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Design and Development of Peristaltic Soft Robot Using Shape Memory Alloy Actuators with different control strategies

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Abstract: This paper presents design, development and different optimal control strategies for a spiral, shape memory alloy (SMA) actuators for robotics applications. The actuator material used is thermally activated Ni-Ti SMA which exhibits high torque capacity. SMA based actuators are widely used in robotics applications because of their large energy density and super-elasticity. Here describe the multi-direction movement of soft robot based on SMA actuators. To controlling precise position in minimum time for SMA actuator suitable controller require. Here we investigated the different ideal controlling method for design soft robot model. The Control strategies for soft robot developed using Matlab Simulink; here we investigate P, PI, PD and PID types of controller. For real-time controller implementation we compare the controller responses with respect to the desired set point of operating robot. Thus, we can identify the PID controller is suitable for real-time designing the soft robot model depending upon different controlling responses and least 3.47 integrate absolute error (IAE) and 2.119 integrate square error (ISE).

1. Introduction:

Humans have often looked at biological systems for that answers are engineering problems throughout our existence. Self-assembly, Self-healing abilities, resistance, hydrophobicity, and environmental exposure tolerance etc, this type of engineering problem solving inspired by nature. This ability and knowledge of designing and building bio motivated apparatus are known as biomimicry or biomimetic [1]. The inspiration for designing of a soft robot has come from the snake and earthworm creatures. Here the designing of the soft robot is based on PET (Polyethylene terephthalate) material and SMA actuator for providing the flexible movement of robot body [2].The mechanisms of traditional rigid-body consist of stiff links coupled at movable joints, but in a dynamic environment, they may not survive. Thus, flexible mechanism helps to change the shape and geometry of robot according to nature. However, the rigid mechanism also transfers motion, force, and energy. But the major difference is that the flexible mechanism is more advantageous than rigid one in respect to the mobility point of view. Most of the flexible mechanisms are a single body and does not encounter any frictional losses. Limbless crawling is a primary form of biological locomotion adopts by a wide selection of species, including the earthworm, snails as well as the snake. To achieve a successful peristaltic locomotion certain elements are required. Polyethylene terephthalate material used as a body of the soft robot, it also useful for longitudinal movement of the robot. At the initial stage, PET material was a hard type of material. Therefore, the training of PET segment is essential [3]. Thus, the training of PET tube is done by MS rod in a furnace. We have fixed the PET tube around the 5cm MS steel rod and put inside the furnace at 225°Ctemperatures up to 15 minutes. Therefore, the PET tube is flexible towards the longitudinal movement of the soft robot. Moreover, for radial muscle movement, the combination of normal bias spring and SMA spring are used. We have specifically used the SMA spring material; SMA shows unique properties of shape memory effect and super elasticity with the application heat energy. SMA is a material which remembers its original shape or properties. Thus, when the SMA material deformed due to the external force, it returns to its pre-defined shape due to the application of heat above its actuation temperature. Moreover, when the electric supply provided to the SMA spring, the compression of SMA spring was observed. Further, the force generated from the bias connected normal spring helped to bring the SMA to its original position [4, 5 &6]. This paper described the fabrication of peristaltic soft robot and developed the different type controller to control the directions of the soft robot by using Simulink. Here different types of controller used like proportional, proportional integral, proportional derivative, cascade PID. Each controller has their own application and advantages like Proportional (P) controller used for stabilized the gain of system response but produces steady state error because of that integral action required to reduce offset error. The Proportional integral (PI) controller used to reduce steady-state error as well as stabilize the gain of the system, but system response gets slow. To improve system response derivative action is required but in proportional derivative (PD) steady state error still present. Cascade PID controller take all advantage of proportional, integral, derivate and operated on the system, PID also type intelligent controller. To design the ideal controller for soft robot help to reach at the précised position in the least time as well as least losses.

