Development of a Real Time Simulator Based on the Analysis of 6-Degrees of Freedom Motion of a Biomimetic Robot with Two Undulating Side Fins

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Abstract—In this study, the motion of a squid-like underwater robot with two undulating side fins has been investigated through towing tank experiment and simulation of 6-DOF mathematical model in 3D space with the aim of developing a real time simulator. The comparison between simulation results and experimental results confirmed the accuracy of the simulation. The real time handling simulator was developed based on the mathematical model by using Open Dynamic Engine (ODE). It was confirmed that the robot in this simulator can move in the similar way as real robot’s motion by the same control.

Index Terms—Biomimetics, Squid-like underwater robot, Undulating side fin, 6-DOF motion, Real time simulator

I. INTRODUCTION

The increasing demand for high-performance underwater vehicle has been making many researchers interested in studying biomimetic propulsion. A lot of studies have been conducted theoretically, numerically and experimentally with respect to the swimming motion of fishes for understanding the mechanism of the propulsion of fish for applying the mechanism to the artificial underwater vehicle. Many books and review papers have been published (for example, Sfakiotakis et al. [1], Kato et al. [2]). The robotic fishes and test models also have been constructed by many researchers (Proceedings of ISABMEC [3]). The undulating fin, a prospective propulsion system has also been studied by many researchers as a kind of bio-inspired propulsion system (for example, Zhang et al. [4], Low et al. [5]). This type of robot can be controlled precisely for many applications.

In the author’s group, a squid-like robot with two undulating side fins which mimics to those of Stingrays or Cuttlefishes has been studied for a long time, which is now in its fifth generation. Our investigation towards the development of precisely controllable and environmentally friendly underwater vehicle was initiated in 2002 with the construction of Model-1 [6, 7]. In accordance with our continued development efforts Model-2 was constructed in 2004 [8] and subsequently Model-3 in 2006 [9] and finally the present Model-4 in 2009. Recently Model-5 has also been developed and the experiment has been started using this new model. The brief description of the Model-4 along with the force measurement and free-run tests were presented through towing tank experiments in the 4th ISABMEC on 2009 [10]. The study on the performance of the undulating side fins with various aspect ratios using computed flow, pressure field and hydrodynamic forces were reported [11, 12]. A numerical computation was also conducted [13]. The features of the flow field and hydrodynamic forces acting on the body and fin were discussed and a simple relationship among the fin’s principal dimensions was also established.

The swimming performance of Model-4 was demonstrated at Suma Aqua-Life Park with the real fishes (Movie-S1) and in Underwater Robot Festivals in Kobe. The undulating side fins of the robot have been successfully used to make the straight line motions in surge, sway and heave directions and also to make the rotating motions in roll, pitch and yaw directions by changing the frequency and progressive wave direction or the vertical center of standing wave motion on the fin. Our robot swam freely in the environment similar to real coastal water with tidal current. Interestingly, the robot did not annoy the fishes – fishes were not scared swimming together with it and they did not attack it. It proved the environment friendliness of the robot. The robot also showed excellent maneuverability in swimming which is a fundamental ability of a robot in the underwater exploration. Because, during the operation the robot has to move around an unknown geometry in the underwater region to find some untraced items. The Model-4 could move in any direction in the 3D space and could stop suddenly upon braking and coming back by tracing same route. However, the precise maneuverability not only depends on the robot’s capacity but also the ability of the operator. During the experiments, due to operator’s incompetence, at times difficulties arose in controlling the motion of the robot. Training for operators is required for real operation in the real coastal area. But

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the real model cannot be used always for training purpose. So the development of a real-time simulator was conducted in this paper. In the present study, at first the 3-DOF circular motion and 3-DOF vertical motion using only side fins in addition to the motions used in usual operation (using caudal fins) were investigated through experiment and simulation. Then as an example of 6-DOF motion, the spiral motion which is the combination of these two 3-DOF motions was discussed to check the 6-DOF mathematical model. Finally, using the equation of motion the real time simulator was developed with the help of Open Dynamic Engine (ODE).

