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Modeling and Simulation of Robot Fish

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ABSTRACT

Fish are the best swimmers of the sea. The use of flexible tail movements is for good swimmers, for fast swimming and sudden swapping movements. This resulted in fish inspirations in the design of underwater vehicles.In this study, it is aimed to imitate four degrees of freedom (DOF) of the structure of the carangiform fish that is based on the results of previous studies. The equations of the motion of the carangiform type carp fish robot are obtained to simulate angle values required for the robot fish swimming using Matlab/Simulink/SimMechanics software. While determining the backbone structure of the robot fish, four joints are designed considering the dimensions of real carp fish and, also the joints are placed in positions where the robot fish can best mimic the movement of the tail. Moreover three actuators are located to body for advancement, rotation and sinking movements. Modeling and simulations results of the proposed research are given in figures and important findings are realized for future control studies in terms of the modeling approaches.

Keywords*—Carangiform type, carp fish robot, 4 degrees of freedom, modeling, simulation.*

I. INTRODUCTION

Living creatures in nature have adapted very well to their environment. Designers noticed this and started to design by examining the living things in the places where their designs would be used. This design method is called biomimetic design. Biomimetic design is used today in robot technology, aircraft technology and many fields. In this study, a robot fish is designed according to the body size of a fish by using biomimetic design. The reason for choosing fish in this design is that the fish can swim fast in the water and have sudden maneuverability. The forward and rotational movement of the fish is provided by the tail movements of the fish. It provides the sinking and rising movement with air sacs. In this study, the sinking and rising movement was achieved with the help of fins placed next to the fish.

Robot fish studies first started in the 1990s. These studies were initially carried out on a large scale. In the studies, new designs were created by examining the hydrodynamic structure of fish. One of these designs is the eight-joint RoboTuna, developed by MIT in 1994 [1]. In this research, by examining the hydrodynamic structure of the fish, a design has been made in accordance with the dimensions of the real tuna with eight joints in a way that its movement resembles the movement of the fish. Designs that work with a hydraulic drive system have also been made. One of these designs has produced a robot fish called VCUUV, which looks like a Thunniform fish, designed by the Drapper Laboratory [2].This design is a world first as a hydraulic driven design and, itsdimensions are 2.4m long and weigh 173kg. A robot lampreywhich aimed to provide mine countermeasures,was produced by applying shape memory alloy (SMA) by Northwestern University[3]. In Japan, Nagoya University developed a micro robotic fish using ICPF Actuators[4], while Tokai University produced a robot Blackbass[5] in order to research the propulsion characteristics of pectoral fins. The National Maritime Research Institute in Japan developed many kinds of robotic fish prototypes ranging from PF300 to PPF-09[6] to exploit up-down and effective swimming characteristics of fish. Mitsubishi Heavy Industries built a robot fish named coelacanth robot[7]. In China, Beihang University (BUAA) developed three kinds of robot fish[8] and the Institute of Automation Chinese Academy of Sciences (CASIA) made progress in developing four-joint robot fish[9]. Liu and Hu [10],presented a 3D simulator used for studying the motion control and autonomous navigation of roboticfish. The simulator’s system structure and computation flow are presented and simplified kinematics and hydrodynamicsmodels for a virtual robotic fish are obtained.Their experimental results showed that the simulator provides a realistic and convenient way to develop autonomous navigation algorithms for robotic fish.

Korkmaz[11], developed a carangiform type biomimetic robotic fish prototype with two-link flexible tail mechanism, which has three dimensional autonomous swimming ability and, intelligent control of three-dimensional motion of the robotic fish wasrealized with the proposed biomimetic control structure. In this PhD thesis, in order to carry out simulation studies and design control algorithms, three-dimensional 6 Degrees of Freedom (DoF) nonlinear mathematical model of the robotic fish was obtained. Also lagrange method was used to obtain this model and hydrodynamic forces acting on the tail were calculated to derive the realistic effects of water for the design procedure of the robotic fish prototype, morphological characteristics of a real Carangiform carp fish was adapted. Moreover Central Pattern Generator (CPG) model inspired by the spinal cord neurons of Lamprey was applied to perform locomotion control of the robotic fish. The neural Lamprey CPG model was composed of unidirectional and chain linked oscillator series. Rhythmic, oscillatory and sinusoidal output signals were obtained with this model to drive servo motors of the tail. A sensory feedback mechanism based on Lamprey neuron and two different fuzzy controllers were established to achieve the closed loop control structure of the robotic fish and Central Nervous System (CNS) was developed. In order to validate the proposed methods, open and closed loop analyzes of robotic fish prototype were performed both in the simulation environment and experimental pool. In the open loop experiments, forward and turning motions of the prototype were analyzed and characteristic features of the robotic fish were determined. In the closed loop experiments, controls of the yaw angle, autonomous swimming avoiding the obstacles and yaw angle avoiding the obstacles were performed. Thus, sensory feedback closed loop forward and turning motion controls were achieved depending on the characteristic features of the robotic fish. In addition, pitch angle was controlled to provide up/down motions with center of gravity control mechanism of the robotic fish. The effectiveness and performance of the three dimensional motions of the designed robotic fish prototype were shown with the simulation and experimental studies and very successful results have been achieved.

In scope of this work, a robot fish with four joints is designed, inspired by the carangiform fish. The size of the robot fish is decided by determining the carp fish, a type of carangiform fish. Three actuators are used for the swinging motion of the robot fish tail. Robot fish model is created using both Lagrange formulation and rigid body dynamics approach of Matlab/Sim Mechanics software. Also these models are combined to simulate robot fish movements. The content of the article is constituted in that: Section II includes dynamic modeling. Section III describes results and discussion. Finally, conclusion part of the paper is presented in Section IV.