2. Working principle:

To achieve the robotic movements, some important elements are required such as longitudinal muscle, Radial muscle and Coelom. The Table1 details the bio inspired robotics part for earthworm robot;

Table1. Bio inspired soft robotics part mechanism

Sr. No.	Peristaltic Body Part	Robot Body Part
1	Main Body	Braided mesh tube of PET material
2	Radial Muscles	NiTi actuators with bias spring
3	Longitudinal Muscles	Braided mesh tube made of PET or NiTi actuators
4	Coelom	Longitudinal, flexible, tendons
5	Brain	Arduino and Relay
6	Intelligence	Intelligent control algorithm

This investigation describes the fabrication of robot where different parts of the soft robot are detailed in above table1. Figure 1 shows the working principle of the peristaltic soft robot where the robot made by four number of segment and each segment containing two radial actuators. The electric supply provided to the first segment of a radial actuator. Thus, when the first segment compressed, the diameter gets decreased and thereafter expand in a horizontal direction [2]. Longitudinal muscle of PET tube helps to bring back the compressed segment in original position. Similarly, the operating procedure is applied to all the segments sequentially. Thus, the robot moves in forward and backward directions due to the sequential segment movement. Depend upon requirements of application we can arrange the three SMA actuator on the body of the soft robot for achieving the right, left and upward directional movement. Increases in a number of segments improve the flexibility and accuracy in the form of displacement. Figure3 shows the different way of fabrication of real time Peristaltic soft robot. The SMA spring actuator placed inside the body of the robot according to the required movement.

3. Mathematical Model:

The mathematical representation of peristaltic soft robot model [7] with all operating applicable parameter of a mechanical model as shown in below figure 4;
Where,
M_1=M_2= mass of actuator (half of SMA spring and half of PET mesh tube weight) =9.5×10^{-3}kg
K_1 and K=spring constant for 7 no. of turns and 20 no. of turns respectively=10kg/m

F= force in the form 3 Ampere current and a 5Volt voltage applied for movement
B= Friction in terms of the effect of environmental condition, kinematic friction & power losses etc.

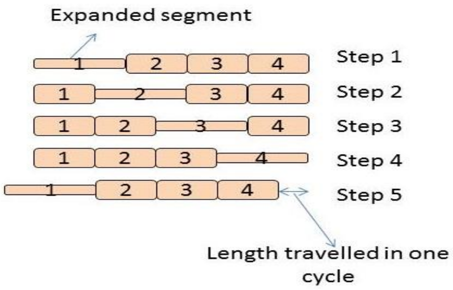

Figure1. Working principle of movement the peristaltic Soft Robot.

Figure2. Configuration of SMA and bias spring actuator for radial muscles Robot.

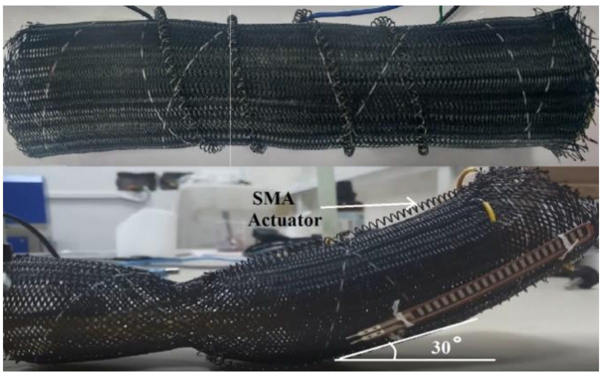

Figure3. Fabrication of real time Peristaltic soft robot model

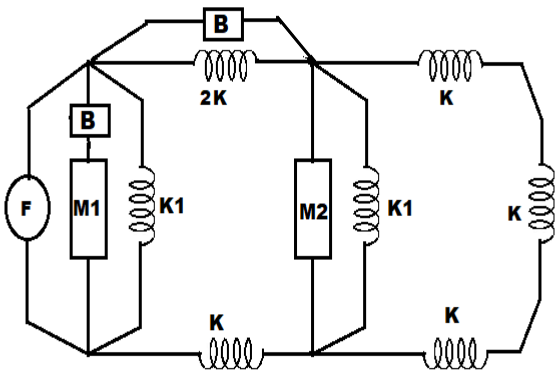

Figure4. Mechanical model of peristaltic soft robot segment

The mathematical representation above mechanical model in the form of linear differential equation and transfer function of s- domain are shown in below equations;

$$BM_1\frac{d^3x_1}{dt^3}+B\frac{d}{dt}(x_1-x_2)+k_1x_1+3k(x_1-x_2)=f \quad (1)$$

$$M_2\frac{d^2x_2}{dt^2}+B\frac{d}{dt}(x_2-x_1)+k_1x_2+3kx_2+3k(x_2-x_1)=0 \quad (2)$$