II. MATERIALS AND METHODS

A. Configuration of Model-4 and Experimental Setup

The configuration of the Model-4 was described in detail in the previous study [10] and the real model can be seen from the Movie-S1. Moreover, the principal particulars of Model-4 are shown in Table 1.

<table>
<thead>
<tr>
<th></th>
<th>Fuselage (m)</th>
<th>Side fin (m)</th>
<th>Tail fin (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>1.4</td>
<td>0.874 (outside)</td>
<td>0.833 (inside)</td>
</tr>
<tr>
<td>Width</td>
<td>0.714</td>
<td>0.075</td>
<td>0.17</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.1</td>
<td>0.0005</td>
<td>0.0005</td>
</tr>
<tr>
<td>Distance</td>
<td>0.0002–0.003*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>between gravity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>buoyancy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>center (BG)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total weight</td>
<td>62.8 (kg)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*BG can be changed from 0.2mm to 3mm by moving vertical gravity center using the device.

The experiment was conducted in the Towing Tank of Osaka University (width 8m, depth 4.5m, length 100m). A picture of the Towing Tank and the sketch of the experimental setup are shown in Fig. 1. As shown in the illustration, the range of movement of the model was 2.6 meter wide and 1.5 meter deep. Two cameras were set at the upper side and in the underwater to take the movie of upper view and side view of the robots motion respectively. 8 ping-pong balls were hanged with the rope at four corners to know the real position from the image. This method lacks high level of accuracy, but it is simple and the results can be compared with the simulation. From the movie, the motion was estimated by tracking the same point on the body of the robot.

B. Simulation

The study aimed to develop a real time simulator for the Model-4. 6-DOF equations of motion were solved using the mathematical model. The Hydrodynamic coefficients were obtained from the towing tank captive test and the numerical computation of fluid force around the fins under the quasi steady assumption. The coordinate system is sketched in Fig. 2; where the space fixed coordinate system \( (X,Y,Z) \) and body fixed coordinate system \( (x,y,z) \) are shown. Here \( u, v, w \) are the advanced velocity of the model in \( x, y, z \) direction respectively and \( p, q, r \) are the angular velocity. Also, \( \phi, \theta, \psi \) are Eulerian angles. The body fixed coordinate system has its origin at the center of gravity and the body was symmetric with respect to \( xz \) and \( yz \) planes due to the neutral buoyancy of the tail fin. With respect to the \( xy \) plane, the body is a little bit asymmetric due to the small distance between gravity and buoyancy center and the shape of the servo motor unit of the real model.

The relationship between space fixed coordinate system and body fixed coordinate system can be expressed as follows (Eq. 1 - Eq. 6) [14]:

\[
\frac{dx}{dt} = u \cdot \cos \theta \cos \psi + v \cdot (\sin \phi \sin \theta \cos \psi - \cos \phi \sin \psi) + \sin \phi \sin \theta \sin \psi + \cos \phi \cos \psi \\
\frac{dy}{dt} = u \cdot \cos \theta \sin \psi + v \cdot (\sin \phi \sin \theta \sin \psi + \cos \phi \cos \psi) + \sin \phi \cos \theta \sin \psi - \sin \phi \cos \psi
\]
\[
\frac{dZ}{dt} = -u \cdot \sin \theta + v \cdot \sin \phi \cos \theta + w \cdot \cos \phi \cos \theta \\
\frac{d\phi}{dt} = p + q \cdot \sin \phi \tan \theta + r \cdot \cos \phi \tan \theta \\
\frac{d\theta}{dt} = q \cdot \cos \phi - r \cdot \sin \phi \\
\frac{dy}{dt} = q \cdot \sin \phi / \cos \theta + r \cdot \cos \phi / \cos \theta
\]

