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Developing a novel SMA-actuated robotic module

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ABSTRACT

Unstructured environments and task based goals require varying robot configurations to fulfill the missions. Modular robotic systems are fast growing solutions for this purpose, where the robot configuration may quickly and easily be changed by connecting or disconnecting different modules. Flexibility of the modules and their degrees of freedom directly affect the overall robot agility and performance. In this paper a novel robotic module, FlexiBot (Flexible Robotic Module) with two degrees of freedom is introduced. The module incorporates shape memory alloy (SMA) springs to create relative motion between two parallel plates hinged to each other. Furthermore the module is developed in an embedded package including a moving mechanism, an electronic driver hardware, and a sensory system. SMA springs are used as the module actuators due to their ability in providing larger displacements, which make them more suitable for robotic applications. Further, the modeling of a SMA spring actuator is introduced along with the dynamic model of the FlexiBot. The model is verified against experimental results.

1. Introduction

Interest in modular robots has increased in recent years due to their potential robustness, reduced costs, and wide range of application. Modular robots consist of interchangeable modules connected into a mechanical and functional assembly. An important feature of a modular robot is the flexibility of module in shock absorption particularly in unstructured environments where there is a serious limitation in satisfying this requirement with regular robots.

A body of research on modular robots is focused on the development of new modules with specific features. The modules can be grouped into two categories: lattice type, and chain type. A lattice type module consists of and reproduces different volumetric constructions while the chain type elements are placed in a string configuration. Suh et al. [1] developed a self-reconfigurable system, telecube as a lattice type that is a contracting/expanding and connecting/disconnecting mechanism. Murata et al. [2] presented a modular system including a cube at the center and six connecting arms attached to six faces of the cube. As a chain type modular system, Yim et al. [3] introduced PolyBot module with a single rotational DOF. A robotic system made of PolyBots can be configured in different configurations such as a spider, a rolling track and a snake. M-TRAN module introduced by Kurokawa et al. [4] consists of two cubes joined through a connecting bar attached to the side faces with two revolute joints. Additionally, ATRON modular system developed by Hallundbæk et al. [5] includes two connected half-spheres that are free to rotate with respect to each other.

SMAs are becoming increasingly popular due to their characteristics such as high energy to weight ratio, smooth and silent operation and simultaneous actuation and sensing. These characteristics make SMAs suitable for actuation in robotics especially when minimal size and weight are desirable.

It should be noted that some limitations such as low speed of operation, nonlinear and hysteresis behavior, complexity of modeling, parameter uncertainty and difficulty in measuring variables such as temperature have so far limited potential applications of SMA actuators. These limitations have caused restriction in the development of SMA-based mechanisms. As a result SMA actuators are usually activated in an on/off mode [6]. Although desirable and attractive for robotic applications, simultaneous sensing and actuating in SMAs may not be possible due to these complexities [7].

Many researchers have reported different applications of shape memory alloys especially as actuators. Chang-Jun et al. developed a micro-wheeled robot using SMA spring through a simple mechanism [8]. Also, Kim et al. introduced an earthworm like micro-robot using shape memory alloy [9]. Additionally novel ideas for using SMA wire and producing a deflection larger than the wire strain is developed [10,11]. However the developed systems are usually

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complex in modeling and precise position control is not normally implemented. Furthermore the controllers do not consider the large stiffness variation range of SMA springs.

Lan presents a compliant link which is activated by SMA wire [12]. The wire is placed relatively parallel to the link providing a large displacement in the link. Consequently, the proposed mechanism creates a very large deflection workspace compared with its slim finger configuration. For the module developed in this study the simplicity, rigidity, large workspace, and controllable stiffness has been studied and demonstrated successfully in the final prototype.

This is a departure from existing body of work where very few modules used SMAs as actuators. Yoshida et al. [13] introduced a modular system consists of micro-modules with SMA torsional actuators. Liu and Liao [14] developed a snake modular robot which the modules are actuated by a pair of formed SMA wires. Activating/deactivating the SMAs change the shape of modules and handle the robot locomotion. Ying et al. introduced a modular system based on SMA wires for angular position variation, the design was not implemented experimentally [15].

Overall, SMAs are less applied in the modular robotic systems with positioning capability. Furthermore the intrinsic properties of SMA spring which shows a large deflection and stiffness controllable provide new opportunity for developing new modular systems.

Dynamics of shape memory alloys are predominantly nonlinear since the energy conversion principle, from heat to mechanical, relies on exploiting phase transition in a metal. This creates significant hysteresis in addition to many other nonlinear effects. Moreover, the dynamic properties of the shape memory alloys vary widely with their metallurgy content, fabrication process, training techniques, aging, and ambient conditions. Thus a great deal of parametric uncertainty is involved [10].

Many control strategies include model based or non-model based methods, are developed in the literature for applying to shape memory alloy based systems [16]. This paper while not directly addressing the control strategies, presents a modeling framework that can be used for simulating the control strategies. Furthermore, the provided design of the FlexiBot facilitates implementing the control strategies.

In this study a modular robotic package, FlexiBot, that employs shape memory alloy springs as the actuation mechanism is designed and fabricated. Mechanical and electrical design requirements of FlexiBot are introduced in details. Although many researches has been performed in the area of modeling of shape memory alloy wire actuators [17–21], relatively less attention has been paid to the modeling of the SMA springs [22]. In this paper a phenomenological model of the SMA spring is developed and verified through experiments on the FlexiBot module.

In the following, in Section 2, design of the FlexiBot module is explained in detail. In Section 3 the modeling of the SMA spring is discussed and employed for dynamic modeling of the module. In Section 4, some experiments are presented to validate the modeling and performance of the module operation.

