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Development of Subcarangiform Bionic Robotic Fish Propelled by Shape Memory Alloy Actuators

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ABSTRACT

In this paper, a shape memory alloy (SMA) actuated subcarangiform robotic fish has been demonstrated using a spring based propulsion mechanism. The bionic robotic fish developed using SMA spring actuators and light weight 3D printed components can be employed for under water applications. The proposed SMA spring-based design without conventional motor and other rotary actuators was able to achieve two-way shape memory effect and has reproduced the subcarangiform locomotion pattern. The positional kinematic model has been developed and the dynamics of the proposed mechanism were analysed and simulated using Automated Dynamic Analysis of Mechanical Systems (ADAMS). An open loop Arduino-relay based switching control has been adopted to control the periodic actuation of the SMA spring mechanism. The undulation of caudal fin in air and water medium has been analysed. The caudal fin and posterior body of the developed fish prototype have taken part in undulation resembling subcarangiform locomotion pattern and steady swimming was achieved in water with a forward velocity of 24.5 mm/s. The proposed design is scalable, light weight and cost effective which may be suitable for underwater surveillance application.

Keywords: Bionic robotic fish; Shape memory alloy; Subcarangiform; Caudal fin

1. INTRODUCTION

Organisms that live underwater possess a natural capability to create locomotion and swim with high performance. Biomimicking such underwater creatures with the same muscle like structures is a challenge for researchers. The biological foundations of the fish swimming can be found elsewhere[1]. With the help of servo motor technology researchers have developed a number of autonomous underwater vehicles (AUV) to mimic the real fish[2-12]. However, the motor based robotic fish is bulkier and not able to generate real fish like locomotion patterns. In recent times, smart materials played an important role in robotics and evolved as an alternative actuator technology in biomimetics. The smart actuator technology includes shape memory alloy (SMA), Ionic Polymer Metal Composites (IPMC), piezoelectric, pneumatic, and Dielectric Elastomer Actuator (DEA)[13]. Shape Memory Alloy (SMA) acts as a viable actuator technology because of its nature of creating muscle-like actuation, noise less locomotion, and less power consumption[14-15]. SMA exhibit unique properties such as shape memory effect and pseudoelasticity. SMA possesses high actuation energy densities and recovers its trained shape against high loads. SMAs can exist in three different crystal structures viz. twinned martensite (low temperature phase), detwinned martensite (upon mechanical loading), and austenite (high temperature phase). Dedicated SMA design for specific application overcomes its drawbacks such as hysteresis. Recently, the SMA is used widely in biomimetics to mimic the muscle like structure of the living organism. Researchers have developed various SMA based biomimetic systems viz. robotic fish[16-21], robotic jelly fish[22], robotic inchworm[23-25], etc. The biomimetic robotic actuating mechanism can be accomplished using different forms of SMAs such as springs, wires, and plates. The SMA wire and plate can be used alone or embedded with soft composite structures. Sung-Hoon Ahn and his research group have developed SMA actuated robots such as inchworm, underwater turtle, and various SMA embedded composites actuators for functional applications[26-30]. Wang[16], *et al.* developed a micro robotic fish propelled by an SMA wire embedded biomimetic fin which imitates the structure of squid/cuttlefish fin. Gao[17], *et al.* developed a biomimetic mantle jet propeller to mimic the propulsion mechanism and body shape of the real cuttlefish. The cuttlefish mantle contraction was mimicked using SMA wires embedded into silica gel in mantle shape along the annular direction. Zhang[19], *et al.* has demonstrated a light weight bioinspired flexible SMA pectoral fin formed by SMA fin rays capable of two-DoFs oscillation. Mao[20], *et al.* presented a star fish like a soft robot with flexible rays and implemented multi-gait locomotion using SMA actuators whereas the soft robot body was constructed using 3D printing technology. Yan[21], *et al.* proposed a novel design of a flexible pectoral fin based on an SMA plate capable of performing 3D motion.

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In conventional motor-based actuation, the motor is used to undulate the last one third portions of the body and caudal fin. Here, the SMA spring is chosen as an actuating mechanism to undulate the posterior body and the fin because of its simplicity, high stroke length, and the ability to exert more compressive force during actuation[30]. To the best of author's knowledge, SMA spring based caudal fin propulsion for robotic fish has not been reported. SMA spring switches between low temperature martensite phase and high temperature austenite phase when subjected to thermal stimulation. The thermal stimulation in the form of hot water, Joule heating, and laser-based can be used for actuating the SMA elements[31-33]. However, electrical actuation or Joule heating is a simple and efficient technique for recovering the induced linear strain of a SMA spring and the actuation can be controlled effectively by varying the input current.