II. DYNAMIC MODELING

Previous studies are examined while determining the backbone structure of the fish. As a result of these studies, it is concluded that the movement of carangiform fish in the water would be better for the design. Therefore, carp fish, which is one of the carangiform type fish, is chosen as the model fish. Since such fish can reach 80 cm in length, so the length of the robot fish is determined as 80 cm.Spine structure of the proposed robot fish is given in Figure 1.

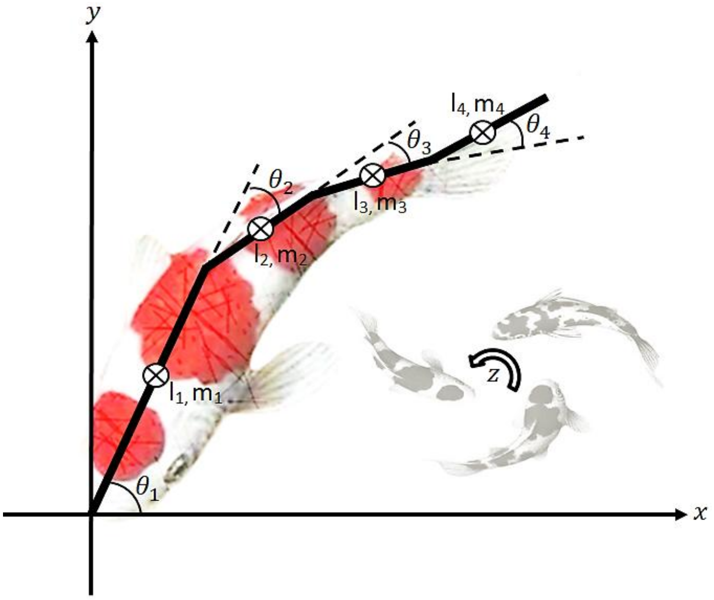


Fig. 1.Spine structure of the robot fish.

In this study, the equationsof the motion of the robot fish whose backbone structure isdetermined, are obtained using the Lagrange formulation with kinetic and potential energies given in Equation (1)

$$\frac{d}{dt}\left(\frac{\partial E_k}{\partial \dot{q}_i}-\frac{\partial E_p}{\partial \dot{q}_i}\right)-\frac{\partial E_k}{\partial q_i}+\frac{\partial E_p}{\partial q_i}=Q_i \quad (1)$$

Whereq$_i$is generalizedcoordinatesandQ$_i$ is generalizedforces. Positionsaredeterminedaccordingtothenose of thefish. Thevelocities of thepositionsarefoundbytakingthefirstderivativeswithrespectto time.

Positions and velocities of the first limb in the x and y axes are given as follows:

$$X_1 = a_1 * \cos\theta_1 \text{and} \dot{X}_1 = -a_1 * \dot{\theta}_1 * \sin\theta_1 \quad (2)$$

$$\dot{Y}_1 = -a_1 * \dot{\theta}_1 * \sin\theta_1 \text{and} \dot{Y}_1 = -a_1 * \dot{\theta}_1 * \sin\theta_1 \quad (3)$$

Positions and velocities of the second limb in the x and y axes are given as follows:

$$X_2 = L_1 * \cos\theta_1 + a_2 * \cos(\theta_1+\theta_2) \text{and} \dot{X}_2 = -L_1 * \dot{\theta}_1 * \sin\theta_1 - a_2 * \left(\dot{\theta}_1+\dot{\theta}_2\right) * \sin(\theta_1+\theta_2) \quad (4)$$

$$Y_2 = L_1 * \sin\theta_1 + a_2 * \sin(\theta_1+\theta_2) \text{and} \dot{Y}_2 = L_1 * \dot{\theta}_1 * \cos\theta_1 + a_2 * \left(\dot{\theta}_1+\dot{\theta}_2\right) * \cos(\theta_1+\theta_2) \quad (5)$$

Positions and velocities of the third limb in the x and y axes are given as follows:

$$X_3 = L_1 * \cos\theta_1 + L_2 * \cos(\theta_1+\theta_2) + a_3 \cos(\theta_1+\theta_2+\theta_3) \text{and,} \quad (6)$$

$$\dot{X}_3 = -L_1 * \dot{\theta}_1 * \sin\theta_1 - L_2 * \left(\dot{\theta}_1+\dot{\theta}_2\right) * \sin(\theta_1+\theta_2) - a_3\left(\dot{\theta}_1+\dot{\theta}_2+\dot{\theta}_3\right) * \sin(\dot{\theta}_1+\dot{\theta}_2+\dot{\theta}_3) \quad (7)$$

$$Y_3 = L_1 * \sin\theta_1 + L_2 * \sin(\theta_1+\theta_2) + a_3 + \sin(\theta_1+\theta_2+\theta_3) \text{and,} \quad (8)$$

$$\dot{Y}_3 = L_1 * \dot{\theta}_1 * \cos\theta_1 + L_2 * \left(\dot{\theta}_1+\dot{\theta}_2\right) * \cos(\theta_1+\theta_2) + a_3 * \left(\dot{\theta}_1+\dot{\theta}_2+\dot{\theta}_3\right) * \cos(\theta_1+\theta_2+\theta_3) \quad (9)$$

