2024 IEEE International Conference on Robotics and Automation (ICRA 2024)
May 13-17, 2024. Yokohama, Japan

Sea-U-Foil: A Hydrofoil Marine Vehicle with Multi-Modal Locomotion

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Abstract— **Autonomous Marine Vehicles (AMVs) have been widely used in many critical tasks such as surveillance, patrolling, marine environment monitoring, and hydrographic surveying. However, most typical AMVs cannot meet the diverse demands of different marine tasks. In this article, we design a new type of remote-controlled hydrofoil marine vehicle, named Sea-U-Foil, which is suitable for different marine scenarios. Sea-U-Foil features three distinct locomotion modes, displacement mode, foilborne mode, and submarine mode, which enable the platform flexible mobility, high-speed and high-load capacities, and superior concealment. Specifically, the submarine mode makes Sea-U-Foil unique among previous studies. In addition, the performance of Sea-U-Foil in foilborne mode outperforms those of most current unmanned surface vehicles (USVs) in terms of speed and payload. To the best of our knowledge, we are the first to introduce a new type of AMV that can work in displacement mode, foilborne mode, and submarine mode. We elaborate on the design principles and methodologies of Sea-U-Foil first, then validate the effectiveness of its tri-modal locomotion through extensive experiments.**

I. INTRODUCTION

AMVs have attracted a lot of attention from academic and industrial communities as a result of technological advancements and the growing passion in exploring ocean resources. As AMVs feature high efficiency, cost-effectiveness, enhanced safety, and reduced environmental impact compared with manned marine vehicles, they are widely employed in many marine tasks, including environmental sampling and inspection, patrol and surveillance, marine resource exploration, search and rescue [1]–[4].

There are many different types of AMVs, such as USVs [5] [6], remotely operated vehicles (ROVs) [7] [8], autonomous underwater vehicles (AUVs) [9], [10], and autonomous wave gliders [11]. While these AMVs can be integrated into various marine operations, their specific designs often restrict them to particular tasks due to structural and propulsion system limitations. For instance, USVs are characterized by rapid response, high payload capacity, and adaptability, making them suitable for surface missions like search and rescue, patrol, and surveillance. However, their inherent buoyancy, which typically far exceeds their gravitational, prevents them from undertaking underwater operations. Similarly, ROVs, primarily designed for underwater tasks, are not optimal for surface operations. Given these constraints, there is a open space for research to find a new type of AMV versatile enough to operate across diverse marine scenarios and tasks.

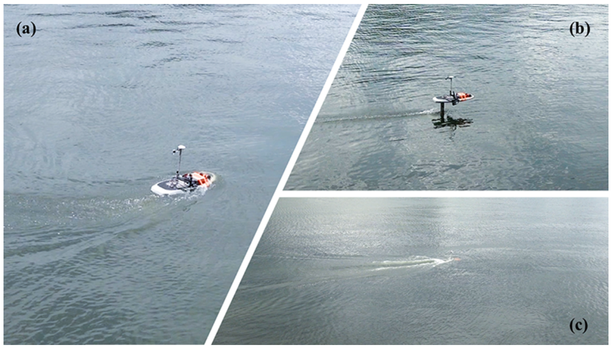

Fig. 1: Different locomotion modes of Sea-U-Foil. (a): Displacement mode; (b): Foilborne mode; (c): Submarine mode.

Many researchers have dedicated significant efforts to expand the application range of unmanned systems by designing cross-domain vehicles [12] [13]. Rockenbauer et al. [14] introduced an aerial-aquatic unmanned vehicle named Dipper, which melds the features of fixed-wing aircraft and underwater vehicles. In the air, Dipper operates as a typical fixed-wing aircraft and transitions to a fully swept configuration for underwater operations. Liu et al. developed an aerial-aquatic vehicle, TJ-FlyingFish, derived from quadrotor designs [15]. Equipped with customized tiltable propulsion units, TJ-FlyingFish can fly as a conventional quadrotor in the air and also navigate efficiently underwater. However, constraints related to battery endurance and the structure of aerial vehicles mean these cross-domain vehicles face limitations in operational range and payload.