In this work, the main focus is to undulate the caudal fin and posterior body using a SMA spring-based mechanism and to achieve forward swimming. The design comprises of three pairs of SMA springs connecting the joints on each side. The body of the fish is made of light weight 3D printed parts driven by SMA spring arrangement. An open loop ON/OFF relay-based control was adopted to control the motion of the sequential spring arrangement and which in turn controls the fish locomotion. Preliminary studies were performed on a single SMA spring to understand the thermo-mechanical behaviour in both air and water. To visualise the dynamics of the proposed design, the SMA based spring mechanism has been simulated using ADAMS. A planar positional kinematic model of the proposed robotic fish was derived using Denavit-Hartenberg (DH) parameters. The variation of caudal fin angle during oscillation was measured on air and underwater. Finally, the forward swimming of the developed robotic fish has been demonstrated.

2. DESIGN AND FABRICATION OF THE PROPOSED FISH

The commercially available Nickel Titanium (NiTi) SMA springs from Dynalloy Inc was used for the study. The specifications and properties of NiTi spring is shown Table 1. The phase transformation temperature was identified using differential scanning calorimetry (DSC). Figure 1 shows the DSC curve of the SMA spring. The martensite and austenite temperatures are M_s=31° C , M_f = -23 °C, A_s = -25 °C and A_f = 35 °C respectively.

Table 1. Specification and properties of the SMA spring

Parameters	Value
Solid length	13.86 mm
Number of turns	18
Wire diameter	0.77 mm
Coil diameter	5.69 mm
Ni (weight %)	55
Ti (weight %)	45

The schematic of proposed propulsion for subcarangiform locomotion using SMA spring arrangement is shown in Figs. 2(a) and 2(b). Three pairs of NiTi SMA Springs were arranged sequentially between O-ring joints on both sides. Individual SMA springs were fixed between the rib joints with an induced strain and thereby detwinning of the low temperature martensite phase will be achieved. The flexible caudal fin made from a UV cured photopolymer was attached to the rear end of the body. Initially, the springs on the right side will be actuated through Joule heating which compresses

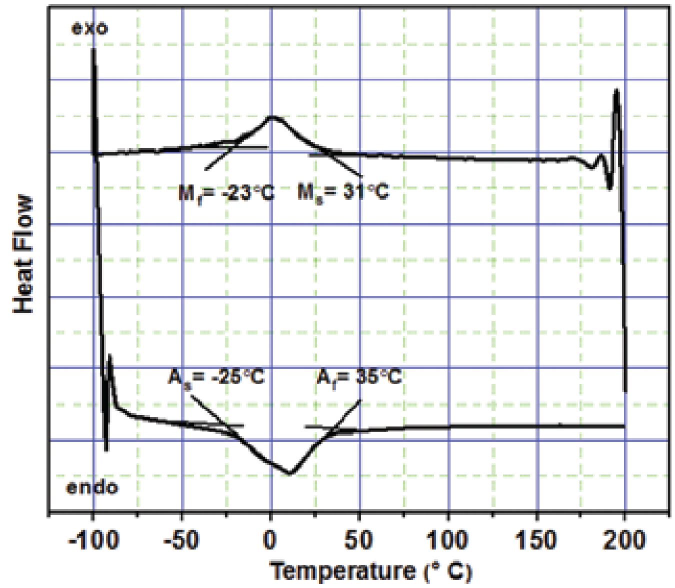

Figure 1. DSC curve of SMA spring.