Positions and velocities of the fourth limb in the x and y axes are given as follows:

$$X_4 = L_1 * \cos\theta_1 + L_2 * \cos(\theta_1+\theta_2) + L_3 \cos(\theta_1+\theta_2+\theta_3) + a_4 * \cos(\theta_1+\theta_2+\theta_3+\theta_4) \text{and,} \quad (10)$$

$$\dot{X}_4 = -L_1 * \dot{\theta}_1 * \sin\theta_1 - L_2 * \left(\dot{\theta}_1+\dot{\theta}_2\right) * \sin(\theta_1+\theta_2) - L_3\left(\dot{\theta}_1+\dot{\theta}_2+\dot{\theta}_3\right) * \sin(\theta_1+\theta_2+\theta_3) - a_4 * \left(\dot{\theta}_1+\dot{\theta}_2+\dot{\theta}_3+\dot{\theta}_4\right) * \sin(\theta_1+\theta_2+\theta_3+\theta_4) \quad (11)$$

$$Y_4 = L_1 * \sin\theta_1 + L_2 * \sin(\theta_1+\theta_2) + L_3 * \sin(\theta_1+\theta_2+\theta_3) + a_4 * (\theta_1+\theta_2+\theta_3+\theta_4) \quad (12)$$

$$\dot{Y}_4 = L_1 * \dot{\theta}_1 * \cos\theta_1 + L_2 * \left(\dot{\theta}_1+\dot{\theta}_2\right) * \cos(\theta_1+\theta_2) + L_3 * \left(\dot{\theta}_1+\dot{\theta}_2+\dot{\theta}_3\right) * \cos(\theta_1+\theta_2+\theta_3) + a_4 + \left(\dot{\theta}_1+\dot{\theta}_2+\dot{\theta}_3+\dot{\theta}_4\right) * \cos(\theta_1+\theta_2+\theta_3+\theta_4) \quad (13)$$

As a result of the examination of previous studies [11], hydrodynamic forces acting on the tail finare given in Figure 2.

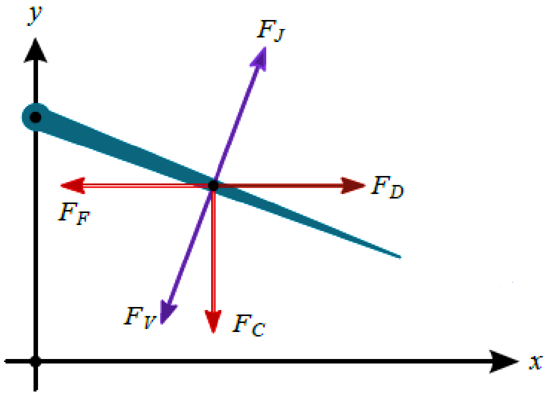


Fig. 2.Forcesacting on a limb of a fish.

Where $F_D$representsthedragforce, F_V is theaccelerationforce, F_J is thebuoyancyforce, F_F is theresultantforce on the x-axisand, F_C is theresultantforce on the y axis.

$$F_V = \left(\pi * \rho * L * C^2 * \dot{U} * \sin\alpha\right) + \left(\pi * \rho * L * C^2 * U * \dot{\alpha} * \cos\alpha\right) \qquad (13)$$

Whereρ is thedensity of thefluidand α is theangle of attack of thelimb, U is therelativeflow rate, L and C aretheverticallength of thetailfinandhalfthelaterallength,respectively.

$$F_J = (2 * \pi * \rho * L * C^2 * U * \sin\alpha * \cos\alpha) \qquad (14)$$

$$F_F = \left(F_V - F_J\right) * \sin(360 - \textstyle\sum_{i=1}^{N} \theta_1) \qquad (15)$$

$$F_C = \left(F_V - F_J\right) * \cos(360 - \textstyle\sum_{i=1}^{N} \theta_i) \qquad (16)$$

Theequationforthetailmovements of therobot fish is obtainedandtheequations of themotionforeachlimbaregiven as follows, respectively.

$$\begin{aligned}
&\ddot{\theta}_1 = \Big[F_C l - F_F l \theta_1 - \tfrac{\theta_1 \dot{\theta}_1{}^2 c}{2} - \tfrac{c}{2}\ddot{\theta}_2\left(4\theta_1\theta_2 + \theta_1{}^2 + 3\theta_2{}^2 + 3\right) - \tfrac{c}{2}\dot{\theta}_2\left(4\theta_1\dot{\theta}_2 + 2\theta_2\dot{\theta}_2 + 4\dot{\theta}_1\theta_2 + 6\theta_1\dot{\theta}_1\right) - \\
&\tfrac{c}{2}\dot{\theta}_1\left(6\theta_1\dot{\theta}_2 + 2\theta_2\dot{\theta}_2 + 6\dot{\theta}_1\theta_2 + 18\theta_1\dot{\theta}_1\right) - \tfrac{50c}{4}\ddot{\theta}_2 - \tfrac{26c}{4}\ddot{\theta}_3 - \tfrac{7c}{4}\ddot{\theta}_4 + c\Big(\tfrac{5}{2}\theta_1 + \tfrac{3}{2}\theta_2 + \tfrac{1}{2}\theta_3\Big)\Big(-\tfrac{1}{2}(\theta_1 + \theta_2 + \\
&\theta_3)(\ddot{\theta}_2 + \ddot{\theta}_3) - (\theta_1 + \theta_2)\ddot{\theta}_2 - \tfrac{1}{2}\left(\dot{\theta}_1 + \dot{\theta}_2 + \dot{\theta}_3\right)^2 - \left(\dot{\theta}_1 + \dot{\theta}_2\right)^2 - \left(\left(\dot{\theta}_1\right)^2\right) + c\Big(\tfrac{7}{2}\theta_1 + \tfrac{5}{2}\theta_2 + \tfrac{3}{2}\theta_3 + \\
&\tfrac{1}{2}\theta_3\Big)\Big(-\tfrac{1}{2}(\theta_1 + \theta_2 + \theta_3 + \theta_4)(\ddot{\theta}_2 + \ddot{\theta}_3 + \ddot{\theta}_4) - (\theta_1 + \theta_2 + \theta_3)(\ddot{\theta}_2 + \ddot{\theta}_3) - (\theta_1 + \theta_2)\ddot{\theta}_2 - \tfrac{1}{2}(\dot{\theta}_1 + \dot{\theta}_2 + \dot{\theta}_3 + \\
&\dot{\theta}_4)^2 - \left(\dot{\theta}_1 + \dot{\theta}_2 + \dot{\theta}_3\right)^2 - \left(\dot{\theta}_1 + \dot{\theta}_2\right)^2 - \left(\dot{\theta}_1\right)^2\Big) - I_2\ddot{\theta}_2 - I_3\left(\ddot{\theta}_2 + \ddot{\theta}_3\right) - I_4\left(\ddot{\theta}_2 + \ddot{\theta}_3 + \ddot{\theta}_4\right) + \tfrac{c}{4}\theta_1\dot{\theta}_1{}^2 + \\
&\tfrac{c}{4}\left(\dot{\theta}_2 + 3\dot{\theta}_1\right)\Big(\theta_2\left(\dot{\theta}_1 + \dot{\theta}_2\right) + \theta_1\left(3\dot{\theta}_1 + \dot{\theta}_2\right)\Big)\Big] / \Big[\tfrac{c}{4}\left(\theta_1{}^2 + 1\right) + \tfrac{c}{2}\left(6\theta_1\theta_2 + \theta_2{}^2 + 9\theta_1{}^2 + 9\right) + \tfrac{74c}{4} + \\
&c\Big(\tfrac{5}{2}\theta_1 + \tfrac{3}{2}\theta_2 + \tfrac{1}{2}\theta_3\Big)^2 + c\Big(\tfrac{7}{2}\theta_1 + \tfrac{5}{2}\theta_2 + \tfrac{3}{2}\theta_3 + \tfrac{1}{2}\theta_3\Big)^2 + I_1 + I_2 + I_3 + I_4\Big] \qquad (17)
\end{aligned}$$

