the design specification for 22.5° rotation. Under continuous forced convective cooling technique the time taken to cool SMA wire actuator is considerably reduced from 5.81s to 3s; thereby achieving fast actuation but limiting the maximum displacement. Further controlled forced convective cooling technique is utilized to eliminate this limitation without much compromise in displacement. Controlled forced cooling technique is proved to be best when compared to uncontrolled cooling. Controlled forced cooling accelerated the cooling phenomenon at a rate of 36.5% and 84.5% in comparison with uncontrolled cooling and natural cooling respectively. The SMA wire is used only to open the finger while the stored energy in the passive spring is utilized to hold the object; hence the gripping action consumes less power. The gripper can handle objects for longer duration and also handle wide sizes of objects for a chosen application.

References

Adelaide, N., Stefano, B., Simone, P., Elena, V. and Stefano, V. (2010), "The high potential of shape memory alloys in developing miniature mechanical devices: A review on shape memory alloy mini-actuators", *Sensor. Actuat. - A: Phys.*, **158**(1), 149-160.

Anupam, P., Diann, B. and Jonathan, L. (2010), "Transformation strain based method for characterization of convective heat transfer from shape memory alloy wires", *Smart Mater. Struct*., **19**(3), doi:10.1088/0964-1726/19/3/035005.

Asua, E., Etxebarria, V., Garcia, A. and Feuchtwange, J. (2009), "Micropositioning control of smart shape-memory alloy-based actuators", *Assembly Autom*., **29**(3), 272 - 278.

Filippo, M., Rezia, M. and Cepolina, F. (2004), "Miniature gripping device", *Proceedings of the IEEE International Conference on Intelligent Manipulation and Grasping IMG*, Genova, Italy, 1-2 July.

Gorbet, R.B., Morris, K.A., and Chau, R.C.C. (2009), "Mechanism of bandwidth improvement in passively cooled SMA position actuators", *Smart Mater.Struct*., **18**(9), doi:10.1088/0964-1726/18/9/095013.

http://www.dynalloy.com/TechData_Metric.html.

Huang, W. (2002), "On the selection of shape memory alloys for actuators", *Mater. Design*., **23**, 11-19.

Inderjit, C. (2002), "Review of state of art of smart structures and integrated systems", *AIAA J*., **40**(11), 2145-2187.

Kianzad, S., Karkouti, S.O. and Taghirad, H.D. (2011a), "Force control of intelligent laparoscopic grasper," *J. Medical Imaging Health Inform*., **1**, 284-289.

Kianzad, S., Amini, A. and Karkouti, S.O. (2011b) "Force control of laparoscopy grasper using antagonistic shape memory alloy", *Proceedings of the IEEE Int. Conf. on Biomedical Engineering*, Sharjah, 21-24 Feb.

Kode, V.R.C. and Cavusoglu, M.C. (2007), "Design and characterization of a novel hybrid actuator using shape memory alloy and DC micromotor for minimally invasive surgery applications", *Mechatronics IEEE/ASME Trans*., **12**(4), 455-64.

Koji, I. (1990), "Micro/miniature shape memory alloy actuator", *Proceedings of the IEEE Int. Conf. on Robotics and Automation (ICRA)*, Cincinnati, OH, USA, 13-18 May.

Kornbluh, R., Perline, R., Eckerle, J. and Joseph, J. (1998), "Electrostrictive polymer artificial muscle actuator", *Proceedings of the IEEE Int. Conf. Robotics and Automation (ICRA)*, Leuven, Belgium, 3, 16-20 May.

Kyung, J.H., Ko, B.G., Ha, Y.H. and Chung, G.J. (2008), "Design of a microgripper for micromanipulation of microcomponents using SMA wires and flexible hinges", *Sens. Actuat. - A Phys*., **141**, 144-150.

Madden, P.G.A., John, D.W. M., Nathan, A.V., Patrick, A.A., Arash, T., Rachel, Z.P., Serge, R.L., Paul, A.W. and Ian, W.H.M. (2004), "Artificial muscle technology: physical principles and naval prospects", *Ocean. Eng*., **29**, 706-28.

Mertmann, M. and Hornbogen, E. (1997), "Grippers for the micro assembly containing shape memory actuators and sensors", *J. Phys. IV*., **7**(5), 621-626.

Price, A.D., Jnifene, A. and Naguib, H.E. (2007), "Design and control of a shape memory alloy based dexterous robot hand", *Smart Mater.Struct*., **16**, 1401-1414.

Shaoze, Y., Xiajie, L., Feng, X. and Jinhui, W. (2007), "A gripper actuated by a pair of differential SMA springs", *J. Intel. Mater. Syst. Str*., **18**(5), 459-466.

Sofla, A.Y.N., Elzey, D.M. and Wadley, H.N.G. (2008), "Cyclic degradation of antagonistic shape memory actuated structures", *Smart Mater. Struct*., **17**(2), 1-6.

Sreekumar, M., Nagarajan, T., Singaperumal, M., Zoppi, M. and Molfino, R. (2007), "Critical review of current trends in shape memory alloy actuators for intelligent robots", *Ind. Robot*., **34**(4), 285-294.

Sun, L., Huang, W.L., Ding, Z., Zhao, Y., Wang, C.C., Purnawali, H. and Tang, C. (2012), "Stimulus-responsive shape memory materials: A review", *Mater. Design*., **33**, 577-640.

Zhong, Z.W. and Chan, S.Y. (2007), "Investigation of a gripping device actuated by SMA Wire", *Sensor. Actuat. - A Phys*., **136**(1), 335-340.

Zhong, Z.W. and Yeong, C.K. (2006), "Development of a gripper using SMA wire", *Sensor. Actuat. – A Phys*., **126**(2), 375-381.

CC