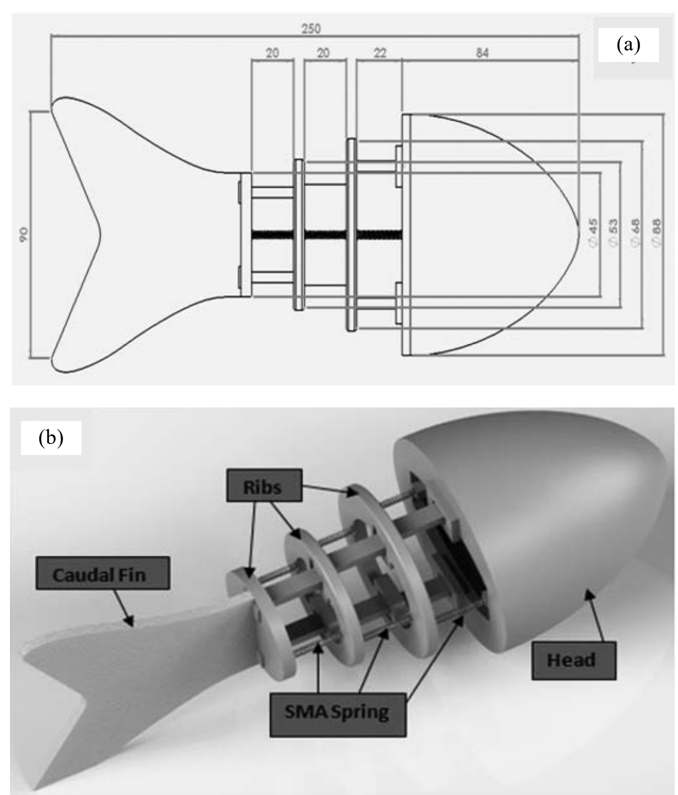

Figure 2. (a) Configuration of the proposed bionic robotic fish in mm and (b) Skeletal structure of the proposed bionic robotic fish.

the springs and transforms to high temperature austenite phase. This actuation enables the fin to oscillate in one direction. Then the springs on the left side will be actuated and thus the two-way oscillation of the fin will be achieved. The SMA spring actuation in the left side will induce a pull force to the right side i.e. the right side SMA spring which is in twinned martensite state will get transformed into detwinned martensitic state with the help of the pull force provided by the actuation of left side SMA spring.

The heating/cooling actuation cycle of the SMA springs was controlled via Arduino-relay based switching control. The actuation of the SMA springs on either side one after another enables the fin to oscillate and eventually undulate the posterior body of the fish. Initially, few spring designs have been evaluated to verify the functioning of the proposed mechanism. Based on the trails, and improved skeleton model was fabricated as shown in Fig. 3.

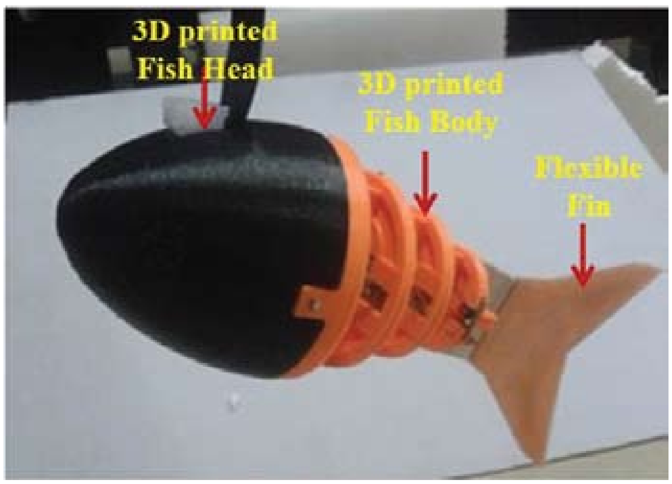

Figure 3. Fabricated bionic robotic fish.

3. KINEMATICS MODELLING AND SIMULATION

To describe the kinematic analysis, a planar positional kinematic model for the proposed bionic robotic fish was obtained. The kinematic model frame diagram for the proposed fish is shown in Fig. 4.

The generalised homogeneous transformation matrix is as follows. The transformation matrix is a function of all joint variables.

$$ {}^{i-1}_{\;\;i}T = \begin{bmatrix} C\theta_i & -S\theta_i & 0 & \alpha_{i-1} \\ S\theta_i C\alpha_{i-1} & C\theta_i C\alpha_{i-1} & -S\alpha_{i-1} & -S\alpha_{i-1} d_i \\ S\theta_i S\alpha_{i-1} & C\theta_i S\alpha_{i-1} & -C\alpha_{i-1} & -C\alpha_{i-1} d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