$$\ddot{\theta}_2 = \Big[F_C l - F_F l(\theta_1+\theta_2) + T_1 - \tfrac{c}{4}\dot{\theta}_2\big(2\theta_1\dot{\theta}_2 + 2\theta_2\dot{\theta}_2 + 2\dot{\theta}_1\theta_2 + 2\theta_1\dot{\theta}_1\big) - \tfrac{c}{4}\dot{\theta}_1\big(4\theta_1\dot{\theta}_2 + 2\theta_2\dot{\theta}_2 + 4\dot{\theta}_1\theta_2 + 6\theta_1\dot{\theta}_1\big) - \tfrac{50c}{4}\ddot{\theta}_1 - \tfrac{18c}{4}\ddot{\theta}_3 - \tfrac{5c}{4}\ddot{\theta}_4 + c\left(\tfrac{3}{2}\theta_1 + \tfrac{3}{2}\theta_2 + \tfrac{1}{2}\theta_3\right)\Big(-\tfrac{1}{2}(\theta_1+\theta_2+\theta_3)(\ddot{\theta}_1+\ddot{\theta}_3) - (\theta_1+\theta_2)\ddot{\theta}_1 - \tfrac{1}{2}(\dot{\theta}_1+\dot{\theta}_2+\dot{\theta}_3)^2 - (\dot{\theta}_1+\dot{\theta}_2)^2 - (\dot{\theta}_1)^2\Big) + c\left(\tfrac{5}{2}\theta_1 + \tfrac{5}{2}\theta_2 + \tfrac{3}{2}\theta_3 + \tfrac{1}{2}\theta_3\right)\Big(-\tfrac{1}{2}(\theta_1+\theta_2+\theta_3+\theta_4)(\ddot{\theta}_1+\ddot{\theta}_3+\ddot{\theta}_4) - (\theta_1+\theta_2+\theta_3)(\ddot{\theta}_1+\ddot{\theta}_3) - (\theta_1+\theta_2)\ddot{\theta}_1 - \tfrac{1}{2}(\dot{\theta}_1+\dot{\theta}_2+\dot{\theta}_3+\dot{\theta}_4)^2 - (\dot{\theta}_1+\dot{\theta}_2+\dot{\theta}_3)^2 - (\dot{\theta}_1+\dot{\theta}_2)^2 - (\dot{\theta}_1)^2\Big) - I_2\ddot{\theta}_1 - I_3(\ddot{\theta}_1+\ddot{\theta}_3) - I_4(\ddot{\theta}_1+\ddot{\theta}_3+\ddot{\theta}_4) - c/2(\dot{\theta}_1+\dot{\theta}_2)((\theta_1+\theta_2)(\dot{\theta}_1+\dot{\theta}_2)+\theta_1\dot{\theta}_1))\Big] / \left[\tfrac{c}{4}\left(2\theta_1\theta_2 + {\theta_2}^2 + {\theta_1}^2 + 1\right) + \tfrac{34c}{4} + c\left(\tfrac{3}{2}\theta_1 + \tfrac{3}{2}\theta_2 + \tfrac{1}{2}\theta_3\right)^2 + c\left(\tfrac{5}{2}\theta_1 + \tfrac{5}{2}\theta_2 + \tfrac{3}{2}\theta_3 + \tfrac{1}{2}\theta_3\right)^2 + I_2 + I_3 + I_4\right] \tag{18}$$