2. FlexiBot design

The design of FlexiBot is based on developing an embedded system including the mechanism, actuators, sensors and the hardware into a package. In the following section the design process is discussed in details.

2.1. Conceptual design

From Section 1, it may be concluded that the angular motion of parts of a module is very useful in providing high maneuverability. Then, the first idea would be on the development of an angular actuator in modular assembly with sufficient DOFs. As a result, two perpendicular DOFs seem to produce a better dexterity for the modular actuator that is proposed in this paper as presented in Fig. 1.

Fig. 1. The general concept of the FlexiBot module.

Actuation of the module can be provided through simple gear motors, but this motor-driven actuation will not provide the required flexibility that was explained in Section 1. In order to accommodate the flexibility, to improve the shock absorption capability of the module, and to limit the actuator weight, we decide to use the SMAs as the module actuators. SMAs, while minimizing the size of the developed package, have the potential functionality of handling a large deformation and of applying an almost constant level of force in the working range. These properties are desirable and will potentially make the module more flexible and versatile.

The simplest form of SMAs which is usually employed in applications is wire. SMA wires have widely been used in the robotic systems. However, the strain provided by the SMA wires (about 5%) is not suitable for large deflections and motions. For instance, the two corners of the plates illustrated in Fig. 1 can be connected by an 8 cm wire. After activation, the wire length will be reduced to 7.6 cm. It is clearly concluded that this amount of deflection is not enough to create an acceptable variation in the angle of the module and results in a limited workspace for the module. As a result, SMA wires may result in a complex design, because of the limited deflection of wires and additional elements required to amplify the motion. A few novel ideas have been introduced by researchers to produce better deflections from the limited strain of SMA wires. Grant and Hayward developed a linear actuator which employs SMA wires with an acceptable deflection [10]. Their idea was to use weaving SMA wires to generate a larger deflection in comparison to a simple wire. Khidir et al. developed a linear actuator with large deflection by attaching two SMA wires on two flexible symmetric beams [11]. Also Lan developed a compliant finger activated by a SMA wire [12]. Ying et al. introduced a modular system based on SMA wires for angular position variation, not implemented experimentally [15].

In this work SMA springs are used to produce larger deformation wires needed for the FlexiBot module. It should be noted that SMA springs while having larger deflection (more than 200%) offer smaller level of force. In summary, one of the initial ideas in developing FlexiBot is to use the SMA wires and implementing a novel mechanism to increase the wire length that results in a larger deflection/workspace. But one of the major drawbacks of this idea is the complexity of the design. Consequently it is decided to use the SMA springs instead. However, using a large diameter of the spring wire increases the response time of the module and any improvement in decreasing the response time may increase the FlexiBot performance. To overcome this drawback, the design of FlexiBot allows us to incorporate multiple SMAs in parallel for actuating every DOF. In other words, a few SMAs with fast response time substitute each SMA spring. Furthermore, one may increase the torque capacity of the module to handle more loads by adding SMAs in parallel.

2.2. Detailed design

The detailed design consists of two parts: mechanical and electrical design.

2.2.1. Mechanical design

The module consists of two plates connected to each other through a universal two DOFs joint. Four SMA springs connect the edges of the plates to each other and provide two separate differential DOFs. As most of SMA actuators act in one direction (usually in tension), a differential form of design is employed for actuation of each DOF. Each DOF's workspace depends on the SMA length, the geometry of the plates and the attachment points of the SMA springs to the module. In the proposed design this ranges between -30° and $+30^\circ$ rotation of plates with respect to each other initially placed parallel. Position sensors embedded in the module's joints provide angular sensory information. A schematic design of the module is illustrated in Fig. 2.

Every rotary DOF utilizes separate slippery bearing to produce a firm rigidity. A cross-section of one DOF of the module is given in Fig. 3. The perpendicular direction of rotation axes increases the maneuverability of the module that results in lower required modules in developing a modular structure. The modules may be connected to each other through a docking mechanism which are made of pins and set screws.

The module is manufactured from aluminum alloys, and plastic parts isolate metal parts from each other under applied voltages. The shape memory alloys are purchased in spring type with wire diameter of 0.75 mm and the spring diameter of 6 mm [23].

2.2.2. Electrical design

The block diagram of the module's electrical design is shown in Fig. 4. It includes a microcontroller (ATMEGA32), SMA drivers (Darlington transistors, TIP122), position sensors, and communication drives. The microcontroller is used to manage the driving of the SMAs, to handle the communication requirements, and to provide A/D conversion. The sensory data are angular positions and currents of the SMA springs to prevent undesired high temperatures. SMA drivers are power transistors providing high currents for a fast actuation.

Also Fig. 5 presents the block diagram of a modular system electrical design. In this configuration, different modules communicate to each other through a common bus. Additionally they are managed through a PC as a central controller.

The communication protocols between the modules are RS-485. Throughout this design, a common bus (RS-485) connects all modules together. A central controller, which is a PC with an I/O board, manages the activation and communication between modules.

The specifications of the FlexiBot module is summarized in Table 1. The experimental setup of FlexiBot is also shown in Fig. 6a.

Table 1
Parameters used in the paper.

Parameter	Definition	Unit
τ	Shear stress	GPa
G	Shear young module	GPa
γ	Shear strain	–
ξ	Martensite fraction	%
ξ_s	De-twinned martensite fraction	%
T	temperature	°C
y	Displacement of SMA spring	mm
F	Force of SMA	N
V	Applied voltage	V
θ_1	Module's first DOF angle	°
θ_2	Module's second DOF angle	°
$\dot{\theta}$	Angular velocity of module's first DOF	°/s
$\ddot{\theta}$	Angular acceleration of module's first DOF	°/s^2
F	Border of SMA forces	N
r	Border of torque arm of the SMA forces	mm

As we know, one of the properties of the SMAs is their simple activation from the heat generated by transmitting current. This property makes the actuator naturally low pass, and thus its higher order dynamics is not affected by step or impulse inputs. On the other hand, a simple way of implementing control strategies especially for differential type systems is switching method. As a result, switching method is a good candidate for control purposes of the system. Implementing the control strategies on this system is done through the activation of SMAs. However a proper timing for turning the SMAs on/off is necessary in control. For example the PWM method which is a common method of implementing the control is demonstrate by turning on/off the SMA in the small period of time. The microcontroller based design of the system provides the opportunity of implementing this method for every strategy of control.

