Dolphin-like Swimming Modeling for a Biomimetic Amphibious Robot

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Abstract: This paper focuses on a dolphin-like swimming hydrodynamics problem for a biomimetic amphibious robot capable of both fish- and dolphin-like swimming modes. A Lagrangian reduction has been established in terms of rigid-body dynamics. For robust gait control, a central pattern generator-based approach is incorporated into the model serving as explicit joint angle control. Consequently, a simultaneous kinematics and dynamics system has been established to investigate the dolphin-like swimming. The rough comparisons between fish and dolphin-like propulsion are very promising, which verify the effectiveness of the proposed model and further provide an insight into more efficient underwater propulsor.

Keywords: Modeling and control, dolphin hydrodynamics, amphibious robot, gait control.

1. INTRODUCTION

The research on highly efficient, manœuvreable and flexible autonomous underwater vehicles (AUVs), has drawn a great deal of attention related to both bionics and engineering applications. As living organisms present very robust and elegant solutions to that problem, some engineers have resorted to biology for inspiration. From the bionic perspective, roboticists endeavor to mimic them in morphology characterized by streamlined body, crescent fins, elastic skeleton, etc. From the viewpoint of a control subject, a considerable number of control approaches (i.e., sine based, model based, especially neurobiology based), are responsible for evocativeness of oscillatory fish body wave for thrust generation. The related studies have been widely reported in the literature involving various underwater biomimetic thrusters, e.g., robotic fish (Grillner et al., 1991; Kato, 2000; Mason and Burdick, 2000; Yu et al., 2004), turtle (Zhao et al., 2009), snake (Lu et al., 2005; Crespi and Ijspeert, 2008), toad (Hirano et al., 2009), robotic dolphin (Lang et al., 1975; Nakashima and Oni, 2002; Nakashima et al., 2004; Dogangil et al., 2005; Yu et al., 2007a,b, 2009a), amphibious salamander (Ijspeert et al., 2007). Of all the underwater propulsors, robotic fish and dolphin receive more attention regarding propulsive efficiency and robustness. To be distinct from fish-like lateral undulation, in particular, dolphin’s dorsoventral locomotion exhibits more excellent performance in drag reduction mechanism, swimming hydrodynamics, maneuverability, etc. which has been widely investigated, especially best known as “Gray’s Paradox”.

The research on robotic dolphin has been popularized in the literature by Fish and Rohr (1999); Romanenko (2002). It is worth noting that vertical fluke oscillations exhibited by dolphin predominate to form up-and-down movements whereas lateral movement is greatly in favor of enhanced planar maneuvers. Another issue is unmatched capabilities bestowed upon dolphins such as remarkable bursting out of water, amusement attraction for aquariums, etc. The current research has brought about some encouraging efforts, yet still remains a great number of unresolved problems regarding hydrodynamics, available biological data, etc.

A submerged body through a fluid experiences hydrodynamic forces which play a central role in the locomotion. On many existing efforts in the literature (Fish and Rohr, 1999), dolphins tend to exhibit complex, interactive hydrodynamics that result in leading-edge suction and vortex rings with a reversed rotational direction which will in return contribute to thrust generation. The dolphin hydrodynamics problem involves interaction of an undulatory body with a fluid, through which an internal muscular force of the body is translated into an external propulsive force exerted on the fluid, and vice versa. Concerning the hydrodynamics, Dogangil et al. (2005) investigated the dolphin dynamical behavior using Newton-Euler formulations, but no experimental data was provided. Yu et al. (2009b) utilized Schiehlen method to establish a representation of the equations of motion, and extended it to a three-dimensional dynamic model (Yu et al., 2008). However, no striking evidence was provided on whether the dolphin swimming precedes fish swimming under some evaluation indexes such as energy consumption, maneuverability, etc. Under this view, we make an attempt to construct a biomimetic amphibious robot that incorporates both fish-like and dolphin-like patterns in a compact
Fig. 1. Overall design of an amphibious robot capable of both fish- and dolphin-like swimming modes.

Fig. 2. Activity of the joint signals governed by CPGs. Note that some discontinuities appear at the initial time which will be smoothened by spline fitting for simulation purposes.

Fig. 3. Systematic model of dolphin-like swimming.