The Denavit Hartenberg (DH) parameters for the proposed fish were obtained from the frame diagram. A frame can be used as a description of one coordinate system relative to another which represents both position and orientation. Each link can be kinematically described by 4 quantities viz. 2 describe the link itself and the other two describe the link's connection to the neighboring link. Table 2 shows the DH parameters for the proposed fish from Fish head $\{H\}$ to the center of mass position of the fish caudal fin $\{F\}$. The individual homogeneous transformation matrices are obtained from the DH Table. The number of independent kinematic parameters are θ_1, θ_2 and θ_3. From the values of the link and joint parameters, the individual link-transformation matrices are computed. Then, the individual homogeneous matrices were multiplied to get the final homogeneous transformation matrix.

$$ T = \begin{bmatrix} C(\theta_1+\theta_2+\theta_3) & -S(\theta_1+\theta_2+\theta_3) & 0 & L_1C(\theta_1)+L_2C(\theta_1+\theta_2)+L_3C(\theta_1+\theta_2+\theta_3)+L_{fc}C(\theta_1+\theta_2+\theta_3) \\ S(\theta_1+\theta_2+\theta_3) & C(\theta_1+\theta_2+\theta_3) & 0 & L_1S(\theta_1)+L_2S(\theta_1+\theta_2)+L_3S(\theta_1+\theta_2+\theta_3)+L_{fc}S(\theta_1+\theta_2+\theta_3) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

Table 2. DH parameter table

i	α_{i-1}	α_{i-1}	d_i	θ_i
1	0	0	0	θ_1
2	0	L_1	0	θ_2
3	0	L_2	0	θ_3
4	0	L_3	0	0
5	0	L_{fc}	0	0

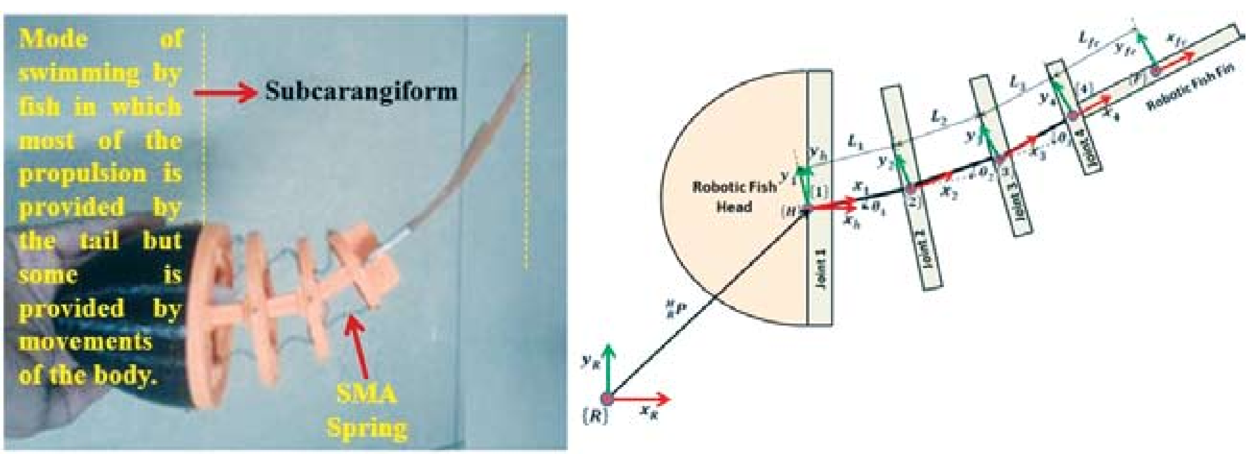

Figure 4. Planar configuration for the proposed bionic robotic fish.

The planar positional kinematic model of the proposed fish at the centre of mass position of the caudal fin $\{F\}$ from the fish head $\{H\}$.

$$x_{fc} = L_1C(\theta_1) + L_2C(\theta_1+\theta_2) + L_3C(\theta_1+\theta_2+\theta_3) + L_{fc}C(\theta_1+\theta_2+\theta_3)$$

$$y_{fc} = L_1S(\theta_1) + L_2S(\theta_1+\theta_2) + L_3S(\theta_1+\theta_2+\theta_3) + L_{fc}S(\theta_1+\theta_2+\theta_3)$$

To get the transformation from the reference $\{R\}$, the final transformation matrix T is multiplied for the position vector ${}^{H}_{R}P$. In order to visualise the dynamic motion of the proposed model and fish fin oscillating mechanism in air medium, a simulation was performed with ADAMS. The proposed fish model was developed in solid works and then imported into ADAMS for performing the dynamic simulation.