The torque capacity of the module is defined as the maximum torque that the module can exert in each DOF. This capacity is calculated by adding a specific load to one side of each DOF and activating the opposite side of SMAs to handle the load (Fig. 6b).

3. System modeling

A variety of models have been developed to describe the thermo-mechanical behavior of SMA. Among them, the constitutive Tanaka based models have been more attractive for researchers, because of the simplicity of application. However, the proposed researches focused on one dimensional behavior of SMAs; thus they are implemented in the applications where wire form of SMA is used. Brinson [17] developed a phenomenological model based upon previous works by Tanaka [18] and Liang and Rogers [19]. Following that, Elahinia showed the shortcomings of the existing models for complex loadings [20] and introduced an enhanced SMA phenomenological model [21]. These basic models have let the researchers to develop actuators for new applications in the recent years [24–26].

However, one-dimensional spring models have not been comprehensively investigated especially for precise positioning. Although Liang and Rogers [22] described a simple modeling for SMA springs, there are several shortcomings for complex loadings. In this research Brinson's model modifications are added to the Liang's work to improve SMA springs modeling. The parameters used in the paper are presented in Table 2 and the coefficients applied for the modeling and simulation are reported in Table 3 of the paper.

Based on the multi-dimensional constitutive relation of Liang and Rogers [19], one-dimensional shear stress and strain relation

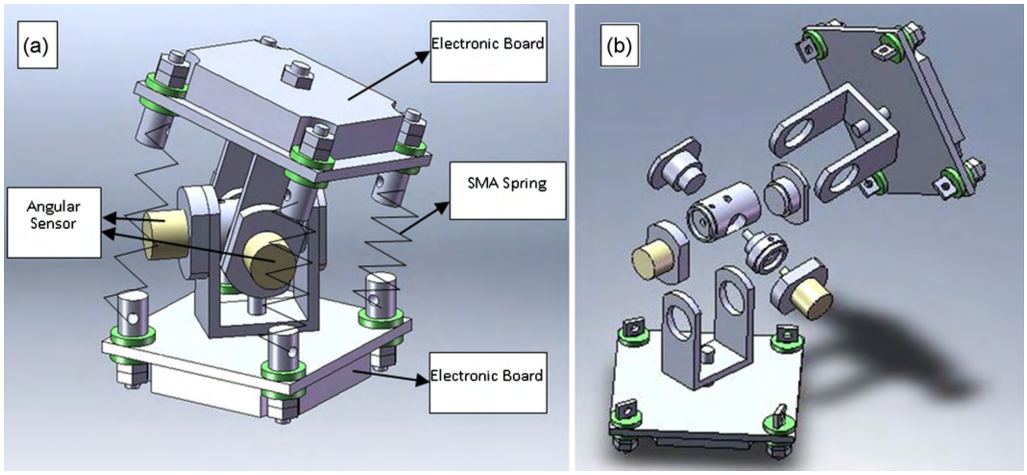

Fig. 2. Schematic of the FlexiBot (a) assembly design and (b) exploded view.

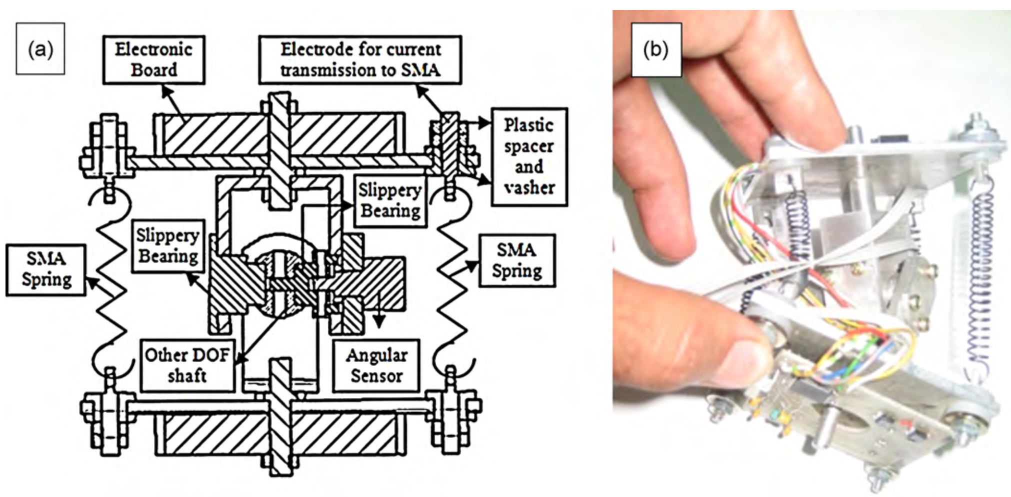

Fig. 3. Detailed mechanical design of the FlexiBot (a) a cross-section of one of the DOFs and (b) the actual module.