For bio-inspired engineering purposes, the dolphin-like dorsoventral motions can be regarded as a locomotor organism of multi-link connected rigid body immersed in an incompressible fluid. A diagram of the kinematic profile is schematically illustrated in Fig. 3. Since the robot consists of a rigid body, four oscillating joints and two laterally-hinged pectoral joints, it will be modeled as a planar serial chain of N links (N=7 in this paper), where the 0th link is comprised of the head attached by the first unit coupled by the swivelling body mechanism. Take special notice that the dynamics description slightly differs from rotational joints characterized by N servomotors (J1–J7, where J5 and J6 represent the left and right pectoral fins, respectively). Further, as no necessary actuator is provided for maneuver (i.e., turning steering) in the horizontal plane due to space limitation, the locomotion in the Y direction is ignored here. The left and right pectoral fins are also assumed to be identical mechanical dimension and joint activation to ensure a planar motion (in the XOZ plane). However, it deserves to be pointed out that asymmetric pectoral flapping may lead to yawing motion in the Y direction which would exceed the scope of this paper.

Assume that the robot initially submerges underwater and maintains balance, i.e., in a state of neutral buoyancy. The center of buoyancy and center of gravity are also assumed to coincide within the body of the robot. Define the water surface as the reference plane of potential energy, and let $E(\tilde{z}) = -Mg\tilde{z}$ where $M = \sum m_i$ represents the total mass of the robot, $g$ denotes the acceleration of gravity, $\tilde{z} = \sum m_i z_i/M$ is the center of gravity by rough measurement. Suppose that $\tilde{z}(t)|_{t=0} = 0$ at the initial time. Consequently, the Lagrangian formalism can be expressed as:

$$L = \sum_{i=0}^{N-1} \frac{1}{2} m_i \dot{v}_i^2 + \sum_{i=0}^{N-1} \frac{1}{2} I_i \dot{\theta}_i^2 - E(\tilde{z})$$

$$= \sum_{i=0}^{N-1} \frac{1}{2} m_i (\dot{z}_i^2 + \dot{\theta}_i^2) + \sum_{i=0}^{N-1} \frac{1}{2} I_i (\dot{\theta}_i)^2 - E(\tilde{z})$$

(1)
where \((x_i^0, z_i^0)\) represents the barycenter of the \(i\)th link, \(\theta_i\) denotes the joint angle relative to the horizontal plane, i.e., the \(X\) direction, \(m_i\) denotes the mass of the \(i\)th link and \(I_i\) is the estimated moment of inertia in terms of rigid body dynamics.

To describe the kinematics of the robot, the generalized coordinates are specified as: \(x_1, z_1\) and \(\theta_1\), and let \(X = x_1, Z = z_1, \Theta = \theta_1\). When substituting the joint angles \(\varphi_i\) in Fig. 2 into (1), the Lagrange’s equations of the second kind can be obtained:

\[
\begin{align*}
F_X &= \frac{d}{dt} \frac{\partial L}{\partial X} - \frac{\partial L}{\partial X} + \frac{\partial \Phi}{\partial X} \\
F_Z &= \frac{d}{dt} \frac{\partial L}{\partial Z} - \frac{\partial L}{\partial Z} + \frac{\partial \Phi}{\partial Z} \\
M_\Theta &= \frac{d}{dt} \frac{\partial L}{\partial \Theta} - \frac{\partial L}{\partial \Theta} + \frac{\partial \Phi}{\partial \Theta}
\end{align*}
\]

(2)

3.2 Hydrodynamic Analysis

The dynamic model presented in this work is concerned only with motions of a rigid body of six degrees of freedom (J1-J6) through a stationary, incompressible and ideal fluid, and the forces acting on a propulsive element are due to the motion of that element in the fluid. To calculate the resultant forces, a large Reynolds number is adopted. Considerations of unsteady fluid, deformable fish body, or Karman vortex street effect also fall outside of the scope of this work. Take one element as an example. The resultant hydrodynamic force perpendicular to the surface of the moving body is approximated by:

\[ F = -\mu v |v|, \]

where \(\mu = \rho CS/2\) is the drag coefficient (kg-m\(^{-1}\)), \(\rho\) is the water density (kg-m\(^{-3}\)), \(C\) is the shape-dependent drag coefficient (dimensionless), \(S\) is the effective area (m\(^2\)) of the element that confronts the fluid, and \(v\) is the velocity (m-s\(^{-1}\)) of the element.

The force acting on the surface can be resolved into components normal and tangent to the element, respectively. Considering the robot be composed of a five-link serial mechanism coupled with two additional revolute pectoral links as shown in Fig. 3, the basic motions of dolphin-like swimming are governed by the following three forces: pressure on links, approach stream pressure and friction drag.