The SMA spring design was developed using an inbuilt spring force function. All joints were considered as revolute joints for the simulation. The tail was fixed with respect to the last joint to hold it in position and the fish head was considered as fixed. To create the fish fin like oscillation each spring was provided with external periodic force in compressive direction. The force was decided with the preliminary load study conducted on the individual SMA spring. The forces considered for the simulation were 0.01 N, 0.02 N, and 0.03 N. The force less than 0.01 N would not be able to actuate the fish as it cannot overcome the inertial resistance, whereas the force more than 0.03 N would be redundant due to geometrical constraints. This was confirmed by the analysis as the simulation showed negligible motion at a force less than 0.01N and unstable motion if the force applied exceeded 0.03 N. The spring stiffness coefficient was taken to be 3 Kg/s^{-2} while the damping coefficient was taken to be 1 Kg/s. A series of simulations were performed to get the dynamic behaviour of the bionic robotic fish for different force parameters.

The fish was assumed to actuate without cover and surrounding water for this analysis in order to get a better insight into the motion of the proposed SMA based mechanism. Through ADAMS analysis the fish fin oscillation was visualised at a frequency of 0.1 and 0.5 Hz. The simulated tail oscillation for the proposed SMA spring-based mechanism is shown in Fig. 5(a). The fin displacement with respect to the time was plotted and shown in Fig. 5(b).

The displacement was periodic like a sine wave which showed the proper fin oscillation. This can be observed in the displacement curves near the middle position of the fin. The data depicted the presence of symmetry which plays a vital role in the actuation of SMA springs. From the simulation, it was confirmed that the proposed design could produce a smooth fish fin like oscillation which can be further investigated in real-time experimentation.

4. REAL-TIME EXPERIMENTATION

The entire fish body was fabricated using 3D printed acrylonitrile butadiene styrene (ABS). To investigate the performance of final 3D printed SMA spring based bionic robotic fish, we conducted a set of experiments both in air and underwater. The fin displacement and maximum angle during the actuation were the key factors evaluated from the experiments. The overall weight and length of the fish without battery and electronic control board were 416 grams and 25 cm respectively. Figure 6 shows the experimental setup of the proposed bionic robotic fish at water channels.

The actuation behaviour of SMA depends on input power and ambience. Here, the input current affects the rate of actuation of SMA spring and water temperature affects the cooling rate. This input current and water temperature have influence on the undulation of the bionic robotic fish. In air medium, experimentation was conducted with an input current of 3 A at which the proper undulation resembling the subcarangiform fish has been obtained. However, the proper undulation under water has been obtained at an input current of 10 A. The input current required for proper undulation has increased due to the increased heat transfer and pressure conditions experienced by the robotic fish under water. Using an infrared thermometer, the water temperature in the tank was found to be 24 °C. A