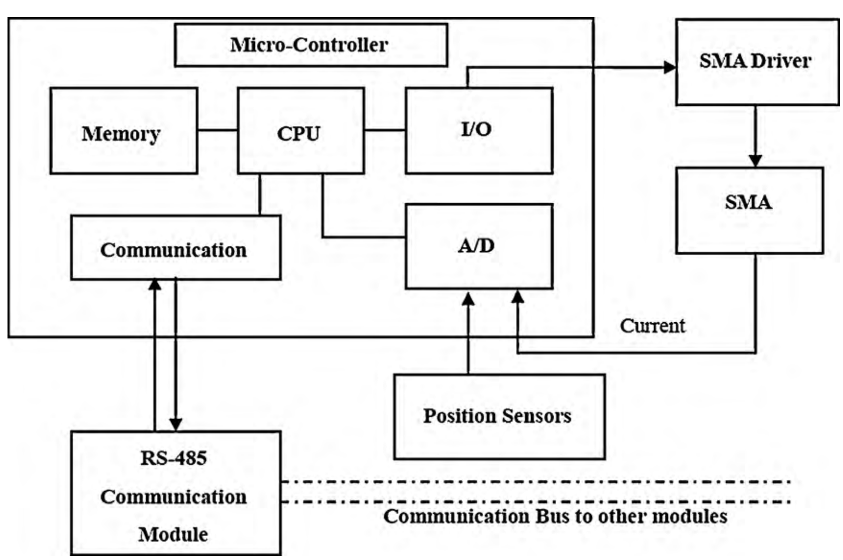

Fig. 4. Block diagram of the FlexiBot electrical design.

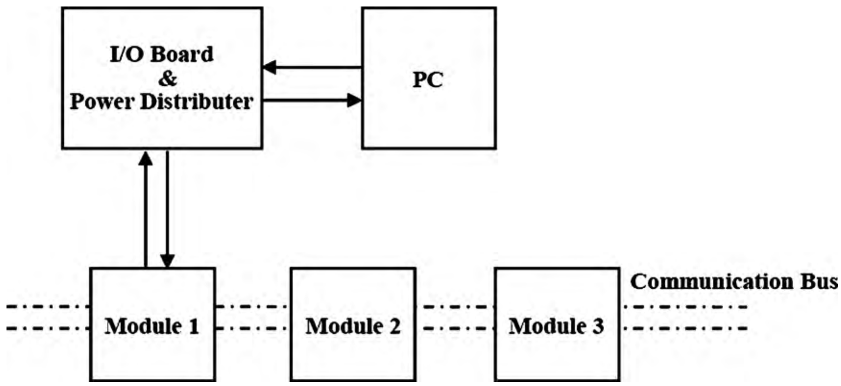

Fig. 5. Block diagram of the modular system electrical design.

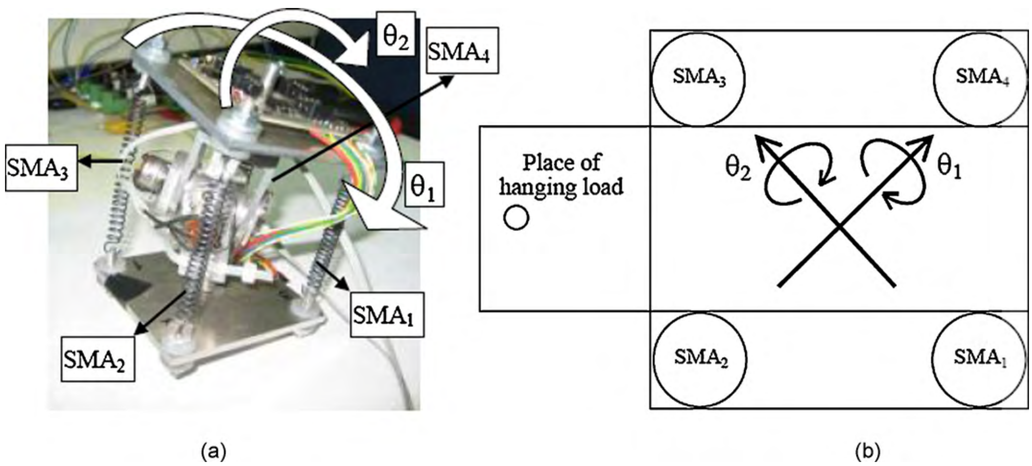

Fig. 6. (a) FlexiBot setup and (b) the SMAs arrangement and the external load place.

of shape memory alloys is expressed as:

$$\tau - \tau_0 = G(\gamma - \gamma_0) + \frac{\Omega}{\sqrt{3}}(\xi - \xi_0) + \frac{\theta_T}{\sqrt{3}}(T - T_0) \quad (1)$$

where G is the elastic shear modulus, Ω is the phase transformation tensor (which can be calculated from $-G\gamma_L$, where γ_L is the maximum recoverable strain), and θ_T is the thermo-elastic tensor related to thermal expansion of the SMA. T is the temperature and ξ is the internal variable describing the percentage of martensite.

In this equation the thermo elastic term is negligible in comparison to other terms, especially for the spring which has large strains. So the equation can be abstracted by considering the initial condition as zero:

$$\tau = G\gamma + \frac{\Omega}{\sqrt{3}}\xi \quad (2)$$

Table 2
Major properties of FlexiBot.

FlexiBot module	
Mechanical	
Shape	Cube
Degrees of freedom	2 rotary
Size	70 mm × 70 mm × 100 mm
Mass	100 g
Workspace	30°
Torque	0.4 N m
Docking	Guidance pin and set screws/Offline
Electrical	
Actuator	Shape memory alloy spring
Design	Microcontroller based
Communication	RS-485
Sensors	Rotation (potentiometer)
Drive	Darlington transistor

Table 3
Coefficients used in the modeling.