$$M_1\frac{d^2x_1}{dt^2}+B\frac{d}{dt}(x_1-x_2)+k_1x_1+2k(x_1-x_2)=f \quad (3)$$

$$M_2\frac{d^2x_2}{dt^2}+B\frac{d}{dt}(x_2-x_1)+k_1x_2+2kx_2+2k(x_2-x_1)=0 \quad (4)$$

$$T_1(s)=\frac{S^2+17S+42.5}{S^5+4S^4+16S^3+55S^2+50S+36} \quad (5)$$

$$T_2(s)=\frac{S^2+18S+40.5}{S^4+55S^3+30S^2+63S+47} \quad (6)$$

The number of segment are connected into the series because of that the overall transfer function of peristaltic soft robot model is,

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$$T(S) = \frac{S^4 + 31S^3 + 261S^2 + 1063S + 1620}{S^9 + 8S^8 + 65S^7 + 282S^6 + 1031S^5 + 2531S^4 + 4644S^3 + 5832S^2 + 4419S + 1620} \quad (7)$$

4. Controller Designing:

Designed soft robot model is nonlinear type system. Thus, we required to developing a nonlinear controller which will control the model. The designed controllers will subsequently reduce the delay time in process monitoring and command in the mesh worm to drive in the desired trajectory and it works earlier it will be highly effective in terms of energy saving capabilities [8]. Here we implement a different controller for soft robot model in matlab Simulink, response of soft robot model which help to identify the better controller to implement in real-time system with hardware of soft robot model [9].

4.1. PID controller:

Each controller has its own application and advantages. The P controller used for stabilized the gain of system response but produces steady-state error because of that integral action required to reduce offset error. The PI controller used to reduce steady-state error as well as stabilize the gain of the system. However, the system response gets slow. To improve the system response, a derivative action is required. In the cascade PID controller, each controller responses are performs separately, because of that we get all controller advantages. Moreover, an ideal controller designing for the soft robot we have to compare the controller output responses, Integral absolute errors (IAE), and integral square errors (ISE). The basic block diagram of PID controller block diagram is shown in figure 4. The parameters of PID controller are calculated with the help of Ziegler- Nichol's method [10 &11]. The block diagram of cascade PID controller shown in below Figure 5 and its basic differential equation is,

$$u(t) = k_p e(t) + k_i \int_0^t e(\tau)d\tau + k_d \frac{d}{dt}e(t) \quad (8)$$

By using the Z-N method the standard parameter of PID controller, from below table2 and a table3 parameter of PID used to find out different controller responses of the system.

Table2. Standard value of controller by Z-N method

Controller	$K_p = 0.6K_{cr}$	$K_i = 1/T_i = 1/0.5P_{cr}$	$K_d = T_d = 0.125P_{cr}$
P	1	0	0
PI	1	0.9242	0
PD	1	0	0.72
PID	1	0.9242	0.72

Table3. Tuned value of controller by Z-N method [12]

Controller	K_p	K_i	K_d
P	1.1621	0	0
PI	0.01825	0.2134	0
PD	1.04421	0	0
PID	0.2477	0.3081	0

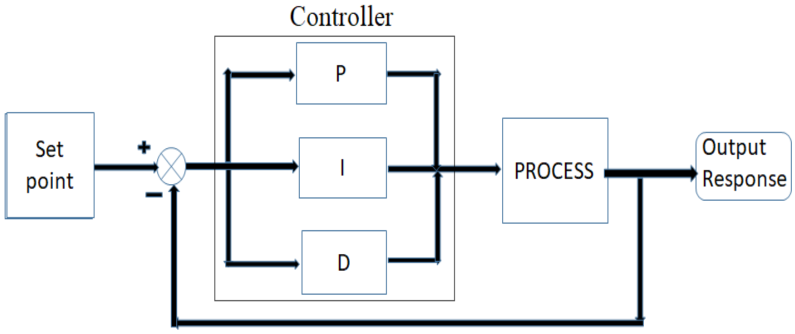

Figure5. Block diagram of cascade PID controller

5. Result and discussion:

Based on the mathematical model of the soft robot, we have investigated the controller which will perform better than the other controllers. By tuning the parameters of PID controller we have calculated different type error in the form area under the response like an ISE and IAE etc. Table 4 and table 5 show the ISE and IAE for standard PID Z-N parameter and tuned PID parameter. Based on the observation from both table, tuned PID parameters gives the best performance. It is also observed that cascade PID controller encounter less error which provides a great support towards the controller design in real time. Based on the analysis of the data (table 4 and table 5), we can conclude that cascade PID controller with tuned parameter generates less error and provides the value near to desired set point. Also, we observed that standard Z-N integral parameter is not suitable for the system because it covers a large amount of error area [1].