Eqs. 7 - Eq. 12 represent the 6-DOF equations of motion in body fixed coordinate system [15]. The first three equations represent the translation in \(x\), \(y\) and \(z\) directions respectively and the latter three represent the gyration around \(x\), \(y\) and \(z\) axes respectively. By solving these equations (Eq.7-Eq.12), the new gravity center position in space fixed coordinate system and Eulerian angles were found from the previous equations (Eq.1-Eq.6). The hydrodynamic forces were obtained based on quasi-steady assumption (similar as MMG model in ship maneuvering field [16]) from the model experiment and the CFD computation. More terms seem to be required for detailed consideration; but the following equations using state variables were used in this study for simplicity. The results were compared with experiment and validated in the section III.

Equations of motion for translation:

- \(x\)-direction
  \[
  (M + M_f) \frac{du}{dt} = F_x - (M + M_f) \cdot q \cdot w + (M + M_f) \cdot r \cdot v
  \]

- \(y\)-direction
  \[
  (M + M_f) \frac{dv}{dt} = F_y - (M + M_f) \cdot r \cdot u + (M + M_f) \cdot p \cdot w
  \]

- \(z\)-direction
  \[
  (M + M_f) \frac{dw}{dt} = F_z - (M + M_f) \cdot p \cdot v + (M + M_f) \cdot q \cdot u
  \]

Equation of motion for gyration:

- Around \(x\)-axis
  \[
  (I_{xx} + J_x) \frac{d\theta}{dt} = T_x - (I_x + J_x) \cdot \left(\theta \cdot \sin \phi \cdot \sin \theta + \frac{1}{2} \cdot \sin \theta \cdot \sin \theta \cdot \sin \theta \right)
  \]

- Around \(y\)-axis
  \[
  (I_{yy} + J_y) \frac{d\phi}{dt} = T_y - (I_y + J_y) \cdot \left(\phi \cdot \cos \theta \cdot \sin \phi \cdot \sin \theta \right)
  \]

- Around \(z\)-axis
  \[
  (I_{zz} + J_z) \frac{d\psi}{dt} = T_z - (I_z + J_z) \cdot \left(\psi \cdot \cos \theta \cdot \sin \phi \cdot \sin \theta \right)
  \]

Since the body fixed coordinate system had its origin at the center of gravity and the shape of the body was symmetric then products of inertia were zero [15] and some added products of inertia are ignored due to the small effect compared with other terms because the thickness in \(z\) direction was very small and almost symmetric with \(xy\) plane. The forces, \(F_x\), \(F_y\), and \(F_z\) and the moments \(T_x\), \(T_y\), and \(T_z\) were expressed as follows (Eq.13 – Eq.19):

\[
F_x = f_{\theta x} \cdot \sin \theta \cdot \cos \theta + f_{\phi x} \cdot \sin \phi \cdot \cos \theta + f_{\theta y} \cdot \sin \phi \cdot \cos \theta + f_{\phi y} \cdot \sin \phi \cdot \cos \theta
\]

\[
F_y = f_{\theta y} \cdot \sin \theta \cdot \cos \theta + f_{\phi y} \cdot \sin \phi \cdot \cos \theta + f_{\theta z} \cdot \sin \phi \cdot \cos \theta + f_{\phi z} \cdot \sin \phi \cdot \cos \theta
\]

\[
F_z = f_{\theta z} \cdot \sin \theta \cdot \cos \theta + f_{\phi z} \cdot \sin \phi \cdot \cos \theta + f_{\theta z} \cdot \sin \phi \cdot \cos \theta + f_{\phi z} \cdot \sin \phi \cdot \cos \theta
\]

\[
T_x = f_{\theta x} \cdot \sin \theta \cdot \cos \theta \cdot \sin \phi \cdot \sin \theta + f_{\phi x} \cdot \sin \phi \cdot \cos \theta \cdot \sin \theta \cdot \sin \theta \cdot \sin \theta \cdot \sin \theta + \frac{1}{2} \cdot \sin \theta \cdot \sin \theta \cdot \sin \theta \cdot \sin \theta \cdot \sin \theta \cdot \sin \theta
\]

