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Modeling and Simulation of a Shape Memory Alloy Spring Actuated Flexible Parallel Manipulator

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Abstract

Parallel platforms are known for its positioning ability. Adding flexibility to a robotic system gives an advantage to better interact with the environment. In this paper a 2 DOF flexible parallel platform has been developed which consist of a triangular top and base plate connected by a universal joint at its centroid. The Shape memory alloy (SMA) springs are used as an actuator because of its large strain and are connected between the top and base plate on all the three vertices of the platform. The top plate provides desired orientation with respect to base plate on SMA actuation. The work intends to understand the system behavior by developing a mathematical model of the system .Two separate models, one to understand the kinematics and dynamics of the platform and other to understand the dynamics of the SMA spring actuator has been developed. The models were then integrated to understand the complete system behavior. The paper focuses on the integration of various system level equations to develop a general model of the SMA actuated platform and the algorithm incorporated for the same has been discussed in the work. The mathematical models were developed in MATLAB/Simulink .The kinematic model of the platform was verified on the experimental set up .The dynamic model of SMA actuator described by Liang was used and the results obtained were found to characterize the SMA. The integrated model simulation results were also verified on the experimental set up.

Keywords: *Manipulator;Mathematical Modeling;SMA spring;Flexible;2 DOF;Kinematics and dynamics*

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1. Introduction

Parallel manipulators are appreciated for its precise positioning ability compared to serial manipulators [1]. Flexibilty to such manipulators adds an advantage of better interaction with the environment. Hence parallel manipulators with additional compliance have been a major research area. The flexibility to the system widens the scope of actuator selection which inherently is an important factor that defines the compliance. Shape memory alloys and other polymer based smart materials are best choice because of its flexibility and ease of use. Sreekumar et.al [2] has developed a compliant manipulator fabricated from Be-Cu actuated by three SMA Ni-Ti wires of 0.3mm diameter separated by 120 degrees. The authors have also presented the coupling effect and the displacement static analysis of the fully compliant mechanism. Alireza et.al [3] has developed a SMA spring actuated robotic module made up of aluminium square plates supported by universal joints and has presented the mathematical model of the SMA spring. Eric et.al [11] have also demonstrated a compliant mechanism actuated by SMA wires to control the orientation of automotive mirror and a sliding mode control have been implemented to overcome the non linearties of the SMA. The nonlinearity exhibited by SMA has created enormous challenge for control. Hence, mathematical modeling of SMA to understand its behavior is important to design any optimum control algorithm. Many researchers have worked in the area of modeling and control of SMA wire. Jayender et.al [9] presented nonlinear state space model of SMA wire with LQR based control and forced cooling which improved the tracking response of SMA. Roberto et.al [8] presented the effect of forced cooling based on thermo electric effect on the response of SMA. Authors in [14] have also worked on the system identification method of modeling to overcome complex mathematical computation . Fuzzy logic control has also gained importance in the SMA control [13] because of its simplicity in implementation and non requirement of mathematical model. Shi Zhenyum et.al [15] developed a 2 DOF ball and socket joint actuated by SMA wires that use resistance feedback for measuring strain and has presented various fuzzy rule for the implementation.

The paper presents the development of a flexible parallel robotic module actuated by SMA springs . SMA springs are preferred over wire to overcome the limited strain of the later. Even though use of SMA springs increases the response time because of large cooling time but can be reduced by having forced cooling methods to improve performance. The paper though does not deal with the control strategies for performance improvement but proposes an idea of an integration of equations derived from various models to develop a general model of a SMA actuated system. The equations used are derived models from various literatures and a comparative analysis of various SMA constitutive models is given by Sayyaadi et.al [12] for the optimum selection.

In the following brief description of the parallel platform is given. Section 3 illustrates the kinematic and dynamic equations for the platform and also includes the governing equations to derive the SMA spring actuator model. The section also briefs the integration of derived equation to frame the complete model of the system. Section 4 describes the test set up and simulation results. As the work presented here only intends to derive the mathematical model, still much analysis has to be done to validate the results for optimum control design. Section 5 concludes with the proposed further developments.