$$\ddot{\theta}_3 = \Big[F_C l - F_F l(\theta_1+\theta_2+\theta_3) + T_2 - \tfrac{26c}{4}\ddot{\theta}_1 - \tfrac{18c}{4}\ddot{\theta}_2 - \tfrac{3c}{4}\ddot{\theta}_4 + c/2(\theta_1+\theta_2+\theta_3)\Big(-\tfrac{1}{2}(\theta_1+\theta_2+\theta_3)(\ddot{\theta}_1+\ddot{\theta}_2) - (\theta_1+\theta_2)(\ddot{\theta}_1+\ddot{\theta}_2) - \tfrac{1}{2}(\dot{\theta}_1+\dot{\theta}_2+\dot{\theta}_3)^2 - (\dot{\theta}_1+\dot{\theta}_2)^2 - (\dot{\theta}_1)^2\Big) + c\left(\tfrac{3}{2}\theta_1 + \tfrac{3}{2}\theta_2 + \tfrac{3}{2}\theta_3 + \tfrac{1}{2}\theta_4\right)\Big(-\tfrac{1}{2}(\theta_1+\theta_2+\theta_3+\theta_4)(\ddot{\theta}_1+\ddot{\theta}_2+\ddot{\theta}_4) - (\theta_1+\theta_2+\theta_3)(\ddot{\theta}_1+\ddot{\theta}_2) - (\theta_1+\theta_2)(\ddot{\theta}_1+\ddot{\theta}_2) - \tfrac{1}{2}(\dot{\theta}_1+\dot{\theta}_2+\dot{\theta}_3+\dot{\theta}_4)^2 - (\dot{\theta}_1+\dot{\theta}_2+\dot{\theta}_3)^2 - (\dot{\theta}_1+\dot{\theta}_2)^2 - (\dot{\theta}_1)^2\Big) - I_3(\ddot{\theta}_1+\ddot{\theta}_2) - I_4(\ddot{\theta}_1+\ddot{\theta}_2+\ddot{\theta}_4)\Big] / \left[\tfrac{10c}{4} + \tfrac{c}{4}(\theta_1+\theta_2+\theta_3)^2 + c\left(\tfrac{3}{2}\theta_1 + \tfrac{3}{2}\theta_2 + \tfrac{3}{2}\theta_3 + \tfrac{1}{2}\theta_4\right)^2 + I_3 + I_4\right] \tag{19}$$

$$\ddot{\theta}_4 = \Big[\tfrac{F_C l}{2} - F_F l(\theta_1+\theta_2+\theta_3+\theta_4) + T_3 - \tfrac{7c}{4}\ddot{\theta}_1 - \tfrac{5c}{4}\ddot{\theta}_2 - \tfrac{3c}{4}\ddot{\theta}_3 + c/2(\theta_1+\theta_2+\theta_3+\theta_4)\Big(-\tfrac{1}{2}(\theta_1+\theta_2+\theta_3+\theta_4)(\ddot{\theta}_1+\ddot{\theta}_2+\ddot{\theta}_3) - (\theta_1+\theta_2+\theta_3)(\ddot{\theta}_1+\ddot{\theta}_2) - (\theta_1+\theta_2)(\ddot{\theta}_1+\ddot{\theta}_2) - \theta_1\ddot{\theta}_1 - \tfrac{1}{2}(\dot{\theta}_1+\dot{\theta}_2+\dot{\theta}_3+\dot{\theta}_4)^2 - (\dot{\theta}_1+\dot{\theta}_2+\dot{\theta}_3)^2 - (\dot{\theta}_1+\dot{\theta}_2)^2 - (\dot{\theta}_1)^2\Big) - I_4(\ddot{\theta}_1+\ddot{\theta}_2+\ddot{\theta}_4)\Big] / \left[\tfrac{c}{4} + \tfrac{c}{4}(\theta_1+\theta_2+\theta_3+\theta_3)^2 + I_3 + I_4\right] \tag{20}$$

Whilefindingtheequation of motion in the Z axis, it is assumedthattheweight of thefishandthebuoyantforceexertedbythewaterare in balance. Inotherwords, the robot fishstays in balancewhenplaced in thewater. Itsupanddownmovement is providedbytheliftingforcecreatedbythefins on theside. Bymakingthisforcedownward, the robot fish is allowedtosink. Thefin is placed in thecenter of gravity of the robot fish in such a waythat it creates a liftingforce. Solution is realizedusing Newton formulation.

$$F_L = m\ddot{z} \tag{21}$$

Where $F_L$is buoyancycreatedbythefinanddefined as:

$$F_L = C_L\alpha\frac{1}{2}\rho c V^2 \tag{22}$$

Where C_L is thecoefficient of buoyancy, α is theangle of attack,ρindicatesthedensity of water,V referstothespeed of thefish, and c representsthewingwidth.

Therequiredforcesaremodeledtosolvetheequations of themotionusingMatlab/Simulinksoftwaregiven in Figure 3.Alsoapart of theequations of themotion is shown in Figure 4.