\[
T_y = f_{\theta y} \cdot \sin \theta \cdot \cos \theta \cdot \sin \phi \cdot \sin \theta \cdot \sin \theta \cdot \sin \theta \cdot \sin \theta \cdot \sin \theta + f_{\phi y} \cdot \sin \phi \cdot \cos \theta \cdot \sin \theta \cdot \sin \theta \cdot \sin \theta \cdot \sin \theta \cdot \sin \theta \cdot \sin \theta
\]

\[
T_z = f_{\theta z} \cdot \sin \theta \cdot \cos \theta \cdot \sin \phi \cdot \sin \theta \cdot \sin \theta \cdot \sin \theta \cdot \sin \theta \cdot \sin \theta + f_{\phi z} \cdot \sin \phi \cdot \cos \theta \cdot \sin \theta \cdot \sin \theta \cdot \sin \theta \cdot \sin \theta \cdot \sin \theta \cdot \sin \theta
\]

Here, \(M\) : weight of the model (kg); \(M_x\), \(M_y\), \(M_z\) : added mass in \(x,y,z\) directions (kg); \(I_{xx}\), \(I_{yy}\), \(I_{zz}\) : moment of inertia along \(x,y,z\) directions (kg.m\(^2\)); \(J_x\), \(J_y\), \(J_z\) : added moment of inertia along \(x,y,z\) directions (kg.m\(^2\)); \(F_x\), \(F_y\), \(F_z\) : total hydrodynamic force in \(x,y,z\) directions (N); \(T_x\), \(T_y\), \(T_z\) : total hydrodynamic moment around \(x,y,z\) directions (N.m); \(C_{xx}\), \(C_{yy}\), \(C_{zz}\) : constant for drag force in \(x,y,z\) directions (Kg/m); \(C_{xxo}\), \(C_{yyo}\), \(C_{zzo}\) : constant for drag moment (Kg); \(C_{xuv}\), \(C_{yuv}\), \(C_{zuw}\) : coefficient for lift force due to drift angle and trim angle; \(BG\) : vertical distance between the center of buoyancy and the center of gravity (m); \(\theta_x\), \(\theta_y\), \(\theta_z\) : center position of fin’s angle; \(bB\) : body breadth (m); \(bF\) : fin breadth (m); \(bL\) : body length (m); \(tL\) : tail length (m); \(ang\) : tail fin angle (degree).

In this paper, the progressive wave motion of fin was used. The shape of the fin was expressed by the Eq. 20.

\[
\theta = \theta + \Theta(x) \cdot \sin(2\pi k x - 2\pi N t) = k \cdot \lambda / \lambda = fL
\]

Here \(\Theta(x)\) was same as previous paper [10]. Usually frequency \(N\) is positive; but in this paper, \(N\) was positive when the phase velocity of fin was in tail direction (making thrust in \(x\) positive direction). \(N = 0\) meant that the fin was flat without producing thrust. The moments of inertia were calculated by using mass distribution. The added masses and added moments of inertia were obtained by using Hess-Smith method [17]. The values are summarized in the Table 2.

| \(M_x\) | 5.957 | \(I_{xx}\) | 2.278 | \(J_{xx}\) | 8.78 |
| \(M_y\) | 14.552 | \(I_{yy}\) | 7.996 | \(J_{yy}\) | 27.988 |
| \(M_z\) | 397.6 | \(I_{zz}\) | 10.133 | \(J_{zz}\) | 1.438 |