2. Parallel Manipulator design

The aim of the design was to develop a parallel platform with flexibility and modularity. The manipulator has a top and a base plate made up of steel with triangular shape of each side 10cm. The plates are connected using a universal joint of 6cm height at the centroid of the triangle with connectors attached to each plate. The top plate moves with respect to the base plate and has two degrees of freedom motion namely pitch and yaw. The use of actuators is important to realize the flexibility of structures. Hence the use of motors or other sources like pneumatics etc increases the weight and also reduces the flexibility. The manipulator developed has used shape memory alloy springs for its actuation. The shape memory alloy actuators were chosen because of its high power to weight ratio, ease of use due to less electronics involved and also due to its flexibility to be accommodated in any structures. The Ni-Ti shape memory alloy (SMA) springs procured from Dynaalloy of 0.75mm wire diameter and 6 mm outer diameter were used. The specification and other details of the actuator is provided in Table 1. SMA springs were preferred over wires because of its large strain and compactness. Three SMA springs are connected in three vertices of top and base platform with suitable connectors insulated from the plates. The initial length of each SMA springs was 6 cm. The detailed design is shown in Fig.1.

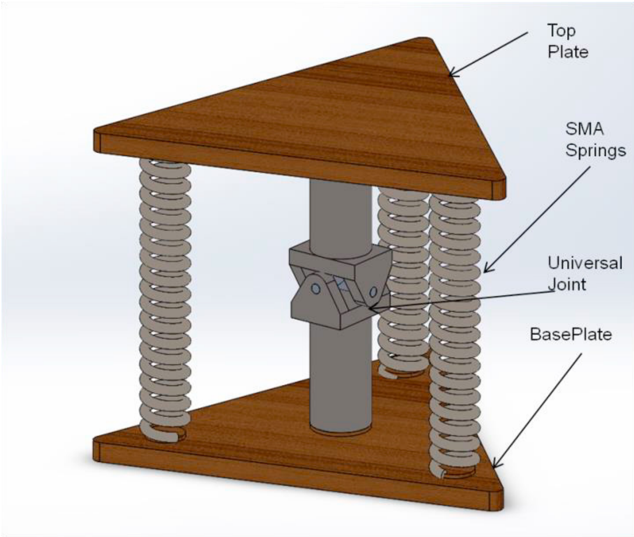

Fig. 1. Flexible SMA actuated parallel platform

3. Modeling

The mathematical model presented in the work is classified in three section namely Kinematic modeling of the platform, dynamics of the platform and the dynamics of the SMA spring actuator. The three models connected together by governing physics detail the behavior of the complete system.

3.1. Kinematic Modeling

This section details the inverse kinematic modeling of the 2 DOF parallel platforms which is used to determine the net SMA spring strain to be actuated for a given orientation of the top platform. The Fig.2 illustrates the frame assignment of the top and base plate with control points denoted as A_0,A_1 and A_2 and stationary base points as B_0,B_1 and B_2 for the derivation of kinematics. The Z axis is pointed downward and all the axis is fixed as per the right hand convention . The frame {M} denotes the frame assignment of the top platform with centre at the centroid of the top triangle namely M-XYZ and frame {B} denotes the frame assignment of the base platform with centre at the centroid of base triangle. The co ordinates of the base platform is taken as (X_B,Y_B,0).All the control point locations are calculated with respect to the base frame {B}. As the manipulator is restricted to 2 DOF motion namely rotation about X axis and rotation about Y axis ,the orientation of the platform is obtained by co- ordinate transformation matrix [17] given by equation 1

$$\mathrm{Rot}(Y,\beta)=\begin{bmatrix} cos\beta & 0 & sin\beta \\ 0 & 1 & 0 \\ -sin\beta & 0 & cos\beta \end{bmatrix} \qquad \mathrm{Rot}(X,\alpha)=\begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\alpha & -sin\alpha \\ 0 & sin\alpha & cos\alpha \end{bmatrix} \tag{1}$$

$$T_i = \mathrm{Rot}(Y, \beta)\ \mathrm{Rot}(X, \alpha)$$

By applying the transformation T_i in each of the control points in the top platform, the effective length can be found out by the equation 2 as given

$$\Delta L = AiTi - Bi \tag{2}$$

where i denotes the index of control points i=0,1,2. ΔL is the effective strain of SMA.