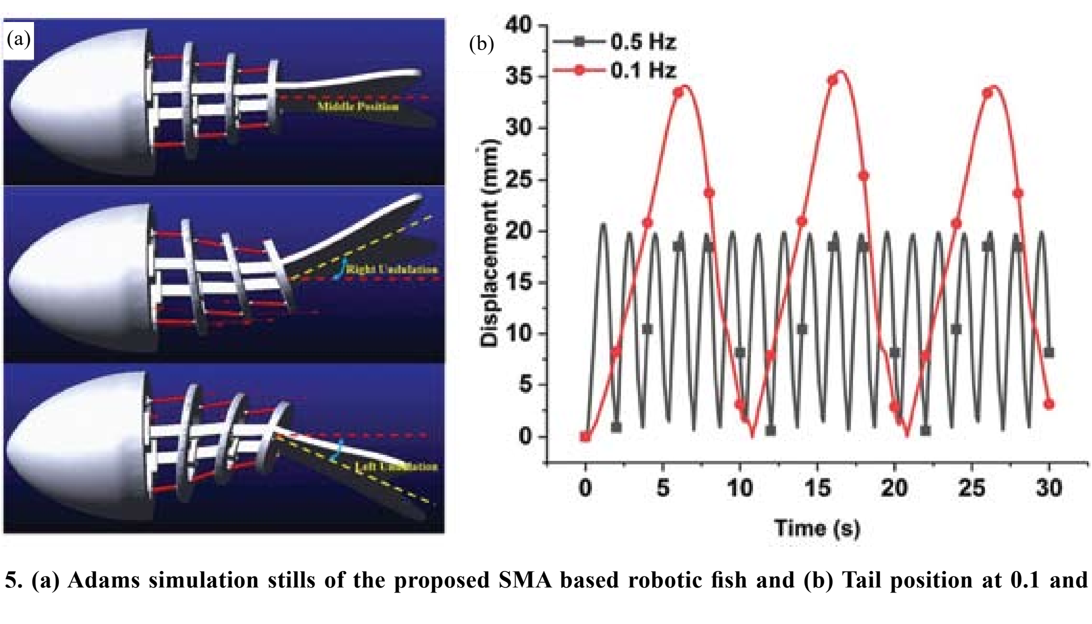

Figure 5. (a) Adams simulation stills of the proposed SMA based robotic fish and (b) Tail position at 0.1 and 0.5 Hz.

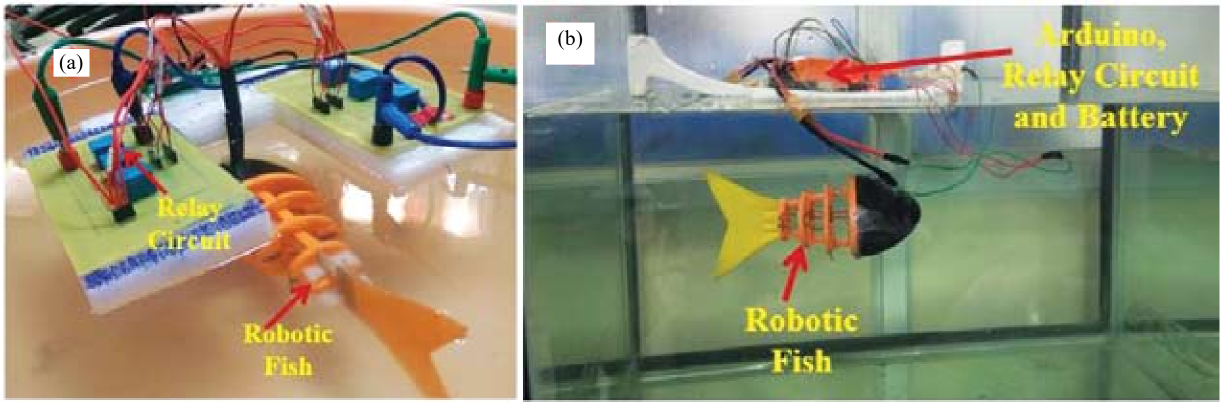

Figure 6. Experimentation of the proposed bionic robotic fish at water channels.

laser displacement sensor was placed perpendicular to the fish fin to measure the fin displacement during the undulation. The measured displacement with respect to time is plotted in Fig. 7(a). The schematic of displacement measurement is shown in Fig. 7(b). The graph shows that the proposed SMA based mechanism generated an undulatory motion like a fish.

To know the maximum amplitude during the oscillation of the proposed design, the angle was measured manually using a protractor.

The maximum angle was measured on both sides of the bionic robotic fish fin in air and water medium. The angle was measured with actuating single spring, two springs together, and three springs together on both sides. In the air medium, a maximum angle of 51° on the right side and 50° on the left side was achieved. Whereas in the water medium, a maximum angle of 50° on the right side and 49° on the left side was attained. The measured angle in both air and water with one spring, two springs, and three springs were plotted and shown in Fig. 8(a) and 8(c). Figure 8(b) shows the schematic of the maximum angle measurement. The forward swimming of the proposed bionic robotic fish using the SMA based caudal fin actuation mechanism is shown as a sequence of images in Fig. 9.