**Pressure on links** While oscillating, the hydrodynamic force acting perpendicular to the surface of the \(i\)th link is the thrust force for advancement, which is given by:

\[ F_i^+ = -\mu_i v_i^+ |v_i^+|, \quad i = 0, \ldots, N - 1 \]

where \(v_i^+ = \dot{z}_i^f s\theta_i - \dot{z}_i^f c\theta_i\) (\(i = 0, \ldots, N - 3\) for the links along the longitudinal axis), \(v_i^+ = \dot{z}_i^f s\beta_i - \dot{z}_i^f c\beta_i\) (\(i = N - 2, N - 1\) for the lateral links representing pectoral fins) is the component of the velocity perpendicular to the surface of the \(i\)th link, as shown in Figs.4(a) and (b), \((x_i^f, z_i^f)\) is the centroid of the \(i\)th link, calculated analogously from (A.1)-(A.3) by substituting the centroid for the barycenter. Similarly, \(\mu_i^+ = \rho C_1 S_i/2\) is the drag coefficient with \(C_1\) of flat plate type (Benson, 2004), i.e., \(C_1 = 1.28\). \(S_i\) is the effective area of the \(i\)th link.

**Approach stream pressure** Motion of any object through a stationary fluid causes an increase in pressure in front of it and a decrease behind it. This makes the fluid in front move away and return again behind the object. The different pressures on the two sides also give a drag force on the object, counteracting the movement, i.e., the approach stream pressure acting on the head in opposition to the motion of the robot.

Due to a large cross-section of the head followed by small-amplitude oscillations of the rear body, the drag forces acting on the posterior links can be ignored except the head. The drag force on the head can be calculated as

\[ F_0^- = -\mu_0 v_0^- |v_0^-|, \]

where \(v_0^- = \dot{z}_0^f s\theta_0 + \dot{z}_0^f c\theta_0\) is the projection of the velocity vector \((\dot{x}_0^f, \dot{z}_0^f)\) along the direction parallel to the head, as shown in Fig. 4(c). \(\mu_0^- = \rho C_2 S_\Delta/2\) is the drag coefficient with \(C_2\) of bullet type (Benson, 2004), i.e., \(C_2 = 0.295\). \(S_\Delta\) is the cross-section area of the head.

**Friction drag** This is the resistance to motion experienced by the animal on account of viscous forces. The movement of the robot’s propelling units through the fluid causes friction drag parallel to the propelling units, resulting in drag forces which act in opposition to the motion, as shown in Fig. 4(d). It is evaluated empirically (20%–50%) of the approach stream pressure, i.e., \(F_f = (0.2 \sim 0.5)F_0^-.\) In terms of the matte body of the robot, 50% is adopted here: \(F_f = 50\%F_0^-\).

**Composition of hydrodynamic forces** By resolving all the above forces in the XOZ plane, the components of the forces in the direction of \(X\)-axis and \(Z\)-axis can be expressed as:

\[
\begin{align*}
F_X &= \sum_{i=0}^{N-1} F_{ix}^{\pm} + F_{0x}^- + F_{fx} \\
F_Z &= \sum_{i=0}^{N-1} F_{iz}^{\pm} + F_{0z}^- + F_{fz}
\end{align*}
\]

(3)

where \(F_{ix}^{\pm} = F_i^+ s\theta_i, F_{iz}^{\pm} = -F_i^+ c\theta_i\) (\(i = 0, \ldots, N - 3\), \(F_{ix}^{\pm} = F_i^+ s\beta_i, F_{iz}^{\pm} = -F_i^+ c\beta_i\) (\(i = N - 2, N - 1\), \(F_{0x} = F_0^- c\theta_0, F_{0z} = F_0^- s\theta_0, F_{fx} = F_f c\theta_0, F_{fz} = F_f s\theta_0, F_f = F_f c\theta_0, F_{fz} = F_f s\theta_0, \) and \(F_f = (0.2 \sim 0.5)F_0^-\).
The composition of moment acting on the hinged joint point \((X, Z)\) is determined by:

\[
M_\Theta = N - 3\sum_{i=0}^{N-3} (-F_{ix} x^i - X) + \sum_{i=0}^{N-3} F_{iz} z^i - X)
\]