Hence, given the orientation of the platform, the transformation matrix multiplied with the control points (A_0,A_1,A_2) gives the new location of control points and substracted by the stationary points gives the vector distance which is the effective strain of the SMA spring actuator.

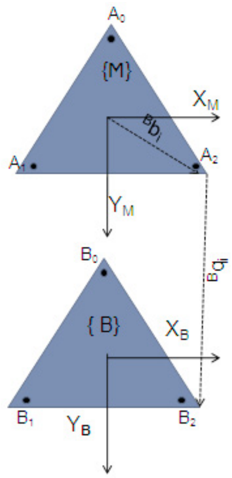

Fig.2.Vector representation of platform.

3.2. Platform Dynamics

The top plate dynamics is solved using torque balance equation as shown in eqn.(3). The dynamics is solved considering the top plate hinged at its centroid and able to orient in two axis namely α and β.

$$F \times r = I\ddot{\alpha} + b\dot{\alpha} \tag{3}$$

where I is the moment of inertia of top plate, b is the damping coefficient of the universal joint ,α and β is the angle of orientation ,r is the distance from vertex to centroid and F is the force exerted on all the vertices by SMA actuator. Here I is calculated as in eqn.(4)

$$I = \frac{sh_t^3}{12} \tag{4}$$

where s is the length of each side, h_t is the height.

3.3. SMA actuator Dynamics

Shape memory alloy possess non linearities which has widen the scope of research in the area of control [5]. To design a suitable control algorithm, understanding the system behavior is important and hence mathematical model helps in the same. Shape memory effect is the consequence of crystalline structural change when subjected to thermal or stress input. The dynamics is characterized by the change of state from martensite (soft phase) to austenite (hot state) and vice versa. Many researchers have developed the non linear model of SMA of which Liang and Rogers [6] and Tanaka model [8]is widely used. The dynamics of SMA is governed by three equations. First equation is to represent temperature dynamics which converts the applied voltage/current (power) to suitable temperature for actuation. Second equation relates the temperature to the phase transformation in the SMA and the last relates the phase transformation to stress and strain.

3.3.1 Temperature dynamics

The SMA spring actuator is actuated by applying input voltage across it to provide sufficient temperature by Joules heating. The temperature dynamics equation from [9] is used in the model which is given below

$$\frac{V^2}{R} = mc_P \frac{dT}{dt} + hA(T - Ta) \tag{5}$$

$$R = R_A + \zeta (R_M - R_A) \tag{6}$$

where V is the applied voltage , R is the resistance of SMA, m is the SMA spring mass and R_A and R_M is the resistance of SMA at martensite and austenite phase

3.3.2 Phase Transformation Condition

Liang [6] has studied the effect of phase transformation of SMA due to temperature and stress and formulated a cosine relationship relating the effect of martensite fraction over changes in temperature and stress. The relationship was able to capture the hysteresis and the characterized the condition of stress induced phase transformation. The phase transformation is governed by four critical temperatures namely A_s (Austenite start),A_f (Austenite finish),M_s (Martensite start),M_f (Martensite finish). As the change in martensite fraction with change in temperature exhibits hysteresis ,two equation were formulated as given by Liang [6] to define the change in martensite fraction from Austenite to Martensite (Cooling) and Martensite to Austenite (Heating).Nomenclatures are given in Table 1 along with the values used for simulation

If Martensite → Austenite

$$\zeta = \frac{\zeta_M}{2} \{\cos[a_A (T - A_s) + b_A \sigma] + 1\} \tag{7}$$

If Austenite → Martensite

$$\zeta = \frac{1 - \zeta_A}{2} \{\cos[a_M (T - M_f) + b_M \sigma] + \frac{1 + \zeta_A}{2}\} \tag{8}$$

where a_M, b_M, a_A, b_A are material constants given by

$$a_A = \frac{\Pi}{(A_f - A_s)}; a_M = \frac{\Pi}{(M_s - M_f)}$$
$$b_A = \frac{-a_A}{C_a}; b_M = \frac{-a_M}{C_M} \tag{9}$$

Liang's phase transformation equation has a problem of continuous updation of martensite fraction during the transformation process. H.J Lee [7] solved the issue of discontinuity by updating the ζ_M and ζ_A at every change of temperature. Hence, the model has also incorporated phase updation using the eqn. (10).

