Robust Forward Speed Control of a Robotic Fish

D. Korkmaz¹, G. Ozmen Koca² and Z. H. Akpolat³

¹University of Firat, Elazığ/Turkey, dkorkmaz@firat.edu.tr
²University of Firat, Elazığ/Turkey, gonca.ozmen@gmail.com
³University of Firat, Elazığ/Turkey, z.h.akpolat@gmail.com

Abstract—In this study, a propulsion model of a carangiform 4-joints robotic fish is presented. The forward speed of the robotic fish is controlled by sliding mode control with integral compensation technique which provides a robust performance for nonlinear and uncertain systems. The closed loop control system is implemented in MATLAB/Simulink environment. Simulation results showing the performance of the closed loop control system are illustrated in the paper.

Keywords—Robotic fish, carangiform fish, motion control, propulsion model, multi-joint robot

I. INTRODUCTION

Fish swim by bending their bodies and/or using their fins and have owned astonishing swim and maneuvering abilities after thousands years of evolution [1]. They can perform very efficient locomotion and maneuvering in the water. According to motion ability, some fish bend their bodies and/or caudal fins (BCF) and other fish use their median and/or paired fins (MPF) [1]. This has inspired many robotic researchers to build new kinds of aquatic robots namely robotic fish. Instead of the classic rotary propellers used in underwater vehicles, robotic fishes use undulation or oscillation movements to generate the thrust force [1-7]. Therefore robotic fishes may be used in many aquatic and military fields such as exploration of fish behavior, underwater biology of cultures, detecting pollution, undersea exploration and robotic education, etc [2,4,7].

In 1994, the first robotic fish named RoboTuna was produced at MIT [8]. It was successfully developed an 8-link RoboTuna, which may be the first free-swimming robotic fish in the world [9]. Inspired by this study, the Draper Laboratory developed undersea vehicle that is VCUUV. Due to this vehicle could avoid obstacles and capable of up-down motion, it is the most known robotic fish [1,2,9]. After its development, researchers developed many kinds of robotic fishes. For instance, North-Western University used shape memory allows (SMA) for robot fish propulsion. In Japan, Nagoya University developed a micro robotic fish using ICPF Actuators [1,2,10]. After a lot of research, in Essex University has the best swimming ability and speed developed a kind of carangiform robotic fish namely G9 (9.Generation). Now, it is exhibiting in London County Hall Aquarium [1]. Ever since based on recent advance in robotics, hydrodynamics and kinematics of fish swimming, control technology, actuators, remote control, rotary propellers, and many research have concentrated on the development of new fish-like vehicles [9,11].

In this paper, the objective is to design a simple propulsive model for carangiform robotic fish and to realize closed loop forward speed control. The model consists of two sections: rigid body and a flexible tail which includes 4-joints flapping mechanism. The forward speed of the fish is controlled by the flapping frequency of the tail and joints angles.

The rest of this paper is organized as follows. In Section 2, propulsion model of a robotic fish is designed by a joint kinematics model. Section 3 describes dynamic model of a robotic fish using hydrodynamics and kinematics model. The controller used in the closed loop system is based on the Sliding Mode Control with Integral Compensation technique, which is given in Section 4. The simulation results are given in Section 5. Finally, conclusions are presented in Section 6.

II. PROPELLION MODEL OF A ROBOTIC FISH

Robotic fish consists of two sections which are anterior rigid body and a flexible tail [12], as shown in Fig. 1. Motion control of the robotic fish mainly depends on the tail of joints kinematics model. If the robotic fish swims like a real fish, tail joints determine how much propulsion force is generated [2].
The motion of the fish tail may be described using a traveling wave function [12], which is given by:

\[ y_{body}(x,t) = (c_1 x + c_2 x^2) \sin(kx + wt) \]  

(1)

where, \( x \) is the displacement along the main axis, \( c_1 \) and \( c_2 \) are linear wave and quadratic wave amplitudes respectively, \( k = 2\pi / \lambda \) is the body wave number (\( \lambda \) is the body wave length) and \( w = 2\pi f \) is the body wave frequency (\( f \) is the flapping frequency of the fish). The amplitude of the travelling wave increases along from nose to tail [2].

Equation (1) may be rewritten to obtain control angles for 4-link actuated by servomotors. Thus, a discrete traveling wave is computed in analytic fitting solution and grouped as a 4xM look-up table in simulation, which is given by [2]:

\[ y_{body}(x,i) = (c_1 x + c_2 x^2) \sin\left(\frac{2\pi}{M} i \right) \text{ for } i \in [0, M-1] \]  

(2)

where, \( M \) is the resolution of the discrete traveling wave. Fig. 2 shows the discrete traveling waves for \( M=18 \), \( c_1=0.3 \), \( c_2 =0 \) and \( k=13.6 \) [2].