Based on (2)–(4), a system of associated equations of motion in terms of \(X, Z,\) and \(\Theta\) can be concluded by

\[
\begin{align*}
F_X &= \sum_{i=0}^{N-1} F_{ix}^i + F_{ix}^0 + F_{fx} \\
F_Z &= \sum_{i=0}^{N-1} F_{iz}^i + F_{iz}^0 + F_{fz} \\
M_\Theta &= \sum_{i=0}^{N-3} (-F_{ix}^i z^i - Z) + \sum_{i=0}^{N-3} F_{iz}^i x^i - X)
\end{align*}
\]

To solve the simultaneous equations, some initial values should be provided. Assume that \((X, Z)\) is at the origin at the initial time and the robot’s body maintains motionless in a line, i.e., \(X(0) = 0, Z(0) = 0, \Theta(0) = 0, X(0) = 0, Z(0) = 0, \Theta(0) = 0\).

The hydrodynamic force model is then determined by (5) and the oscillations of joint angle signals for J1–J6 are obtained from the activity of the CPG model as depicted in Fig. 2. Consequently, the external hydrodynamics rule the time evolution of the joint activation parameterized by the explicit time-dependent joint angle configuration which is governed by CPGs. The simultaneous kinematics–dynamics formulation can thus be solved by numerical method with boundary conditions at the initial time, to acquire the dolphin-like swimming of the robot. The dynamic modeling parameters for simulations are collected from the prototype which will not be listed here due to space limitation.

4. SIMULATIONS AND RESULTS

4.1 Simulations

To investigate the locomotor characteristics of dolphin-like swimming, the dynamic system can be simulated in Mathematica environment. Fig. 5 illustrates the simulated forward movements of dolphin-like swimming when applying the joint actuation in Fig. 2. During testing, the pectoral fins (J5–J6) oscillate relative to the horizontal plane while the posterior body (J1–J4) performs symmetrical vertical oscillations. Fig. 5(a) plots the moving trajectory with a negligible shock due to asymmetrical initial forces shown in Figs. 5(b) and (c). The robot experiences a maximum moment of about 1 N-m around \((X, Z)\) as demonstrated in Fig. 5(d), providing a reference for actuator selection. The system converges to a steady oscillation rapidly with an average speed of 34.7 cm/s.

To characterize the pitching locomotion for enhanced swimming performance, different angles of attack are exerted on the symmetrical pectoral fins, as shown in Fig. 6. For large attack angle, the robot is inclined to descend rapidly. However, asymmetrical body undulation vertically induced by unequal input drives, i.e., \(d_l < d_r\), plays a more remarkable role in the pitching motion, which is maybe due to powerless pectoral fins for thrust-producing purposes. It deserves special notice that oversized angle of attack will induce an approximatively circular movement in the vertical plane guided by the head. Fig. 7 further reveals how the propulsive speed evolves with the angle of attack. The vertical speed rises dramatically for a modest attack angle while the horizontal component degrades inversely. The resultant speed decreases slightly by reason of increased approach stream pressure caused by asymmetric pectoral flapping about the horizontal plane, which also partly verifies that the pectoral fin does not largely contribute to propulsion but modulate the posture and maintain balance.

To exhibit a great appeal to the readers, Fig. 8 depicts the comparison results of fish-like and dolphin-like modes. The simulation demonstrates that the dolphin-like swimming precedes fish-like mode with a higher speed of 6% increase at a maximum input drive \(d_l = d_r = 5\), though less remarkable. Note that the simulated data of fish-like swimming is obtained by modeling the horizontal lateral body oscillations in like manner.

4.2 Results

To advance the progress a further step forward, experiments were conducted to test the developed prototype in a lake. Fig. 8 illustrates the gathered experimental data. As expected, the testing exhibits an encouraging result for dolphin-like swimming in good agreement with the simulations. Note that the small discrepancy between simulated and actual performance would be ascribed to large hydrodynamic drag on an ill-streamlined body as well as insufficient torque fed by the currently used servomotors. More experiments are expected to broaden the exploration further.

4.3 Discussion

As a striking issue, dolphin swimming has been widely pursued by biologists, especially when compared to typical fish-like propulsion. However, system testings and comparison between different underwater vehicles are still rare, partly because of unaccessible data or experiment conduc-
tion. As an alternative to explore swimming mechanism, this paper makes an attempt to investigate the hydrodynamics of dolphin-like swimming on a well-developed robot incorporating both fish-like and dolphin-like modes, which facilitates the comparison of two distinct propulsors. The simulated and experimental results are of a great attraction, though only 6% of discrepancies have been elicited. In this sense, some oversimplified hydrodynamic forces experienced by the robot make a dent in the efficient swimming as illuminated by Fish and Rohr (1999). It deserves a further exploration of the dynamic model.