$$\xi_M = \frac{2\xi}{[\cos\{a_A(T - A_S) + b_A\sigma\} + 1]}$$
$$\xi_A = \frac{2\xi - 1 - \cos[a_M(T - M_f) + b_M\sigma]}{1 - \cos[a_M(T - M_f) + b_M\sigma]} \tag{10}$$

Table 1 Specification used in the simulation

Parameters	Notation used in model	Value	Reference
Spring Diameter (mm)	D	6	[3]
Wire Diameter (mm)	d	0.75	[3]
Number of turns	N	20	[3]
Spring mass (Kg)	m	0.001	[3]
SMA length (mm)	l	60	[3]
Austenite start temp(°C)	A_s	42.6	[3]
Austenite finish temp (°C)	A_f	50.3	[3]
Martensite start temp (°C)	M_s	43	[3]
Martensite finish temp(°C)	M_f	35	[3]
Ambient temperature (°C)	T_a	25	[3]
Convection heat coefficient	H	150	[3]
Austenite shear young module(GPa)	G_A	26.9	[3]
Martensite shear young modeule (GPa)	G_M	17	[3]
Austenite SMA resistance (ohm)	R_A	0.7246	[3]
Martensite SMA resistance (ohm)	R_M	0.8197	[3]
Stress factor in Austenite (GPa°C^{-1})	C_A	6	[3]
Stress factor in Martensite (GPa°C^{-1})	C_M	12	[3]
Mass of the top plate (Kg)	M	0.075	Design
Length of centroid from any side(cm)	d_c	2.89	Design
Size of platform (mm)(each sideXheight)	-	100X60	Design

3.3.3 Constiutive equation

Constitutive equation captures the dynamics of the SMA by relating the stress, strain, temperature and martensite fraction. Not much researchers have worked on the consititutive model of SMA springs [3]. Hao [4] ,Hyo Jik Lee [5] and AlirezaHadi et.al[3] have modified one dimensional shear stress and strain relationship by Liang and Rogers [6] to the constitutive equation for SMA springs relating the force, deflection and martensite fraction of spring. The modified constitutive equation is given in eqn.(11)

$$\dot{\tau} = A\dot{Y} + B\dot{\xi} + C\dot{T}$$
$$A = \frac{d^4 G}{8nD^3}; B = \frac{\Pi d^3 \Omega}{8\sqrt{3}D}; C = \frac{\Pi d^3 \theta_T}{8\sqrt{3}D} \tag{11}$$

where G is the shear modulus which depends on change in martensite fraction [3] given by

$$G = G_A + \zeta(G_M - G_A) \tag{12}$$

As the spring has large strain, the thermoelastic term θ_T which depends on thermal expansion can be regarded negligible [3] . Hence the equation (11) is modified with only A and B terms and is used to model the SMA dynamics.

3.4. Simulation Algorithm

The block diagram of the simulation and the equations involved is shown in Fig.3.The simulation was carried out in the MATLAB/Simulink with ode45 solver. In the kinematics model developed in Simulink as shown in Fig.4, the input is the desired angle and output is the SMA strain required to achieve the same orientation. The resultant strain is fed as the input to the SMA dynamics model as depicted in Fig.4.