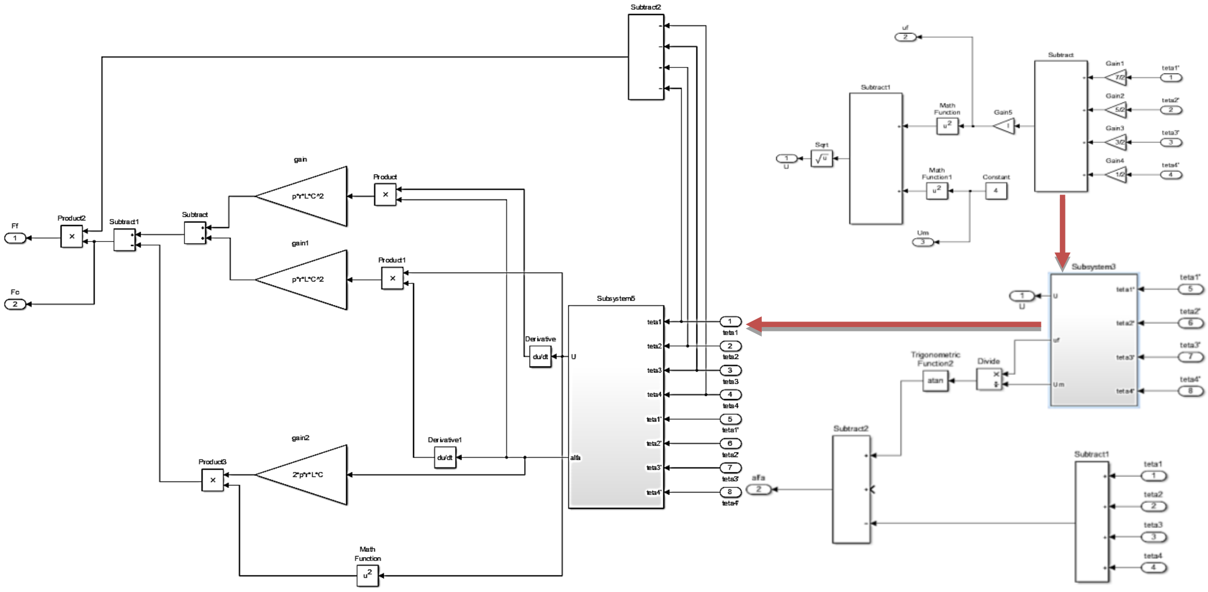


Fig. 3.Themodeling of theforces.

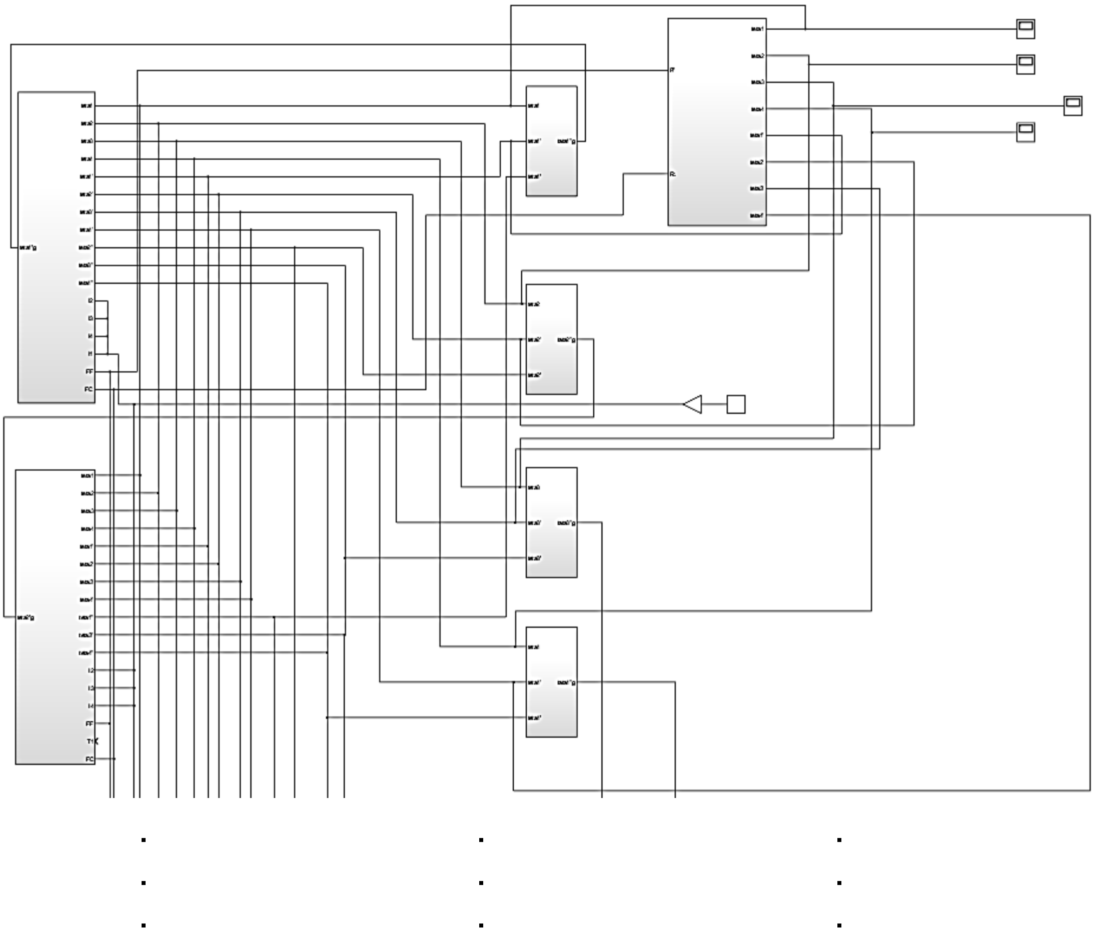


Fig. 4.Themodeling of theequations of themotion.

Indynamicmodeling of theproposed robot fish, theequations of themotion of the robot fish is usedwithMatlab/SimMechanics model torealizedisplacementmotions in x and y axes, rotationmotion in z axis. Thismodelingapproach is given in Figure 5.