Coefficient	Definition	Value	Unit
γ_L	Maximum shear strain	0.0567	–
Ω	Phase transformation contribution factor	$G\gamma_L$	GPa
θ_T	SMA spring thermal expansion factor	–	MPa/°C
T_∞	Temperature of environment	23	°C
D_s	Diameter of SMA spring	6	mm
d_w	Diameter of SMA spring wire	0.75	mm
N	Number of SMA spring coils	20	–
m	SMA spring mass	0.00118	kg
C_p	Specific heat of SMA spring	350	J/kg °C
L	Latent heat	6025	J/kg °C
R_A	SMA resistance in austenite phase	0.7246	
R_M	SMA resistance in martensite phase	0.8197	
h	Convection heat coefficient	150	J/m2 °C s
A_c	SMA spring circumferential area	977	mm2
I	Upper plate of module's moment of inertia	0.001	kg m2
A_s	Austenite start temperature	42.6	°C
A_f	Austenite finish temperature	50.3	°C
M_s	Martensite start temperature	42.7	°C
M_f	Martensite finish temperature	36.7	°C
c	Damping ratio of module joints	0.2	–
l_s	SMA length	75	mm
l_{0s}	SMA initial length	20	mm
G_A	Shear young module in austenite	26.9	GPa
G_M	Shear young module in martensite	17	GPa
C_A	Effect of stress on austenite temperatures	6	°C
C_M	Effect of stress on martensite temperatures	12	°C

Through the improvement done by Brinson [17], the martensite fraction ξ should be substituted by de-twinned martensite fraction ξ_s to better define the shape memory effect property of the SMA. So in the following equations, ξ is substituted with ξ_s.

The deflection of a spring can be derived from the torsional strain as the below relation:

$$y = \frac{D_s}{2} \int_0^{\pi D_s N} \frac{\gamma}{r_w} dx \quad (3)$$

Substituting γ from Eq. (2) in the above equation and doing some mathematical simplifications results in:

$$y = \frac{\pi D_s^2 N}{2 r_w} \left(\frac{\tau}{G} - \frac{\Omega}{\sqrt{3} G} \xi_s \right) \quad (4)$$

From the basic relations of spring, resulting force in a spring may be related to the torsional stress as:

$$\tau_{max} = \frac{F D_s}{\pi r r_s^3} \quad (5)$$

Another assumption made in the modeling is that the amount of torsional stress in the spring wire cross-section is considered the value of τ_{max}. So substituting Eq. (5) to Eq. (4) may result in:

$$y = \frac{8 D^3 N}{G d^4} F - \frac{\Omega N \pi D^2}{\sqrt{3} G d} \xi_s \quad (6)$$

Another important part of dynamic modeling of SMA is the heat transfer. Considering a SMA as a system and using thermodynamic law we can express the heat transfer as below [27]:

$$\dot{E}_{input} = \dot{E}_{loss} + \dot{E}_{absorbed} \quad (7)$$

where E_{input} is the input energy to the system, E_{loss} is the lost energy from the system and $E_{absorbed}$ is the absorbed energy to the system. Substituting the above terms into Eq. (7) results in:

$$\dot{E}_{mech} + \dot{E}_{electrical} = \dot{E}_{strain} + \dot{E}_{conv} + \dot{E}_{radiative} + \dot{E}_{specific} + \dot{E}_{latent} \quad (8)$$

where E_{mech} is the input mechanical work (energy) to the SMA, $E_{electrical}$ is the input electrical energy produced by transmitting current, E_{strain} is the stored mechanical strain energy, E_{conv} is the convective heat loss to the environment, $E_{radiative}$ is the loss energy through radiation and $E_{specific}$ and E_{latent} are the specific and latent heat components of the material undergoing transformation.

As the stress of the SMA is calculated from measuring the exerted force and the strain is also measured form the displacement of the load, the mechanical input energy and the absorbed strain energy are equal:

$$\dot{E}_{mech} = \dot{E}_{strain} \quad (9)$$

The electrical energy is produced by transmitting current from the SMA which is considered as a resistance. Consequently the generated heat is defined by:

$$\dot{E}_{electrical} = \frac{V^2}{R} \quad (10)$$

The resistance R depends on the martensite fraction of the SMAs. In the simulations, the resistance R and the elastic module G are continuously updated varying linearly from totally martensite to totally austenite. Assuming the ξ to be the martensite fraction of the SMA, R is derived from:

$$R = R_A + \xi (R_M - R_A) \quad (11)$$

$$G = G_A + \xi (G_M - G_A) \quad (12)$$

in which R_M is the resistance of the SMA in the martensite phase and R_A is the resistance of the SMA in the austenite phase.

The convection heat transfer for material is usually defined by the below classic equation:

$$\dot{E}_{conv} = h A_c (T - T\infty) \quad (13)$$

The value of the convective heat transfer coefficient depends on the experimental environment. A typical value of h from the literature is considered for simulation [21]. A_c is the actuator surface and defined in the simulation by:

$$A_c = \pi d_w \times \pi D_s \times N \quad (14)$$

where d_w and D_s denote the diameter of the spring wire and the diameter of the spring respectively, and N represents the number of spring coils.

The irradiative heat transfer is negligible because of the low temperature of the SMA. The absorbed specific and latent energies may be defined as:

$$\dot{E}_{specific} = m c_p \dot{T} \quad (15)$$

$$\dot{E}_{latent} = m L \dot{\xi} \quad (16)$$

Consequently the rate of heat transfer in the SMA spring may be defined by:

$$m C_p \frac{dT}{dt} + m L \dot{\xi} = \frac{V^2}{R} - h_c A_c (T - T_\infty) \quad (17)$$

In the FlexiBot, four SMA springs are coupled antagonistically to control the angular position of the module. In the simulations the bottom plate of the module is fixed. Thus, when the module is activated the upper plate is positioned in the desired angle. The dynamics of the upper plate is considered as:

$$[F][r] - c \left[\dot{\theta}\right] = [I] \left[\dot{\theta}\right] \quad (18)$$

Simulation of the module is performed in MATLAB through Simulink environment. In Simulink, a block is developed to present the model of each SMA spring as shown in Fig. 7.