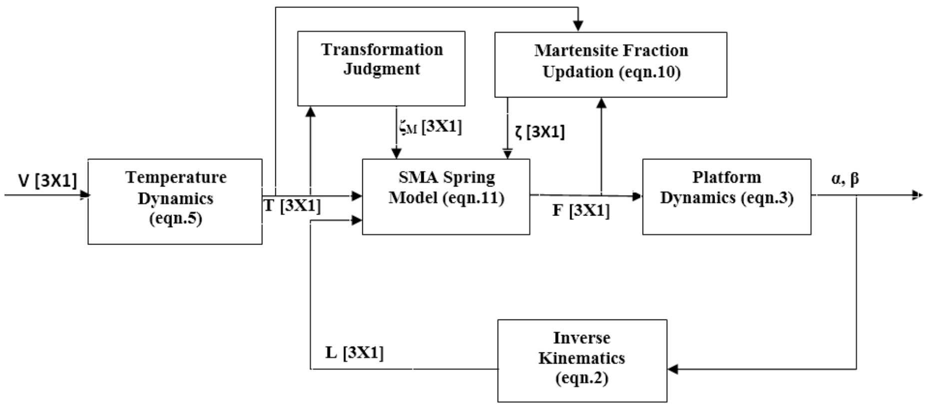

Fig. 3. Block diagram used for simulation

The SMA dynamics model has two input namely temperature and strain and the output is the force.The force calculated from the SMA dynamics is the input to the platform dynamics as given in equation (3).The force calculated from SMA dynamics is also used to check the occurrence of stress induced phase transformation. The martensite fraction is updated at every transformation to obtain the continuity. The transformation judgement which is the function of temperature and stress is used to switch between martensite and austenite condition.

If the temperature is above A_s and less than A_f, Austenite condition is simulated to calculate martensite fraction based on condition of temperature.

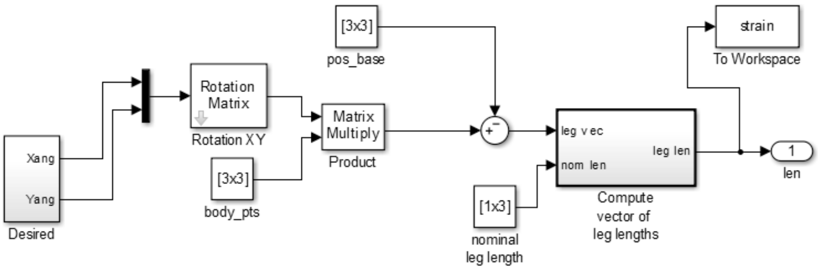

Fig. 4 Simulink model of Platform kinematics

The kinematic model given in eqn. (2) is implemented in simulink as shown in Fig.4. The input is the angle α,β which is used in the transformation matrix to get the new location of control points. The vector lengths are calculated to find the net strain required for the given orientation

4. Experimental set up and results

An experimental set up was developed in the laboratory. Experimental set up consist of a parallel manipulator actuated by 3 SMA spring along with the controller and other electronic circuitry for driving SMA as shown in Fig.5(a).

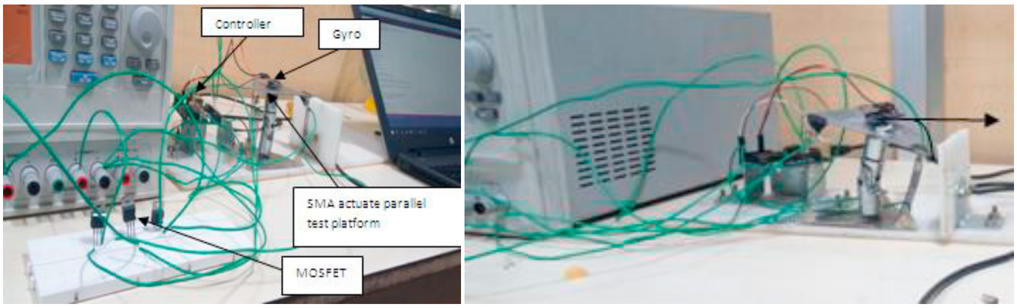

Fig.5 (a)Test platform with electronics (b) Actuated platform oriented along X axis

A basic ON/OFF control was developed where the ON time was determined by the gate activation of MOSFET controlled by the controller. Two different voltages, 3 and 5V was applied to the SMA which drawn a maximum current of 2.5 A for the complete contraction of 3 cm of a SMA spring. The motion of the platform was achieved by the antagonistic approach of activation in which one SMA was activated at a time and other two in cold state.It was found that the response time of the platform decreased on increase in input voltage but the cooling time was more which created a requirement for larger pull force by the opposite SMA spring to bring the platform in initial state. The response time to achieve a rotation of 25 degree along X axis was found to be 18 seconds for 5V and around 30 seconds for 3 V. A 3 axis gyroscope was used to determine the tilt angle of the platform and was fed to one of the input to the controller. The input to the controller is the desired tilt angle and the gate terminal of the MOSFET was kept high until the gyro sets to the desired angle. This experiment was conducted to understand the response time of the system and to validate the simulation result for the same output angle and applied input voltage. The result of the simulation for the SMA phase transformation for the input temperature as shown in Fig.6 (a) is found to follow a hysteresis path as shown in Fig.6(b). It was found that ON/OFF control even though had a faster response but the actuation was not smooth and had an overshoot with oscillations as shown in Fig.7 (b). Hence there is a need to have a optimum control to overcome the non linearities of the system. Various control strategies for the SMA has been discussed by Sreekumar et.al [13] and further studies on the platform need to be made to design an optimum control. Hence, the model has to be further validated for various inputs to understand the dynamics and reliability.