Table4. IAE and ISE of standard parameter

Controller	P	PI	PD	PID	Without Controller
IAE	10.62	24.64	10.29	3.826	12.62
ISE	6.552	39.98	7.19	2.474	7.556

Table5. IAE and ISE of tuned parameter

Controller	P	PI	PD	PID	Without Controller
IAE	9.878	3.474	10.29	3.47	12.62
ISE	6.36	2.73	6.364	2.119	7.556

Figure 6 shows the comparisons of different controller responses to the desired set point. Here we have assumed that the value of the desired set point is 1. Accordingly, all controllers try to get settled into the system at a desired point. Therefore, we can control the real-time system at a required desired location for movement of the soft robot. We already mentioned that depending upon the different movement the SMA actuator fabricated or embedded on a soft robot body. Figure 3 shows the real-time fabrication, which inclined 30 degrees from the ground with the help of top mounted SMA actuator on a tube. However, we can check the performance of robot according to the requirement through simulation before implementation or interfacing with hardware. Similarly, figure 7 shows the comparisons of different controller responses for tuner PID parameter. We can observe from table 5 and figure 7, those tuned PID parameters show improved system control comparing to the standard PID. Figure 7 shows all the responses are trying to reach closer to the desired set point in less error area. Such type of accuracy in controller help to performed desired operation. It is observed that cascade PID controller provide better control response in comparison to the other controller responses.

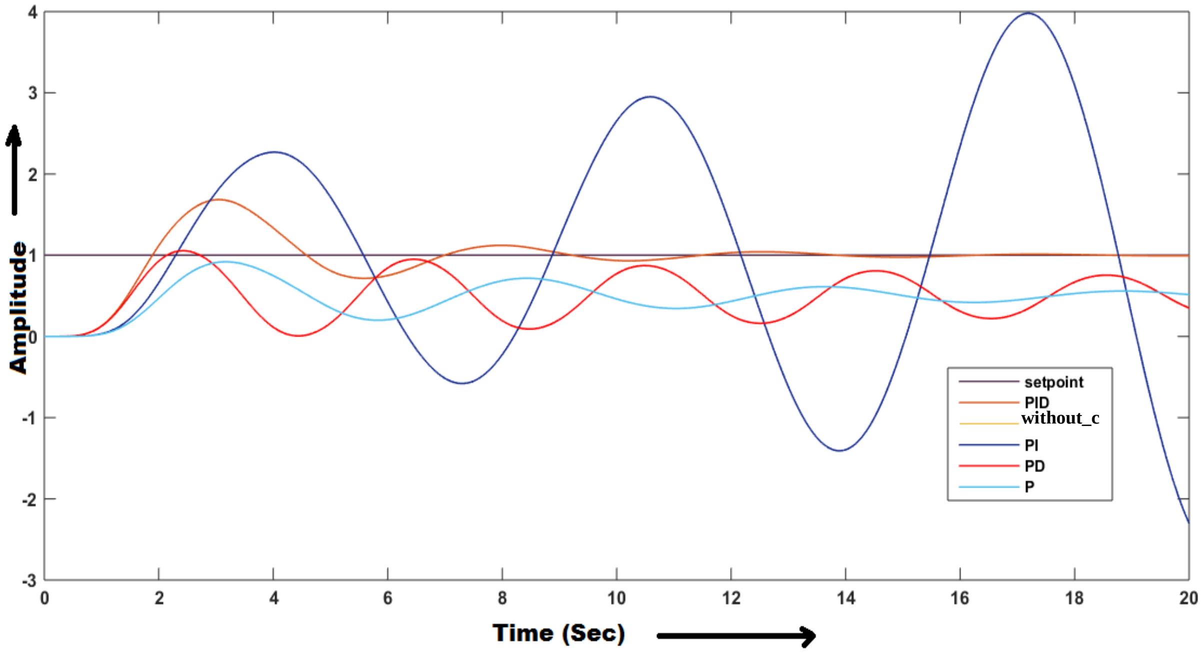

Figure6. Comparisons step response of different controller for standard parameter