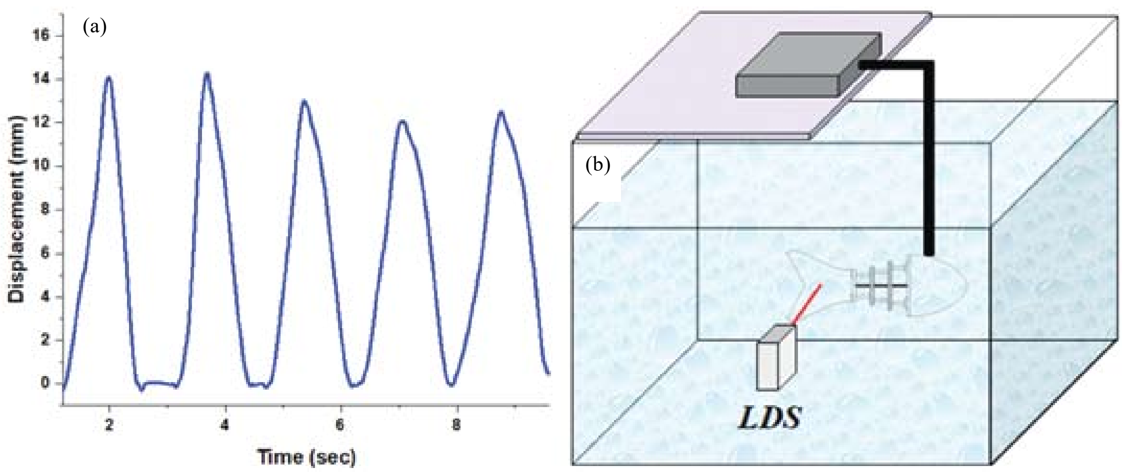

Figure 7. (a) Displacement curve plotted using laser displacement sensor and (b) Experimental setup for displacement measurement.

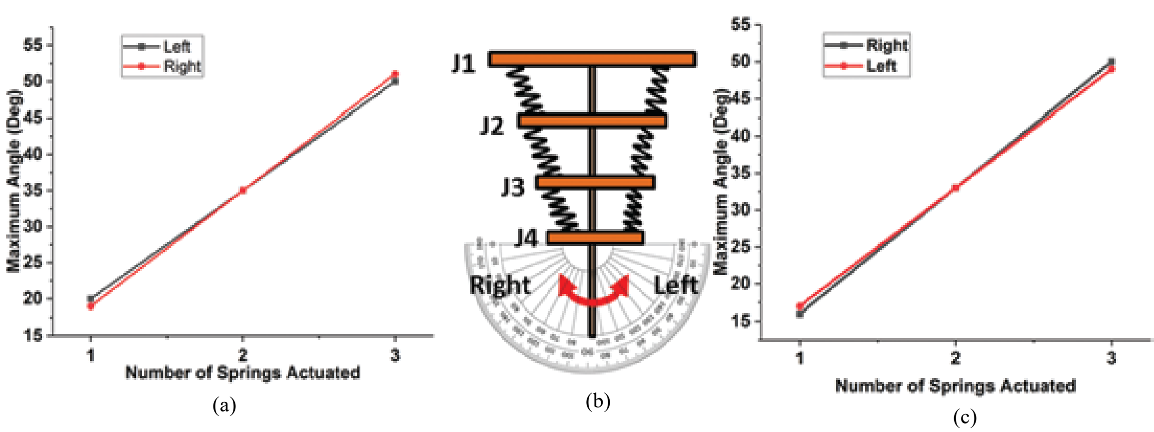

Figure 8. (a) Maximum angle (Amplitude) measurement in air, (b) Schematic of the angle measurement, and (c) Maximum angle (Amplitude) measurement in water.

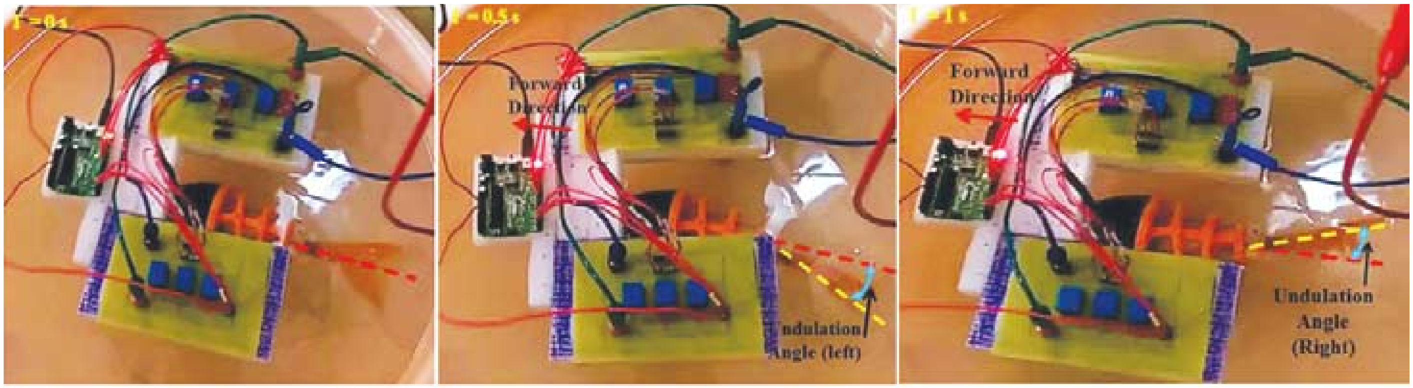

Figure 9. Forward swimming demonstration of the proposed robotic fish.