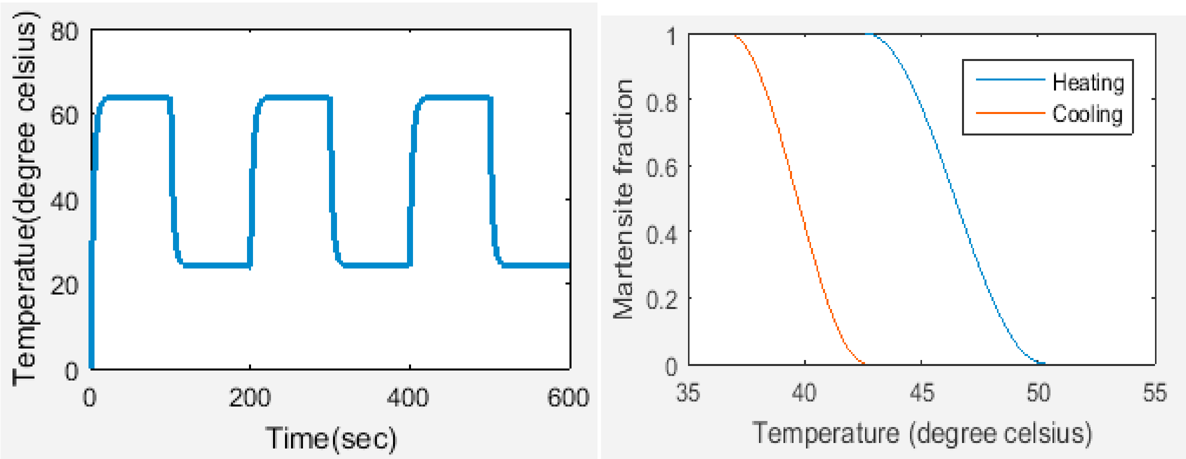

Fig. 6. (a)Simulated temperature dynamics (b) Simulated results for change in martensite fraction with input temperature

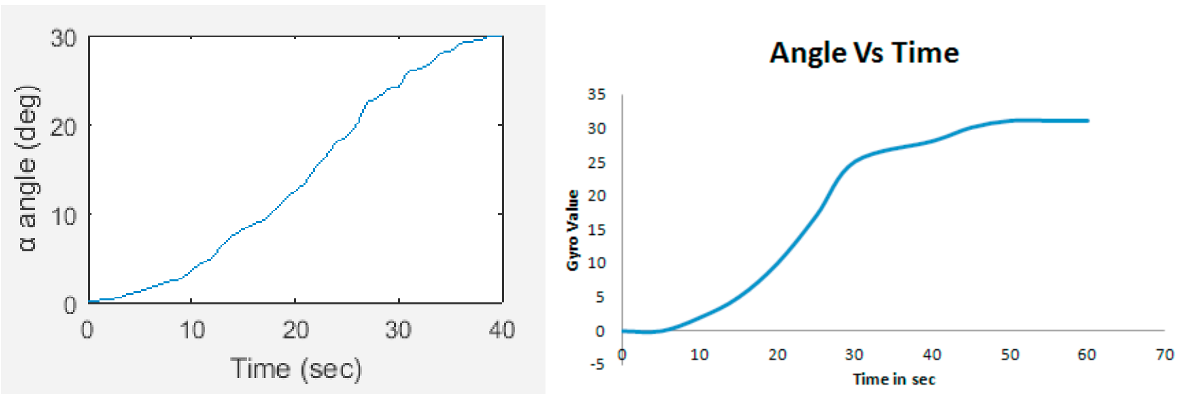

Fig.7. (a) Simulated response (b) Experimental response for 30 degree input along X axis