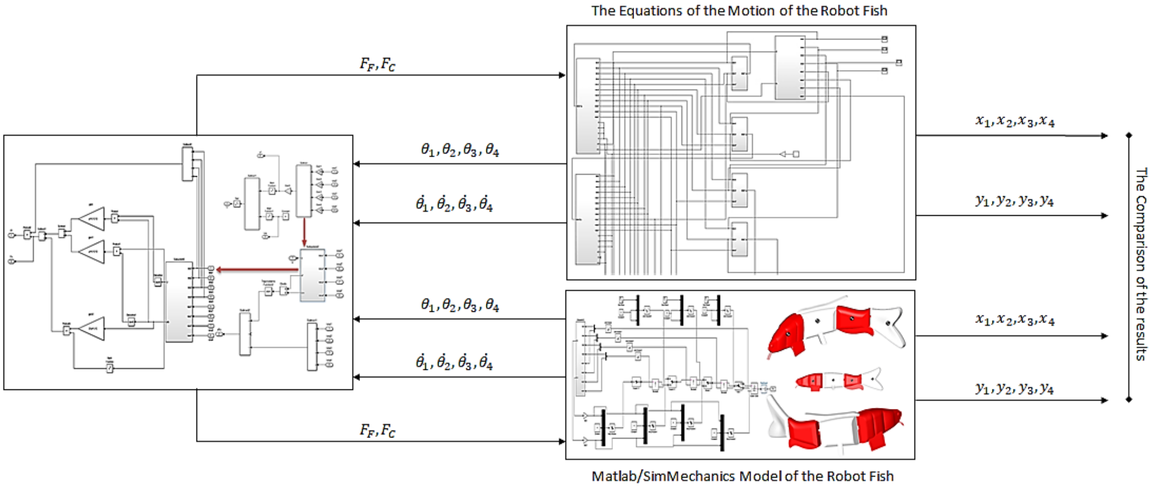


Fig. 5.The dynamicmodelingmethodology of theproposed robot fish model.

III.RESULTS AND DISCCUSSION

The proposed carangiform type carp fish robot is simulated using Matlab/SimMechanics software shown in Figure 6and, the parameters of the system is explained in Table 1.

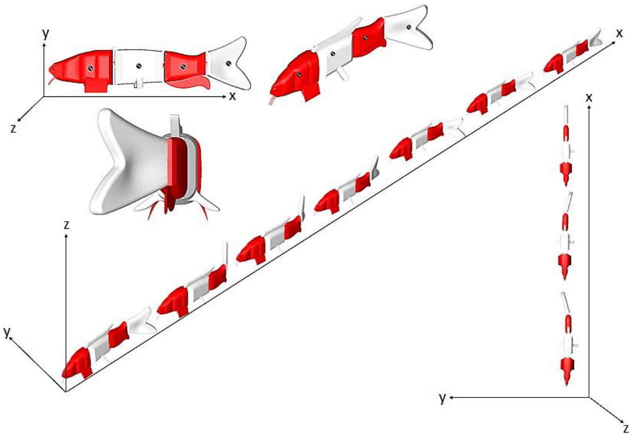
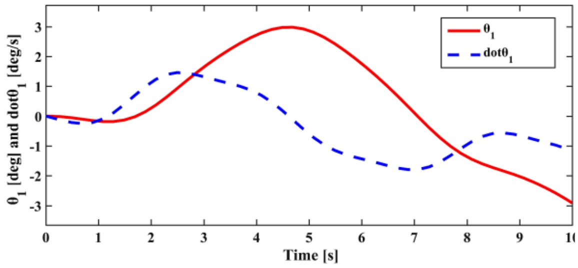


Fig.6.Animations of thesimulations.

TABLE I.Thesystemparameters

Weight	10 kg
Length	0.8 m
Max. Height of the Body	0.23
Max. Width of the Body	0.12

Angleandangularvelocity of the robot fishheadaregivenFigure 7and, Figure 8 showstaildisplacement in y axis. Simulationmeasurementsaretakenfromcenter of thegravity (CG) in allgivengraphicsbetweenFigure 7 andFigure 16. Thedisplacements, velocitiesandaccelerations of the robot head in simulationsaregivenFigures 9-14.



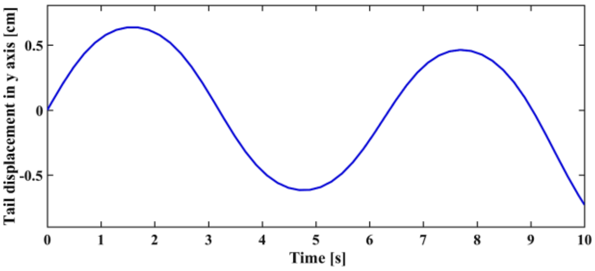
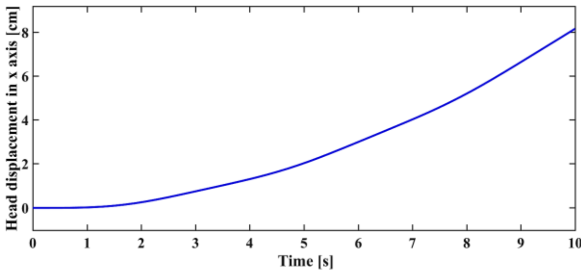


Fig.7.Angleandangularvelocity of the robot fishhead. Fig.8.Taildisplacement in y axis.



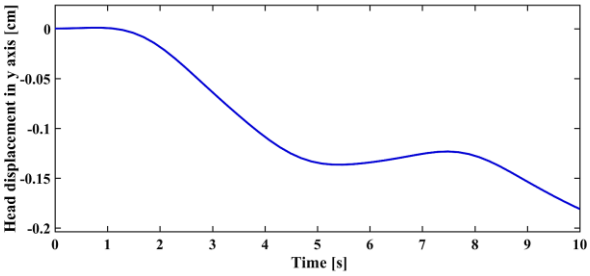
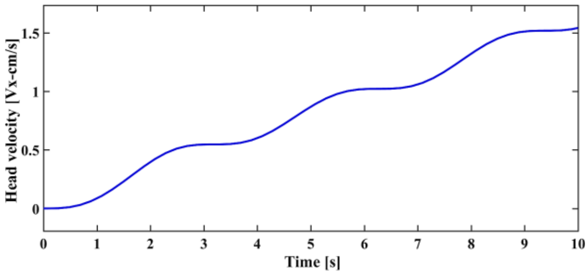


Fig.9.Headdisplacement in x axis.