In the diagram, the inputs are voltage and deflection/force and the output is force/deflection. Depending on the coupling of the models, using Eq. (6), either deflection or force may be considered as input or output. To simulate the dynamic of the module, SMA spring blocks are coupled in order to make a dynamic system as shown in Fig. 8. In this figure, the "Forward Dyananics" block computes the angular position of the module utilizing four SMAs input forces.

In addition, another function delivers the inverse kinematics of the module calculating the SMA lengths from the angular position of the module. Consequently, the output angular position of the module is obtained from the input voltages applied to four SMA springs.

4. Experimental results

FlexiBot module is experimentally tested to evaluate the performance of the system and is compared with simulation results. First, the response of the system is compared for different voltage inputs. The angular positions of the module under 1 V excitation of SMA1 and SMA4 are shown in Fig. 9. As illustrated in Fig. 6b numbering of the SMA actuators is such that the activation of SMA1 and SMA4 may increase the angular positions of θ_1 and θ_2 respectively.

Due to the varying value of the SMA resistance (R) during the phase transformation power consumption is not constant during applying a constant voltage to the SMA. In the experiment, the resistances of martensite and austenite phases are 0.8197 Ω and 0.7246 Ω respectively. Consequently a variable current of 1.22–1.38 A for activation with 1 V and 1.83–2.07 A for activation with 1.5 V is required. Thus mean consumed powers of 1.3 W and 2.0 W are considered for the simulation purposes.

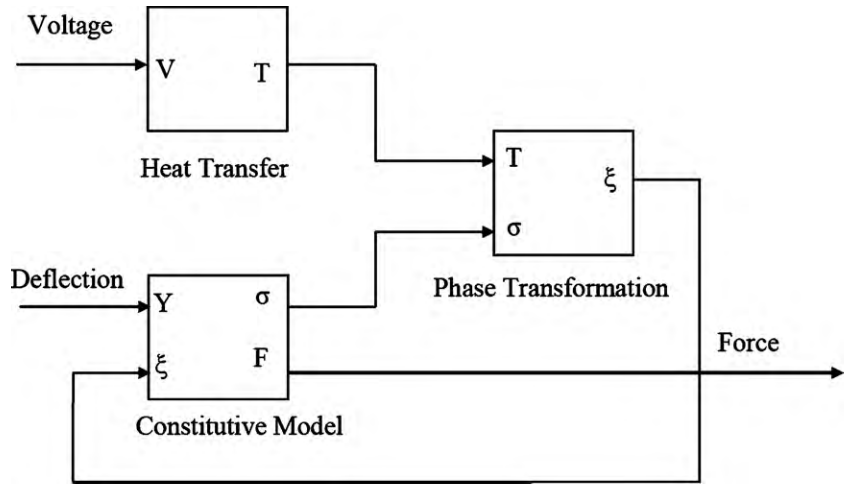

Fig. 7. The block diagram of the SMA spring model.

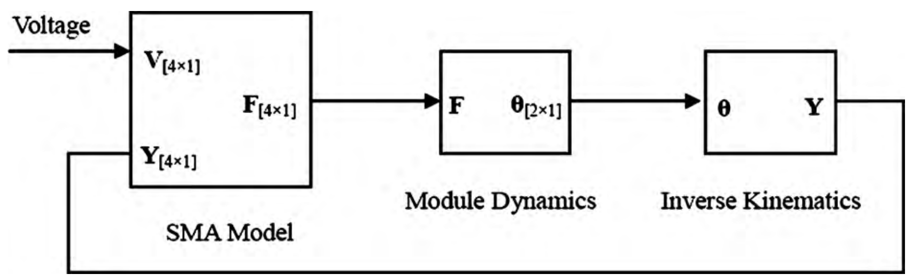

Fig. 8. Modeling the module dynamics through coupling four SMA.

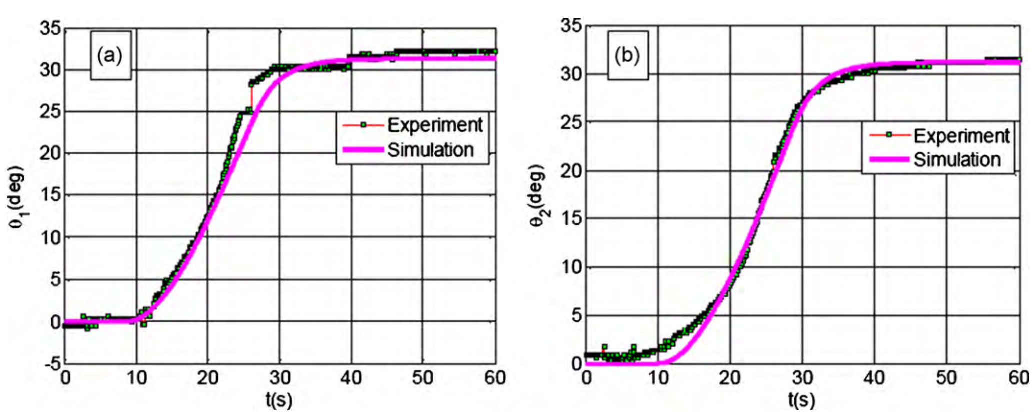

Fig. 9. Module response of activating SMA1 and SMA4 with 1 V (mean power of 1.3 W) (a) θ_1 and (b) θ_2.