5. Conclusion

In the work the complete mathematical model of the system was defined .The modeling process was categorized into two sections, first the platform dynamics and then the actuator dynamics. The later part briefed the integration of the models to understand the entire system. The paper has explained the issues related to the updation of martensite fraction and has given the solution of updating the same for every iteration. The work has also briefed the modeling approach which is applicable to any SMA spring actuated parallel platform in general. The results have also shown the prototype developed with various electronics for control. The model was validated for a single static input and hence the model need to be verified for dynamic input to understand the reliability of the model. An ON/OFF control was implemented as the focus of the work was purely on the derivation of suitable model for the system and hence further studies has to be made to design a nonlinear control for better tracking. Hence, the work briefs the various consideration and challenges for deriving the model of an SMA spring actuated system .

References

[1] J.P Merlett (2006) " Parallel Robots" Springer 2nd edition :1-18

[2] M. Sreekumar,T. Nagaragan and m. Singaperumal (2009) "Design of shape memory alloy actuated compliant smart structure:Elsatica approach" Journal of Mechanical Design 131:1-11

[3] Alireza Hadi,Aghil Yousefi-Koma,Majid M. Moghaddam and,Mohammad Elahinia (2010) "Developing a novel SMA actuated robotic module" Sensors and Actuator A:Physical :72-81

[4] Hao Liu,Yili fu, Zengi Yan ,Peng Wang and Shuguo Wang (2009) " A dynamic model for the active catheter actuated by the shape memory alloy coil spring" Proceedings of the IEEE International conference on Mechatonics and Automation,China :1968-1973

[5] Hyo Jik Lee and Jung Ju Lee (2004) "Time delay control of shape mempry alloy actuator" Smart materials and structures 13:227-239

[6] C.Liang and C.A Rogers (1990) "One dimensional thermomechanical constitutive relations for shape memory materials" Journal of intelligent materials and structures 1:207-234

[7] Hyo Jik Lee and Jung Ju Lee (2004) "Modeling and time delay control of shape memory alloy actuators" Advanced Robotics 18 :881-903

[8] Roberto Romano and Eduardo Aoun Tannuri (2009) " Modeling,control and experimental validation of novel actuator based on shape memory alloys" Mechatronics 19:1169-1177

[9] J.Jayender,R.V Patel,S. Nikumb and M.Ostojic (2008) " Modeling and control of shape memory alloy actuators" IEEE transactions on Control Systems Technology 16:279-284

[10] Patrick Huynh (2004) "Kinematic hybrid position/force control of a 3 DOF In-parallel actuated manipulator" Proceedings of the IEEE Conference on Robotics,Automation and Mechatronics,Singapore :237-243

[11] Eric A. Williams, Gordon Shaw and Mohammed Elahinis (2010) "Control of an automotive shape memory alloy mirror actuator" Mechatronics 20:527-534

[12] H.Sayyaadi,M.R Zakerzadeh and H.Salehi (2012) "A comparative analysis of some one-dimensional shape memoryalloy constitutive models based on experimental tests" Scientia Iranica B 19:249-257

[13] Sreekumar M., Singaperumal M., Nagarajan T., Zoppi M and Molfino R (2007) "Recent advances in nonlinear control technologies for shape memory alloy actuators" Journal of Zhejiang University SCIENCE A :818-829

[14] Elwaleed Awad Khidir, Nik Abdullah Mohamed, Mohd Jailani Mohd Nor and Mohd Marzuki Mustafa (2008) "A new method for actuating parallel manipulators" Sensors and Actuators A 147: 593–599

[15] Shi Zhenyun, Wang Tianmiao, Liu Da , Ma Chen, Yuan Xiangnan (2014) "A fuzzy PID-controlled SMA actuator for a two-DOF joint" Chinese Journal of Aeronautics,27:453–460

[16] Mohammad H. Elahinia, Hashem Ashrafiuon, Mehdi Ahmadian and Hanghao Tan (2005) "A Temperature-based Controller for a Shape Memory Alloy Actuator" Journal of Vibration and Acoustics,127:285-291

[17] Craig J.J (2004) "Introduction to robotics:Mechanics and control,3rd edition,Prentice hall:19-54