When the \(x\)-direction advance velocity at fin’s representative point was obtained, the thrust of \(x\)-direction could be calculated from the \(J_x - K_x\) relations of the previous experimental and numerical studies. The advance coefficient and the \(x\)-direction thrust produced by the left and right side fins can be found from the following formulas (Eq.21 - Eq.23):

\[
J_{ax} = \frac{u \pm \frac{bB_f / 2 + bF}{r}}{N_x \cdot bL}
\]

\[
K_{ax} = 0.5 \cdot 0.0132 \cdot J_{ax}^2 - 0.015 \cdot J_{ax} + 0.005 \cdot \left(\theta_{ax} / \theta_{ax}\right)^3
\]

\[
f_{ax} = \rho \cdot K_{ax} \cdot N_s^2 \cdot bL^4
\]
The $y$-directional forces were calculated in similar way by using the following formulas (Eq.24 – Eq.25):

$$K_{Sy} = 2.67 \left( \dfrac{70.00936}{sL_\Sigma} + 0.000303L_\Sigma \times 0.0008275 \right)$$  

(24)

$$f_{Sy} = \rho \cdot K_{Sy} \cdot N_x^2 \cdot \beta_x$$  

(25)

(Note: In Eq. 21- Eq. 25, the letter $S$ in the suffix was replaced by $r$ or $l$ for right or left fin respectively. Also the upper and lower sign of the double sign was considered for right fin and left fin respectively.)

Here, $J_{xl}, J_{xr}$: Advance coefficient for left and right fin respectively; $K_{xl}, k_{xr}$ and $k_{yl}, k_{yr}$: Thrust coefficients in $x$ and $y$ direction respectively; $f_{xp}, f_{yp}$ and $f_{xp}, f_{yp}$: Thrust forces in $x$ and $y$ direction respectively; $N_l, N_r$: Frequencies and $\theta_{ml}, \theta_{mr}$: Maximum fin angle of left and right fin respectively.

The coefficient in case of translational and the rotational motion were considered as follows:

$$C_x = 47.70$$  

$$C_y = 43.86$$  

$$C_{z} = 2.11 \times 100$$  

$$C_{x} = 14 \times 2.11 \times hB^2$$  

$$C_{y} = 40 \times 2.11 \times hB^2$$  

$$C_{z} = 6.00$$  

(26)

The equations of motion were solved by the fourth order Runge-Kutta Method.

C. Formation of Circular and Vertical Motions

The circular motion was attained by applying variable thrusts into two undulating side fins of the robot. This can be done by controlling the phase difference of undulations between both side fins or by setting the same frequency and variable fin angles to the side fins or by applying variable frequencies to the side fins and keeping same fin angle to both fins. In this study, the latter case was considered for convenience. The frequency of 1 Hz and 0.5 Hz were applied to the right and left fins respectively and the maximum fin angle was kept at 45 degree for both fins (Fig. 3).

For simplicity, only the positive frequency was applied for moving the robot in forward direction and the negative frequency for moving the robot in reverse direction. A simulation was also conducted under the same conditions.

On the other hand, the vertical motion can be achieved by using caudal fins and/or side fins. In this study, the side fins were used to change the depth of the model. The center of oscillation of the side fins was shifted up or down from the horizontal position to move the model down or up respectively. The center of oscillation was shifted to 30 degree up and 30 degree down and the frequency of 1 Hz was applied to both the fins. The technique of shifting the center of oscillation of the side fins is clearly sketched in Fig. 4.

III. RESULTS AND DISCUSSION

The main goal of this study was to investigate the 6-DOF motion of a squid-like robot in order to develop the real time simulator. In the previous study [18], the 1-DOF translation motion in $x$ direction and turning motion at one point were studied for investigating the braking ability of the undulating fin propulsion system of the robot. In this study, to investigate the more complex mathematical model, the 6-DOF model was tested and compared with experiment. At first, the 3-DOF circular motion in $XY$ plane and the 3-DOF vertical motion in $XZ$ plane were investigated through experiment and simulation. Then the result of spiral motion, which was found by combining the circular motion and vertical motion was discussed as an instance of 6-DOF motion. In the following sections, the 3-DOF circular motion, the vertical motion, the 6-DOF spiral motion and finally the development of real time simulator will be discussed simultaneously by means of experimental and simulation results.