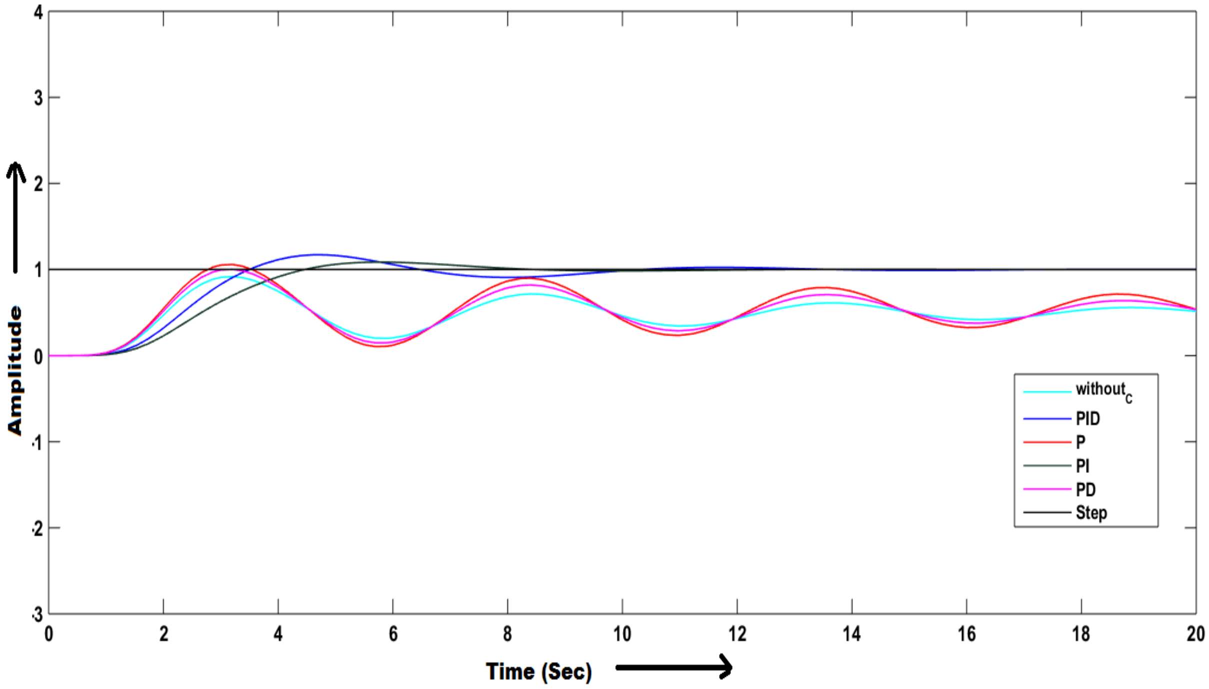

Figure7. Comparisons step response of different controller for tuned parameter

6. Conclusion:

This paper described the fabrication and development of different type PET material soft robot model with SMA actuator and bias spring actuator. We have also investigated the control strategies with the help of real-time mathematical model in Matlab Simulink. From the different controlling response, we identified cascade PID controller response provide better control towards the desired set point of the soft robot. Accordingly, depend upon the requirement of the multi-directional movement of soft robot

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we can easily change the desired position. The comparison of different controller response at a desired position for standard and tuned PID parameter was observed in figure 6 and figure 7. In cascade PID controller, we get steady-state response in minimum time and reduce the overshoot as well as an error of the system at desired position comparing to P, PI, PD and without a controller of the original system for a tuned parameter. From table 4 and table 5, the error (like IAE and ISE) comparisons between standard and tuned PID controller is clearly visible. Cascade PID controller provides less 3.47 IAE, 2.119 ISE and better controlled at desired position comparing to other controllers for tuned parameter [1]. With the help of this controller strategy, we can easily and accurately move the soft robot in different directions, like an example 20° left, 30° right and 30° upward etc according to operator requirement.

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