Development of a Bio-Inspired Underwater Robot Prototype with Undulatory Fin Propulsion

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Abstract: This paper presents the design and experimental evaluation of an underwater robot that is propelled by a pair of lateral undulatory fins, inspired by the locomotion of rays and cuttlefish. Each fin mechanism is comprised of three individually actuated fin rays, which are interconnected by an elastic membrane. An on-board microcontroller generates the rays’ motion pattern that result in the fins’ undulations, through which propulsion is generated. The prototype, which is fully untethered and energetically autonomous, also integrates an Inertial Measurement Unit for navigation purposes, a wireless communication module, and a video camera for recording underwater footage. Due to its small size and low manufacturing cost, the developed prototype can also serve as an educational platform for underwater robotics.

Keywords: Undulatory fin propulsion, Bio-inspired robotic locomotion.

1. INTRODUCTION

Undulatory fin propulsion, inspired by the swimming of knifefish, rays and cuttlefish (Fig. 1), could potentially endow underwater vehicles with precision manoeuvrability and stable station-keeping, in the context of applications such as underwater structure inspection and maintenance [2]. The interest for this bio-inspired propulsion scheme stems mainly from the thrust vectoring capability of undulatory fins, and from the ability to integrate them into rigid-body underwater vehicles. Other postulated advantages of undulatory fins, compared to conventional propellers, include increased energy efficiency, reduced sediment disruption and stealth operation.

In this context, the present paper describes the development of a small underwater robot, which is propelled by a pair of laterally-mounted undulatory fins. Each fin is comprised of three serially arranged fin rays, individually actuated by R/C servomotors, and interconnected via a membrane-like elastic sheet. Section 2 of the paper overviews the kinematics of undulatory fin mechanisms. The construction and motion control of the developed prototype are described in Section 3, while Section 4 presents a series of preliminary experimental results.

![Example of aquatic species that swim by fin undulations](image)

Figure 1: Examples of aquatic species that swim by fin undulations: (a) black ghost knifefish, (b) bluespotted ribbontail ray, and (c) common cuttlefish. [3]

2. UNDULATORY FIN KINEMATICS

A schematic diagram of a generic undulatory fin mechanism is shown in Fig. 2. The mechanism’s structure is a simplified analogue of actinopterygian fins, being comprised by a total of \(N\) serially-arranged rigid fin rays, interconnected by a flexible membrane. The rays are equally distributed along the fin “backbone”, to which they are attached by 1-dof revolute joints...
that enable the rays’ lateral swiveling about the \( x \)-axis. Each joint is driven by an appropriate servomechanism that enables controlling the angular position \( q_i \) of the corresponding fin ray. The propagation of a basic uni-directional wave along the fin can be obtained by imposing the following angular trajectories for the fin ray joints:

\[
q_i(t) = A \sin (2\pi ft - (i - 1)\phi), \quad i = 1...N,
\]

where \( f \) and \( A \) denote respectively the frequency and amplitude of the rays’ oscillation, while \( \phi \) is the inter-ray phase shift. When \( \phi > 0 \) the undulatory wave propagates towards the \( N \)th ray, generating a surge (axial) force along the positive \( x \)-axis (cf. Fig. 2). Conversely, for negative values of \( \phi \) the wave propagates towards the first ray, and the surge force is towards the negative \( x \)-axis. When \( \phi = 0 \), the mechanism oscillates laterally as a single surface, and no axial force is generated. It is noted that, apart from the axially-directed component, the fin undulations also generate lateral (i.e., along the \( y \)-axis) and normal (i.e., along the \( z \)-axis) forces [1].

2.1. CPG-BASED UNDULATION SCHEME

Directly employing (1) to generate the traveling wave has the drawback that the on-line change of the undulation parameters \( \{A, f, \phi\} \) can result in abrupt and un-coordinated changes of the prescribed joint trajectories. Such discontinuities hinder the smooth transition between different undulation patterns, as would be required during precision maneuvers, and could also have a detrimental effect on the actuators driving the rays. These issues can be effectively addressed by employing artificial Central Pattern Generators (CPGs), which are inspired by the biological CPGs found in many organisms, to produce the rays’ coordinated motion patterns. In this work, the undulatory wave is generated via the CPG architecture described in [4], employing a series of coupled linear oscillators, with the desired angular profile of the \( i \)th ray (where \( i = 1...N \)) obtained from the output of the corresponding oscillator, as

\[
q_i = a_i \sin \xi_i,
\]

where the amplitude \( a_i \) and the phase \( \xi_i \) are derived from the following oscillator dynamics:

\[
\ddot{a}_i = k_{a} a_i^2 (A - a_i) - 2k_0 \dot{a}_i,
\]

\[
\ddot{\xi}_i = 2c(N - 1)(2\pi f - \dot{\xi}_i) - c^2 \sum_{j=1,j\neq i}^{N} (\dot{\xi}_i - \xi_j - (i - j)\phi_0).
\]