Flexible tail of fish consists of many rotating hinge joints. It can be modeled as a planar of links along the main axis [13]. There are four links, i.e., \( (l_1 \text{ to } l_4) \), between the joints. \( l_j (j=1,2,...,N) \) is the link length ratio and \( N \) is the joint number. Also two end-point coordinate pairs of each link is determined \((x_j, y_j)\), \((x_{j+1}, y_{j+1})\) respectively and the joint angle between \( l_j \) and \( l_{j+1} \) is \( \theta_j \) [13]. Mathematically, the joint angle of the \( j \) th link can be computed in analytic fitting solution at the time of \( i \) th current wave and set the joint angles in the 4xM Look-up Table (OscData[N][M]). Thus, one swimming function in the discrete travelling wave is used to investigate the motion of the robotic fish, as shown in Fig. 3. In the paper, link length ratio, used for analytic fitting solution \( L = [l_1; l_2; l_3; l_4] \), is set to \( [4; 3.5; 2.5] \) for 4-joints mechanism.

The unit of the angles is degree in the matrix given by (3). The joints kinematics model used in the paper is shown in Fig. 4.

\[ \begin{array}{cccc}
+11.67 & +11.4 & -7.53 & -23.66 \\
+7.62 & +15.57 & +0.12 & -5.97 \\
+3.25 & +21.23 & +3.82 & +4.7 \\
-3.08 & +24.88 & +8.39 & -
\end{array} \]

\[ \begin{array}{cccc}
-9.27 & +25 & +15.38 & +2.71 \\
-13.74 & +23.2 & +21.37 & +5.46 \\
-16.39 & +17.43 & +27 & +8.75 \\
-17.05 & +7.95 & +26.6 & +14.44 \\
-14.28 & -2.66 & +21.73 & +22.68 \\
-11.21 & -10.6 & +8.06 & +21.92 \\
-7.21 & -15.9 & -0.51 & +5.56 \\
-2.83 & -20.12 & -5.12 & +2.5 \\
+3.59 & -19.4 & -13.84 & +1 \\
+9.65 & -24.2 & -15.34 & -3.75 \\
+14.6 & -24.06 & -20.07 & -6.3 \\
+16.39 & -18.5 & -23.01 & -13.6 \\
+17.05 & -7.58 & -27.17 & -13.25 \\
+14.28 & +2.78 & -21.01 & -14.12 \\
\end{array} \]

Figure 3: Link based body-wave curve fitting
4xM Look-up table provides reference angles \( (\Theta^5) \) for the joints kinematics model. The joint angles are controlled by using classic PD controllers.

III. Dynamic Model of a Robotic Fish

A. The Hydrodynamics Model

In this study, using the classification of the fish swimming modes in [14], a Carangiform fish was modeled. The forces effecting a swimming robotic fish in the horizontal direction are thrust, friction, drag and in the vertical direction, weight, buoyancy [10].

According to this model, there is a maximum robotic fish speed \( (V_{\text{max}}) \) which makes viscous drag equal to thrust. Thus, it has a constant swimming speed. Viscous drag can be expressed by [2]:

\[
D_v = \frac{1}{2} C_f S_a V^2 \rho
\]  
\[\text{(4)}\]

where, \( S_a \) is the water surface area, \( V \) is the fish speed and \( \rho \) is water density. \( C_f \) is a drag coefficient which depends on the Reynolds number. The Reynolds number is given by [14]:

\[
R_e = \frac{LV}{\nu}
\]  
\[\text{(5)}\]

where, \( L \) is the robot fish tail length, \( \nu \) is the kinematic viscosity of water (\( \nu = 1.12 \text{ mm}^2/\text{s} \)). Thus, \( C_f \) is derived from the sum of 1.328\( R_e^{0.5} \) and 0.074\( R_e^{-0.2} \) [2].

The parameter named Strouhal number for BCF movement is given by [2]:

\[
S_t = \frac{fA}{V}
\]  
\[\text{(6)}\]

where, \( f \) is the oscillation frequency, \( V \) is the forward speed, \( A = 2(c_1x + c_2x^2) \) is the peak to peak tail amplitude and \( x \) is the tail length. \( S_t \) is set to 0.3 in this paper [2]. So using equation (6), the maximum speed \( (V_{\text{max}}) \) can be calculated.