Fig.10.Headdisplacement in y axis.



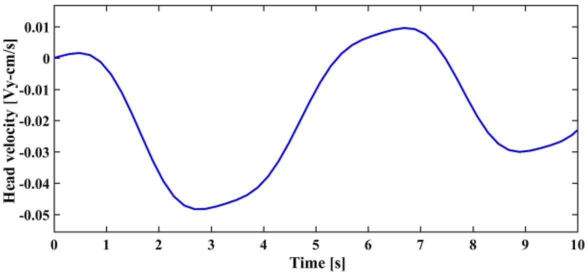
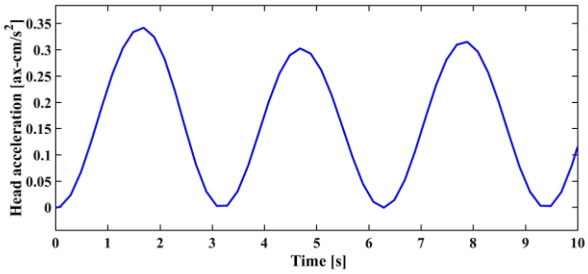


Fig.11.Headvelocity in x axis.

Fig.12.Headveclocity in y axis.



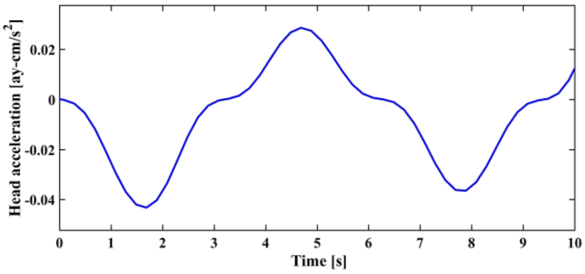
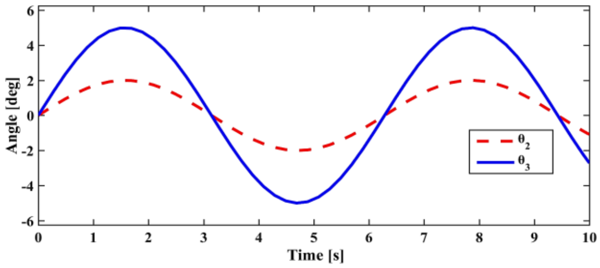


Fig.13.Headacceleartion in x axis.

Fig.14.Headacceleration in y axis.



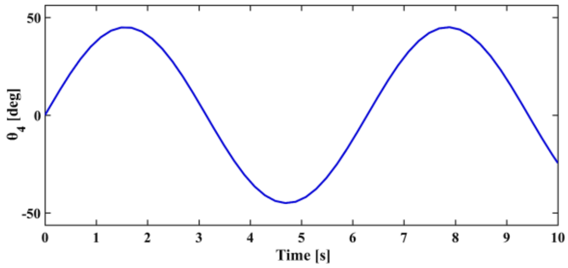


Fig.15.Angles of the rest of the body.

Fig.16.Tailangle of the body.

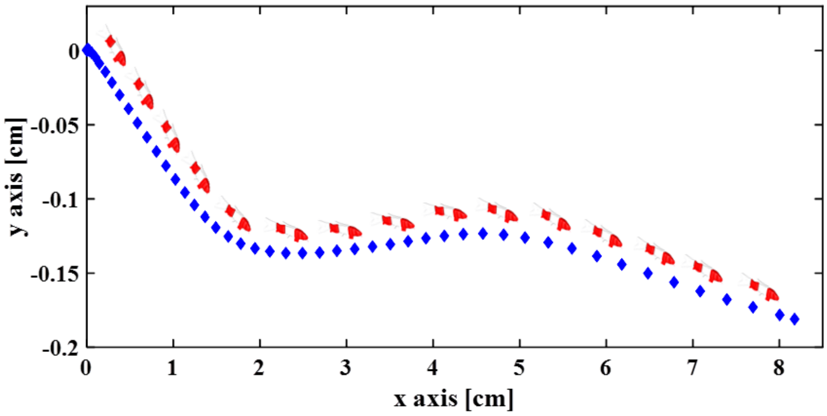


Fig.17.Movement of therobot fish in x and y axes.

Theobtainedangles of the rest of the body in simulationsaregiven in Figures 15-16. Accordingtogivenfigures, theproposed robot fish can movealongthe x and y axiswiththeforcesderivedfromrotatinalmotionaround z axis. Inthesesimulations time is restricted as 10 seconds, otherwisethe robot fishcontinuestoimitatetheswimmingmovement. MoreoverFigure 17 is giventoshowthemovementof the robot fish in the x andy axesmoreclearly. As a result of thesimulations, it can be saidthattheproposed robot fish model acts in both x and y axestoreachthetargetlike a carpfishswimmingmovements.

IV. CONCLUSIONS

In this paper, it is aimed to imitate four degrees of freedom (DOF) of the carangiform type robot fish that is based on the results of previous studies. While determining the spine structure of the robot fish, four joints are designed considering the dimensions of real carp fish and, also the joints are placed in positions where the robot fish can best mimic the movement of the tail. The dynamic equations of the robot fish model are obtained using Lagrange formulation and simulated using Matlab/Simulink/SimMechanics software. According to modeling and simulations results of the proposed study, it is possible to say that the created robot fish model can be developed and used in future control studies.

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