In the above equations, \( f \) and \( A \) represent the desired frequency and amplitude of the oscillators’ outputs, while \( k_a \) determines the rate of convergence for \( a_i \) to its setpoint value, according to the critically damped second order dynamics of (2). The second term in the r.h.s. of (3) describes the CPG interconnection scheme, where \( c \) is the inter-oscillator coupling strength, while \( \phi_0 \) is the steady state phase shift in the outputs between two consecutive oscillators, as per (1).

3. BIO-INSPIRED UNDERWATER ROBOT PROTOTYPE

This Section presents a compact-sized, fully untethered robotic prototype (Fig. 3a), developed as an experimental platform to study the integration of undulatory fins in underwater vehicles.
3.1. MECHANICAL DESIGN AND FABRICATION

The developed prototype (overall length: 24 cm, overall width: 57 cm) features a tube-shaped hull with a pair of laterally-mounted fin propulsors. An exploded view, illustrating the main elements of it’s mechanical assembly, is shown in Fig. 3b. The robot employs a total of 6 individually-actuated fin ray units, 3 per each fin, which are driven by waterproof R/C servomotors (Savox SW1210SG). The overall length of each fin assembly is 14.6 cm and it’s height is 17.5 cm. The elastic membrane used in the fins was created from a 0.275 mm-thick sheet of silicone rubber. Each fin ray is comprised by two 2 mm thick aircraft-grade aluminium rectangular plates (height: 18.5 cm, width: 0.6 cm), with the membrane secured in-between them via 4 pairs of nuts and bolts. The rays are attached to the motor’s output shaft through a CNC-milled custom hub. The servomotor is secured inside a custom housing, built in ABSplus material using a 3d-printer (Stratasys Dimension Elite).

The main hull has been constructed from a Ø100 mm piece of PVC tubing. Two rectangular PVC pieces, serving as the fin “backbones”, were manufactured and glued, one on each side of the hull. The fin ray modules are fastened to these pieces using threaded rods and nuts. Two CNC-machined lids are used to seal the front and back side of the tube. The front lid is made of plexiglass, in order to allow placing a camera inside the vehicle (Fig. 3a), and to facilitate inspection of the enclosed electronics. The rear lid is made of PVC and holds two glands for the servomotors’ wires that exit the hull, a USB connector for programming the onboard microcontroller, and a connector for charging the battery inside the hull. Two backing ring flanges, with a gland milled on their outside flat surface for an o-ring seal, were manufactured out of PVC and glued on the tube’s front and back side. The lids are fastened on the backing rings using M6 nuts and bolts, over a circular pattern of 8 holes drilled on both the backing rings and the lids. A 4-axis Haas VF-2 and a 3-axis Haas TM-1P Vertical Machining Centre, as well as a conventional lathe, a drill press and other tools were used for the manufacturing of the PVC, aluminium and plexiglass parts. All the CAD modelling and CAM programming was done in PTC Creo 2.0 Parametric software.

3.2. ELECTRONICS AND CONTROL ARCHITECTURE

The developed robotic prototype is fully untethered and energetically autonomous, powered by an on-board lithium polymer 7.4 V battery. The main control unit is an 8-bit microcontroller platform (Arduino Mega 2560), running a custom-developed real-time firmware that implements two CPG networks (as described in Section 2.1) to generate the undulatory motion profile for the robot’s two fins, in terms of the rays’ desired angular positions. The latter are then used

![Figure 3: (a) The bio-inspired underwater robot prototype. (b) Exploded view of the robot’s mechanical assembly. The inset shows the components of the fin ray modules.](image-url)
to specify accordingly the PWM control signals, generated by the microcontrollers’ hardware
timers, to the R/C servos driving the rays (Fig. 4). The microcontroller also receives data
regarding the attitude of the vehicle (roll, pitch, and yaw angles, see Fig. 5) from an on-board
Inertial Measurement Unit (Orientus, Advanced Navigation), which are employed for navigation
purposes. A communication protocol, implemented over a bluetooth link, allows the wireless
relay of the IMU data, at a 100 Hz rate, to an external PC.