When the thrust force \( (F_{\text{thrust}}) \) at least equals to the maximum viscous drag \( (D_{\text{max}}) \):

\[
F_{\text{thrust}} = \frac{1}{2} C_{f_{\text{max}}} S_a V_{\text{max}}^2 \rho
\]  
\[\text{(7)}\]

In [15], the detailed expressions for the terms \( C_{f_{\text{max}}} \) and \( V_{\text{max}} \) can be found.

B. The Kinematics Model

The linear acceleration of the robot fish can be calculated as [2]:

\[
a_t = \frac{F_{ty} - D_x}{m}
\]  
\[\text{(8)}\]

where, \( m \) is weight of the robotic fish and \( F_{ty} = F_{\text{thrust}} \cos(\Theta_d) \). \( F_{ty} \) is the component of the thrust force in the heading axis and \( \Theta_d \) is the deflected angle between head and center axis.

Fig. 5 shows a diagram of the derivation procedure for the robotic fish model.

![Figure 5: A diagram of the derivation procedure for the robotic fish model](image)

Fish status gives forward speed of the robotic fish and it is used to feedback to the hydrodynamics model.

IV. Sliding Mode Control with Integral Compensation

Fig. 6 shows a simple closed-loop forward speed control system for the robotic fish model.

![Figure 6: Closed loop control system for robotic fish](image)

\( V_{\text{ref}} (t) \) is the reference and \( V(t) \) is the real speed of the robotic fish. The controller output is the flapping frequency for the forward movement of the robotic fish.

The controller used in the closed loop system is based on the Sliding Mode Control with Integral Compensation technique which provides robust control for nonlinear and uncertain systems [16-18].
Sliding Mode Control (SMC) is a robust control method and a powerful technique to control the uncertain and nonlinear systems [17,18]. In a general SMC system, the switching function is defined as [16,19]:

\[ S = \lambda e + \dot{e} \]  

(9)

where, \( e \) is the speed error of the robotic fish, \( \dot{e} \) is the derivative of the speed error and \( \lambda \) is the slope of the switching line.

The discrete time speed controller structure of robotic fish is shown in Fig. 7 where, \( e(k) \) is the input variable of the controller, \( f(k) \) is the output of the controller.

An anti-windup integrator is added to stop over-integration for the protection of the system [20]. Although the control structure is based on the SMC with integral compensation technique, the structure used in this study does not contain the \( u_{eq} \) term which is the standard term of the classical SMC technique. Thus, a simpler and more practical controller is obtained for the speed control of the robotic fish.

V. SIMULATION RESULTS

Simulation is realized in MATLAB/Simulink environment. Flapping frequency (\( f \)) is the output of the speed controller and forward speed (\( V(t) \)) is the output variable of the closed-loop control system. Parameters used in simulation studies are given in Table II.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water surface area (( S_a ))</td>
<td>6 m(^2)</td>
</tr>
<tr>
<td>Water density (( \rho ))</td>
<td>1000 kg/m(^3)</td>
</tr>
<tr>
<td>Weight of the robotic fish (( m ))</td>
<td>0.93 kg</td>
</tr>
<tr>
<td>Robot fish tail length (( L ))</td>
<td>0.8 m</td>
</tr>
<tr>
<td>Linear wave amplitude (( c_1 ))</td>
<td>0.1</td>
</tr>
<tr>
<td>Quadratic wave amplitude (( c_2 ))</td>
<td>0.05</td>
</tr>
<tr>
<td>Resolution of the discrete traveling wave (( M ))</td>
<td>18</td>
</tr>
<tr>
<td>Body wave number (( k ))</td>
<td>13.6</td>
</tr>
</tbody>
</table>

Fig. 8 shows the relationship between the flapping frequency and the forward speed of the robotic fish. The forward speed increases with the rise of the flapping frequency.

The open loop forward speed response to a step input of 2Hz is illustrated in Fig. 9.

Figs. 10.a, 10.b and 11.a, 11.b show the closed loop forward speed response to a step reference and the output of the controller (flapping frequency) respectively. A good closed loop control performance is obtained as seen in Fig. 10.a and 11.a.
Robust Forward Speed Control of a Robotic Fish

VI. CONCLUSION

A propulsion model of the robotic fish inspired by biological structure of a carangiform swimmer is presented in the paper. A controller based on the sliding mode control with integral compensation technique is used to provide a robust forward speed control for the robotic fish. Simulation results showing the effectiveness of the control performance are illustrated.

Future research will focus on a kinematics model for up-down and turning swimming motion.

REFERENCES