A. 3-DOF Circular Motion

As discussed in the Section II C, in this study the circular motion was attained by applying the frequency of 1 Hz and 0.5 Hz to the right and left fins respectively and keeping the fin angle 45 degree to both fins. The robot took some times to make static circular movement.
after application of variable frequencies to the fins. The robot attained steady state motion when centrifugal acceleration force was balanced by the hydrodynamic force.

Fig. 5 shows the graph of time history of the forces. The thrust force produced by left and right fin and the total hydrodynamic forces in $x$ and $y$ direction are shown. In this figure, it is seen that $F_x$ gives some negative value before the steady state region; this has happened because of the large drag that had originated in that region. The total hydrodynamic moment around $z$-axis is also shown, which is zero in the steady state region.

Fig. 6 Trace of the centre of gravity of the models in circular motion

Fig. 7 Time history of heading angle in circular motion

B. 3-Dof Vertical Motion

The 3-DOF vertical motion in $XZ$ plane leading to the change of depth was also investigated. Usually caudal fins are used for this purpose, and it works well when the robot is only in vertical motion. However, in the experiment of spiral motion, it was observed that when the robot had to move along a small circle then it made some unexpected movement. This had happened because of the flat-shape of the caudal fin, which will be discussed in detail in the next section.

Fig. 8 Time history of the models in $z$-direction for vertical motion at $+30$ degree and $-30$ degree change of center of oscillation

The experimental and simulation results of the trajectories of the center of gravity of the robot in case of shifting the center of oscillation 30 degree up and 30 degree down are shown in Fig. 8. The time series of nose down angle of the body in case of 30 degree down is also shown in Fig. 9. In both of the figures, the...
simulation results agree well with the experimental data.

Fig. 9 Time history of the tilt angle for vertical motion

From the above discussion, it can be concluded that our program is able to simulate 3-DOF circular and vertical motions accurately.

C. Spiral Motion using Side Fin and Caudal Fin

After successful completion of the 3-DOF motions in two dimensional space, the computation was extended to 6-DOF motion in three dimensional space. In this case, the spiral motion was investigated as an example of 6-DOF motion. This motion is a combination of $x$ direction movement (surge), $y$ direction movement (sway), $z$ direction movement (heave), rotation about $x$-axis (roll), rotation about $y$-axis (pitch) and rotation about $z$-axis (yaw). So it was treated as a good example to verify the accuracy of simulation result for 6-DOF motion. Spiral motion was obtained by combining the circular and vertical motions.

D. Spiral Motion using Only Side Fin

To overcome this limitation of caudal fin the second technique, shifting the center of oscillation of the side fins was used for changing the depth. In the rest part of this study this technique will be considered in changing the depth. In this case, the

shows some simulation results of spiral motion where the caudal fins were used for changing the depth. The table tells about the parameters used in the particular computation. The Fig. 10a shows the trajectory of the center of gravity in the XY-plane, Fig. 10b shows the trajectory in the 3D space and Fig. 10c shows the time series of the distance of $z$-direction.

The study was also done in different conditions by changing the parameters and the caudal fin angles. It was observed that when the caudal fin angle increases, the circle drawn by the model became smaller and the distance in the $z$-direction increased. The distance in the $z$-direction was also increased when the value on $BG$ decreases keeping the other parameter same.

As mentioned in the previous sections, the circular motion was created by giving dissimilar frequencies in the side fins; on the other hand the vertical motion can be found by two ways: using caudal fins and by shifting the center of oscillation of the side fins. In this section, the first case was considered for vertical motion. Fig. 10

During the experiment it was found that when the frequency 1 Hz and 2 Hz were applied in the left and right fins and the caudal fin was rotated to 30 degree then the robot made an unexpected movement. The model couldn’t go up in spite of attempting to go up. It was realized that, the caudal fin couldn’t work properly when the diameter of the trace of the center of gravity was less than the body length (like the case drawn in Fig. 6) of the robot. Actually, when the difference of the frequencies of the side fins increased the robot moved along small circle. In that case, the drift angle at the stern also increased and the tail of the robot moved very fast than its head. As a result in that case the caudal fins couldn’t do its duty properly in moving the robot up or down because of its flat shape. This phenomenon was also predicted by the present simulation. Better result was found when the center of oscillation of the side fins was shifted to change the depth (Fig. 11). It was also confirmed that the simulation results were qualitatively corresponding to the movie of free run test.