Another issue to mention is excessively rigid mechanism for sake of modular design and mechanical seal means. Stiff shells alongside unsmoothed trails present unmatchable to actual dolphin swimming. Also, simple motion patterns exhibited by the current pectoral fins related to mechanical design issues, may to some extent circumvent more wonderful agility in movement.
Fig. 5. Dolphin-like forward simulation at a frequency of 1.65 Hz with a zero angle of attack, i.e., $\alpha = 0^\circ$. (a) Simulated trajectory of dolphin-like forward swimming. (b) Resultant force in the X direction. (c) Resultant force in the Z direction. (d) Resultant moment. (e) Simulated forward speed.

5. CONCLUSION

In this paper a dolphin-like swimming dynamic system using Lagrange representation has been proposed for an amphibious robot capable of both fish- and dolphin-like motion patterns. By introducing the hydrodynamic forces experienced by the robot, the dynamic characteristics of the system were investigated through basic motion simulations, where CPG-based control signals were applied to the robot for path generation. Consequently, the model incorporated both CPG-based joint actuation law and the hydrodynamics, and captured the interactions between them. Simulations were conducted to predict the dolphin-like swimming. The roughly comparative results are very encouraging since it primarily verifies the effectiveness of the presented model.

Future work will focus on the refinement of the hydrodynamic model by extensive experiments. Additional efforts will be made to the exploration of a highly efficient, manoeuvrable and energy-saving underwater thruster.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the technical support in the construction of the amphibious robot by Prof. Weibing Wang with the Shihzei University, Xinjiang, China.

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The joint activation signal $\phi_i$ is generated from the CPG model. More mechanism parameters please refer to Fig. 3.

Fig. 8. Comparison of simulated and actual propulsive speeds between fish-like and dolphin-like modes. Note that the oscillatory frequency and amplitude increase linearly with the input drive represented by $d = d_i = d_r$, and the robot rests when $d < 1$.


Romanenko, E.V. (2002). Fish and dolphin swimming, 127.


Appendix A. KINEMATIC ANALYSIS

In this appendix, we provide a brief kinematic scheme based on geometry according to Fig. 3. The barycenter of links can be calculated as:

$$
\begin{align*}
&x_0^g = x_1 - (l_0 - l_0^g)\cos\theta_0, \\
&y_0^g = y_1 - (l_0 - l_0^g)\sin\theta_0, \\
&z_1^g = z_1 + l_1^g\sin\theta_1, \\
&z_1^g = z_1 + \sum_{j=1}^{i-1} l_j \left[ c_{\theta_j} s_{\theta_j} \right] + l_i^g \left[ c_{\theta_i} s_{\theta_i} \right] \\
&\left[ x_1^g, y_1^g, z_1^g \right] = \left[ x_1, y_1, z_1 \right] - \left( l_1, -l_h, l_i \right) \left[ c_{\theta_1} s_{\theta_1}, c_{\theta_i} s_{\theta_i} \right] + l_i^g \left[ c_{\beta_i} s_{\beta_i}, c_{\beta_i} s_{\beta_i} \right], \\
&\left( i = 2, \ldots, N - 3 \right) \\
&\left[ x_1^g, y_1^g, z_1^g \right] = \left[ x_1, y_1, z_1 \right] - \left( l_1, -l_h, l_i \right) \left[ c_{\theta_1} s_{\theta_1}, c_{\theta_i} s_{\theta_i} \right] + l_i^g \left[ c_{\beta_i} s_{\beta_i}, c_{\beta_i} s_{\beta_i} \right], \\
&\left( i = N - 2, N - 1 \right)
\end{align*}
$$

where $c$ and $s$ represent cos and sin, respectively, $\theta_0 = \theta_1 - \varphi_1$, $\theta_i = \theta_1 + \sum_{j=1}^{i-1} \varphi_j$ ($i = 2, \ldots, N - 3$), $\beta_i = \theta_0 + \alpha + \varphi_i$ ($i = N - 2, N - 1$, $\alpha$ represents the angle of attack exerted on pectoral fins). In an analogous fashion, the centroid ($x_i^c, y_i^c$) of each link can be obtained by $l_i^c$. The joint activation signal $\varphi$ is generated from the CPG model. More mechanism parameters please refer to Fig. 3.