Figure 4: The developed control architecture of the robotic prototype.

3.3. MOTION CONTROL

The undulatory motion pattern for each of the robot’s fins is produced by a dedicated CPG
network, as described in Section 2.1. We may then define the kinematic parameter sets for the
left and right fins as $P_L = \{A_L, f_L, \phi_L\}$ and $P_R = \{A_R, f_R, \phi_R\}$, respectively. Similar to differential-
drive land vehicles, when the two fins produce the same thrust, the robot will move in a straight
line (Fig. 6a), in the direction opposite to that of the fins’ undulation. Any asymmetry in the
undulations of the two fins will cause a turning motion of the robot (Fig. 6b). In-place rotations
can be generated when the two fins produce equal thrusts but in opposing directions (Fig. 6c).
These basic motion primitives can be obtained via simple open-loop specification of the two
fins’ undulation parameters, e.g., setting $P_L = P_R$ will yield forward motion along a straight
line, where the surge velocity can be increased/decreased by increasing/decreasing either the
amplitude $A$ or the frequency $f$ of the rays’ oscillations. In practice, this simplistic approach
may be compromised by the effect of external disturbances (e.g., water currents) and/or the
inherent variabilities of the fin ray actuators, both of which will cause the robot to deviate from
its desired trajectory. To address these issues, as well as to allow the implementation of more
advanced path following and navigation strategies, the following closed-loop control schemes
have been developed, in which the undulation parameters of the two fins are adjusted according
Forward swimming with closed-loop heading control: Denoting as $\theta_d$ the desired heading of the robot, a simple proportional controller can be implemented, by adjusting the amplitude of the two fins’ undulations according to the error $e_\theta = \theta_d - \theta$, as per the following law:

$$A_L = A_0 - e_\theta k_p \quad \text{and} \quad A_R = A_0 + e_\theta k_p,$$

where $A_0$ denotes the rays’ oscillation amplitude when the heading error is $e_\theta = 0$, while $k_p$ is the control gain. In this approach, the other two kinematic parameters of the fins’ undulations are specified to be equal (i.e., $f_L = f_R$ and $\phi_L = \phi_R$).

Closed-loop heading regulation via in-place rotations: This motion control scheme, involving regulation of the robot’s heading without simultaneous translation, is obtained by specifying $f_L = f_R$ and $\phi_L = -\phi_R = \phi \text{sgn} (e_\theta)$, while adjusting the rays’ oscillation amplitude according to:

$$A_L = e_\theta K_p \quad \text{and} \quad A_R = e_\theta K_p,$$

where $K_p$ is the gain of the proportional control law.

4. EXPERIMENTAL RESULTS

In order to assess the efficacy of the developed motion control schemes, a series of tests were conducted with the prototype swimming inside a laboratory tank (dimensions: 210 x 90 x 50 cm). An external video camera, positioned above the tank, was used to track the motion of the robot, via a red circular marker mounted on the upper side of it’s main hull.

Indicative results, demonstrating the developed scheme for forward swimming with closed-loop heading control, obtained with $A_0 = 12^\circ$, $k_p = 3.5$, $\phi_L = \phi_R = 60^\circ$, and $f_L = f_R = 1.75$ Hz, are shown in Fig. 7. It can be seen that the robot traverses the length of the tank along a straight-line trajectory, while maintaining it’s heading angle within $\pm 4^\circ$ of the desired value of $\theta_d = 0^\circ$, despite significant disturbances arising from waves reflected at the walls of the tank. The average swimming velocity at steady-state, for this particular run, was about 20 cm/sec.

The results in Fig. 8 demonstrate the behavior of closed-loop heading regulation via in-place rotations, obtained with $K_p = 0.6$, $\phi = 60^\circ$, and $f_L = f_R = 1.5$ Hz. The robot adjusts it’s heading, initially at $\theta = 0^\circ$, to the desired value of $\theta_d = 90^\circ$ with very limited overall translation (Fig. 8a). The heading response (Fig. 8b) exhibits a settling time of about 8s, as well as some transient overshoot and a small steady-state error.

5. CONCLUSIONS

We have presented a compact-sized robotic submersible featuring a pair of undulatory fins, which, as highlighted by our results, may serve as a platform for investigating motion control
and navigation strategies, towards the integration of this bio-inspired propulsion method in full-scale underwater vehicles. Due to its small size and low manufacturing cost, the developed prototype can also serve as an educational platform for underwater robotics.

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7. REFERENCES