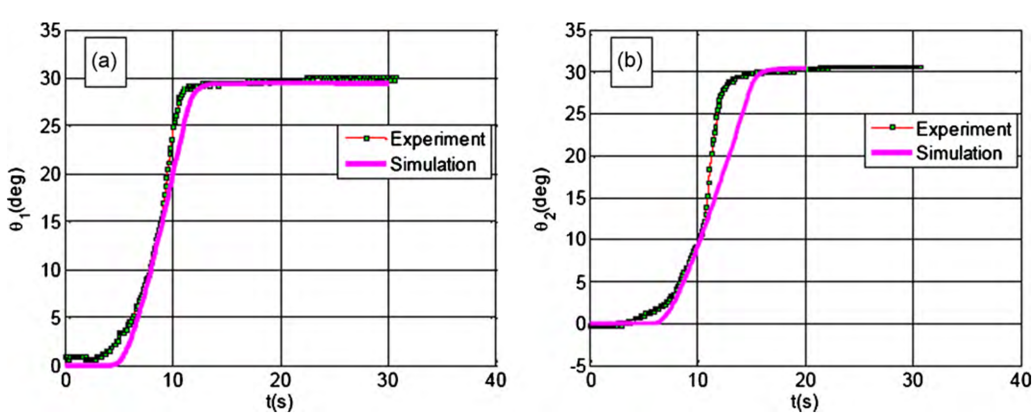

Fig. 10. Module response of activating SMA1 and SMA4 with 1.5 V (mean power of 2 W) (a) θ_1 and (b) θ_2.

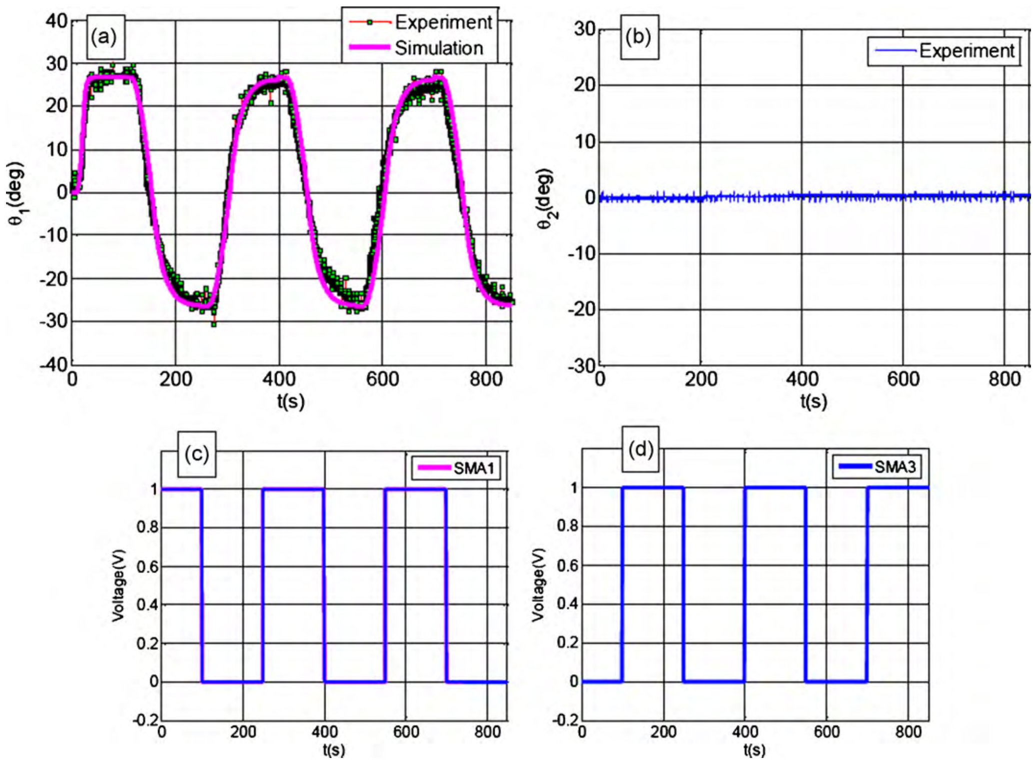

Fig. 11. Activation of SMA1 and SMA3 periodically one after another (mean power of 1.3 W) (a) variation of θ_1 versus time, (b) variation of θ_2 versus time, (c) inserted voltage on SMA1 and (d) inserted voltage on SMA3.

Other inputs such as 1.5 V for SMA1 and SMA4 are used in experiments as in Fig. 10. It can be concluded that an increase in the activation voltage, definitely decreases the response time. However, the final positions achieved through applying different voltages do not change unless the load changes significantly. As illustrated, the simulation results match the experiments well. Few parameters mainly the heat transfer coefficient in the experiments may be tuned for better results.

The module is also tested under a periodic excitation (Fig. 11a and b). SMA1 and SMA3, which directly change θ_1, are activated by square signals shown in Fig. 11c and d. In the experiment the module achieve $\pm 30^\circ$ of the limits of workspace. The differential type of actuation implemented in this experiment provides a symmetric mechanism which tends to bypass the hysteresis behavior, which is one of the biggest challenges in the development of SMA-based systems.

The SMA springs, initially at the room temperature, are in martensite phase. Thus, in the differential mechanism, when one SMA is activated, the other SMA produces a small resistive force. In this stage by heating one SMA, the angle of θ increases quickly (less than 50 s) to its final value. Following that, when the other SMA is activated, the opposite SMA that is already in a high temperature, produces a larger resistive force. Thus to reach to the same negative deflection as the previous case the passive spring should cool off reasonably. The cooling time however is longer, and it takes about 150 s which is almost 3 times longer than heating.

However, in a differential mechanism, the induced force on the passive and already heated SMA through the active SMA causes an increase in the Ms and Mf temperatures. This results in a faster response by the mechanism. Nevertheless, adding cooling mechanisms to the module or using this module in applications where a larger cooling rate is provided increases the actuation frequency.