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frequencies of 1 Hz. and 0.5 Hz. were applied to the right and left fin respectively. The maximum fin angle was set to 45 degree and the displacement angle from the horizontal position was set to +15 degree (down) for both fins. The simulation was also conducted in the same condition and the equations of motion used in the simulation were discussed in the section II.B. The comparison of three dimensional trajectory of the centre of gravity during the spiral motion is shown in Fig. 12.

Fig. 12 Path of the centre of gravity of the models for spiral motion in 3D space

Fig. 13 shows the comparison of the experimental and simulation results of the trajectories of the centre of gravity in a bird’s eye view of the XY plane, YZ plane and ZX plane.

Fig. 13 Trajectory of the centre of gravity of the models in (a) XY-plane, (b) YZ-plane and (c) ZX-plane

In Fig. 13a, it is seen that the radius of experimental result is little bit larger than that of the simulation; which might be because of the difficulty of reading the actual value of the experimental data and/or due to the tension effect of cable.

The Movie-S3 shows the comparison of the experimental and simulation result of spiral motion. The top view looks like circular motion so the side view is shown here for better understanding. From this video it is seen that the model is concurrently in circular and downward motions. It is also observed that the robots are in almost similar motion, which proves the accurateness of the simulation. Finally, from the above discussion it can be concluded that our program can predict the 6-DOF motion in 3-dimensional space successfully.

E. Real Time Simulator

At the last stage, applying the derived mathematical model the real time simulator for Model-4 was developed. The simulation system was developed with the help of Open Dynamic Engine (ODE) based on the equation of motion discussed in the section II.B. ODE is an open source for simulating rigid body dynamics. The model was embedded in the ODE for making the visualization, background etc. The simulator was the combination of the mathematical model and ODE. The operation in this simulation allows operating the model in the simulator by using the controller of a video game which is same as the controller of real robot. In this simulation, the robot in the simulator can be operated by human control. The screen image of the real time simulator, the controller and the joystick are shown in Fig. 14. The motion of each side fins can be controlled by the controller similarly as the real Model-4. Additionally by using the controller, the frequency of each side fins could be changed which made it easier to control the motion of the robot in this simulator.

Fig. 14 Picture of the real time simulator with controller and joystick

With this simulator, it became possible to create any type of regular or irregular motions without complex operation including braking motion. The simulator is very easy to handle. Even the little children can operate the robot in the simulator like video game. Movie-S4 is an example of the simulator, where the robot is avoiding the collision with a stick.
The video of movement of the developed robot in the real time simulator and the real robot in the Towing Tank by the same control are shown in Movie-S5. In this movie the models show the forward motion, stopping motion and rotation motion. It is seen that the model starts movement to forward direction then brakes at 2 seconds and then starts rotation after 4 seconds. From this video, it is also observed that the robot’s motion in this simulator is very similar to the motion of the real Model-4 by the same control. Therefore it can be concluded that this simulator is a practically usable one for operation training to improve the operators’ adeptness.

IV. CONCLUSION

The mathematical model of 6-DOF motion of the Model – 4 of Squid-like underwater robot with two undulating side fins was developed. The simulation was done for free run condition and compared with the experimental results. The accuracy of the model was confirmed. Finally, using this mathematical model, a real-time simulator was developed. It was confirmed that the robot in this simulator can be controlled in the similar way as real robot by the same control. This simulator is capable of making any type of motion. It can be used in the operation training to improve the skill of operators as well as for other purposes.

Reference