The force produced by SMA springs during fin oscillation was measured using a load cell arrangement in the air medium. A maximum force of 0.39 N was observed during the measurement. It can be noted that over a period of time, the force was reduced and becomes constant (the SMA springs reach its high temperature austenite phase). The measured force data was plotted and showed in Fig. 10.

The caudal fin oscillation was performed by actuating the SMA springs in a sequence one after another in both the sides which bends the posterior fish body expect fish head results in steady forward motion. The sequence of operation of SMA spring created a bending motion of the fish body except for the fish head and oscillated the tail, resulted in steady forward locomotion with a forward velocity of 24.5 mm/s. The swimming performance can be improved by increasing the actuation frequency which is mainly restricted by the hysteresis of SMA spring.

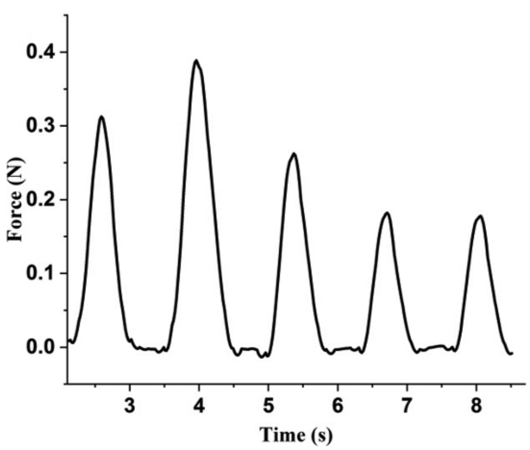

Figure 10. Force produced by the proposed SMA mechanism.

According to the momentum theorem, when fish swim by pushing water away behind them, momentum is transferred from the fish to the surrounding water, and thrust is generated. Other kinds of forces acting on a swimming fish are drag, weight, buoyancy, and hydrodynamic lift in the vertical direction[34]. Aspect ratio, Reynolds number, reduced frequency, and Strouhal number have an important role in the thrust and propulsive efficiency of a caudal fin actuator. Table 3 shows the critical design parameters and its corresponding obtained values for the proposed bionic robotic fish.

For adult fish swimming, lift, acceleration reaction and pressure drag can contribute to thrust generation when the Reynolds number ranges between 10^3 to 10^5 [36]. The Reynolds number for the proposed bionic robotic fish is 6110 which lies between the range. The Strouhal number obtained for the proposed bionic robotic fish is 0.217 which is near optimal for thrust development in oscillation. The implementation of an onboard PCB based electronic control circuit and battery may be considered for future work.

5. CONCLUSION

In this paper, the design and initial experiments of a bioinspired SMA based propulsion method for subcarangiform robotic fish were successfully developed and tested underwater. The maximum amplitude angle during oscillation in both sides was observed. The developed bionic robotic fish achieved forward swimming at a velocity of 24.5 mm/s. Force produced during the fin oscillation was measured and the maximum force of 0.39 N was attained.

Table 3. Critical design parameters for robotic fish[34-36]

Critical design parameters	Formula	Nomenclature	Value for the proposed model
Aspect ratio (AR)	$AR = b^2 / S_c$	b = cadual fin span S_c = cadual fin surface area	1.889
Reynolds number (R_e)	$R_e = L_F U / \upsilon$	L_F = Characteristic length (m) of the fish U= average forward velocity (m/s) υ= kinematic viscosity of water (m^2/s^{-1})	6110
Reduced frequency (σ)	$\sigma = 2\pi f L_A / U$	F = tail beating frequency (Hz) L_A =Characteritic length (m) of the actuating system	21.39
Strouhal number (S_t)	$S_t = fA / U$	$A = A$ is the wake width (m) (usually approximated as the tailbeat tip to tip amplitude)	0.217

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