Results also demonstrated the independent nature of the DOFs of the system. While the activation of SMA1 and SMA3 directly change the angle of θ_1, while the angle of θ_2 almost remains unchanged (Fig. 12b).

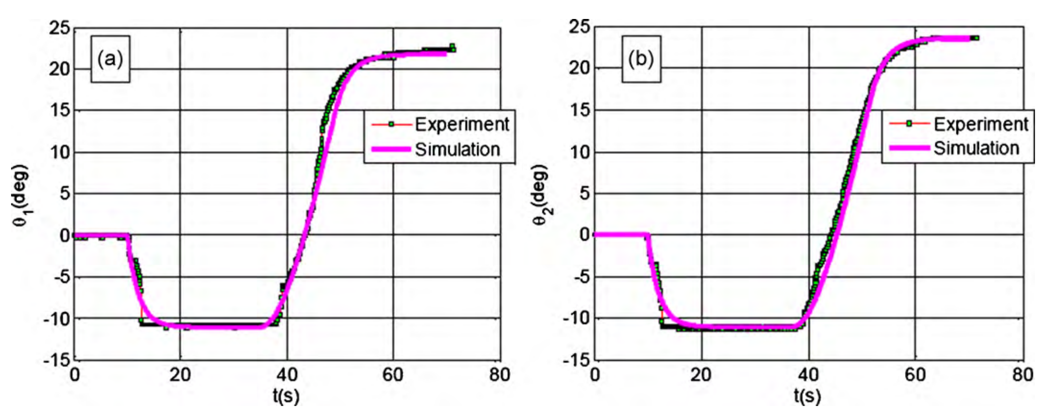

Fig. 12. Activation of SMA1 and SMA4 by 1 V in the presence of load (a) θ_1 and (b) θ_2.

Finally, the module performance is studied under load applications. When positioned at $\theta_1 = \theta_2 = 0$, the module is loaded by a 100 g weight and a voltage of 1 V is then applied to SMA1 and SMA2 and angular positions are measured. In the experiment, a load is applied to the upper plate through an extension rod which is shown in Fig. 6b. The load has been configured to produce the same torques on all DOFs of the module resulting the same values of the θ_1 and θ_2 shown in Fig. 12a and b. Eventhough the simulation results are exactly the same, there are small differences in experimental results due to different joint frictions of DOFs'. However good agreement is observed between simulation and experiment as in Fig. 12.

The variation of module's angle when an external load is applied demonstrates the flexibility and low stiffness of the module. This property may be very useful in the application of the module in mobile modular robots. Generally, as the robot path may be unpredictable, encountering unknown environments may cause external shocks to the module. Although external shocks cannot be modeled in real applications, proper modeling as presented here in addition to uncertainty removal strategies may provide better results in the control system.

5. Discussion

The previously presented modular systems suffer from low DOFs of the modules and increasing the DOFs may add the complexity of the system. One DOF modules like PolyBot, although partially cover the working space, they do not cover the working space thoroughly. Even though, M-TRAN has two rotational DOFs, but the axes of rotations are parallel to each other that limit the maneuverability of the motion. Furthermore, another drawback of the current works is the use of classical DC gear motors that requires many elements to be added to the system and may results in higher rigidity of the modules and limit the shock absorption tolerance.

In the development of the module of this work, the above drawbacks are considered to be solved towards a successful design. Two perpendicular DOFs are implemented into a simple conceptual design, actuated through four independent SMAs. This will result in a compact, high energy to low weight, and high flexibility module that can be utilized in robotic applications.

The main feature of SMAs is their ability to undergo large strains in the martensite phase and recover the strain after phase transformation to austenite through heat treatment afterward. Thus, the actuator length may change due to the external loads that provide flexibility in the mechanism. The SMA length variation depends on the material phase, thus controlling the phase make it possible to manipulate the stiffness of SMAs. This property is particularly applicable in SMA springs where the deflection is much higher than the wires' deflection. In both shape memory and super-elastic behavior, SMA offers an almost constant force in a large range of operation. This feature makes SMAs suitable in shock absorption and has gained much interest compared to classic actuators where there is no passive flexibility. Furthermore, modular robotic systems are often biologically inspired, thus, smart materials such as shape memory alloys are proper choice for this application.

Further to the novel design of FlexiBot presented in this work, a detailed modeling of the SMA springs including the dynamic behavior of the SMA springs is studied and experimentally verified. Experiments show the ability of the modeling in anticipating the module behavior while activated by input voltages (Figs. 9 and 10). To elaborate on the ability of the introduced models in addition to the maneuverability of the module, a periodic excitation was also implemented in Fig. 11. Throughout this experiment it is verified that the module reach to the whole workspace as it was expected for. Finally, it is shown that the module response for a disturbance load matches with the simulation results (Fig. 12).

6. Conclusion

In this study, a novel two DOFs robotic module was developed. An effective combination of different mechanical and electrical components were designed to introduce a basic element for applications in the modular robotic systems. Simplicity and low weight in addition to flexibility of the module will be usefull for robotic system developers. Modeling of the SMA spring as the basic element of the module was performed in details. SMA springs were employed in a differential mechanism in this study. When the module was activated in one direction, one SMA made active and the other one kept passive. Consequently, the active and passive behavior of SMA springs was integrated in the modeling. Good agreement between the simulation and experimental results validated the accuracy of the SMA spring modeling. Moreover, the module functionality under different conditions was investigated.

The mechanical and electrical design, used in this module provide a suitable platform for implementing different control strategies. Additionally, the simple structure of the module provides a good extendibility property which is very important in the development of modular robotic systems.

Although the module is small and light, the new technologies for minimizing the micro electro-mechanical systems provide more options in miniaturization of the module, and the modeling results may be extended for those applications.

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