Electric hydrofoil surfboards, commonly referred to as eFoils, have seen a surge in popularity in recent years, offering a unique watersport experience for riders [16]. The innovation of eFoils stems from integrating a conventional surfboard with a hydrofoil and an electric propulsion system positioned beneath the board. This design allows eFoils to achieve speeds of up to $14\,\mathrm{m/s}$ and support a maximum payload of $120\,\mathrm{kg}$. Building on the eFoil concept, Isaly et al. introduced two novel USVs: UF [17] and Medi-gator [18]. Equipped with additional control surfaces and motion controllers, these vehicles can swiftly glide over the sea surface autonomously, without the need for riders. While UF and Medi-gator retain the advantages of eFoils and surpass the performance of many USVs, their design confines them to surface operations.

The lower sections of both UF and Medi-gator bear

The work was supported in part by the InnoHK of the Government of the Hong Kong SAR via the Hong Kong Centre for Logistics Robotics.
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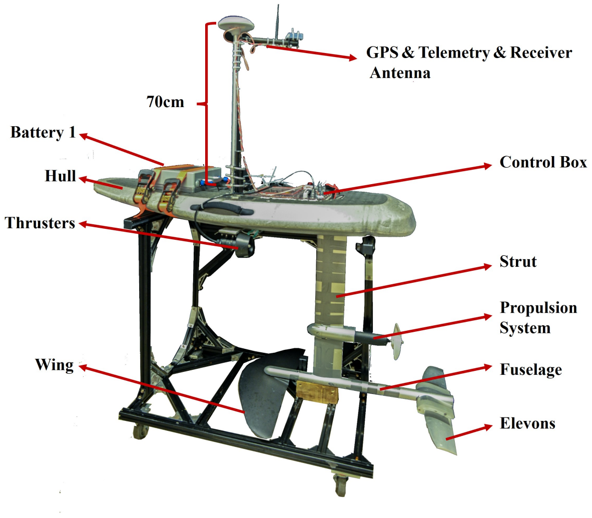

Fig. 2: The prototype of Sea-U-Foil

structural similarities to the flying-wing design, hinting at a potential capability to submerge and undertake underwater tasks. Inspired by this observation and building upon the structure of UF, we introduced a novel hydrofoil marine vehicle named Sea-U-Foil, distinguished by its multi-modal locomotion capabilities as shown in Fig. 1. Sea-U-Foil can operate in three distinct locomotion modes: displacement, foilborne, and submarine modes, based on the configuration of its actuators and its operation scenarios. This tri-modal operation is our main contribution of our work. Each mode endows Sea-U-Foil with unique attributes, enabling it to handle a spectrum of tasks that would traditionally require the collaboration of multiple marine vehicles. The versatile locomotion capabilities of Sea-U-Foil greatly expand its potential applications, positioning it as a preferred option for marine missions.

The structure of this paper is as follows. In Section II, we provide a concise overview of the working principle behind Sea-U-Foil's multi-modal locomotion. Section III elaborates on the prototype design methods. Section IV validates the effectiveness of the three locomotion modes through comprehensive experiments. Finally, Section V presents a brief conclusion.

II. SYSTEM OVERVIEW

As depicted in Fig. 2, Sea-U-Foil represents a novel marine vehicle equipped with a hydrofoil, boasting multi-modal locomotion capabilities. The dimensions of Sea-U-Foil are $170\,\mathrm{cm}$ in length, $73\,\mathrm{cm}$ in width, and $90\,\mathrm{cm}$ in height, with an approximate weight of $50\,\mathrm{kg}$. The vehicle comprises two main sections: the upper and lower parts. These sections are interconnected by a strut, onto which a propulsion system is affixed. The upper section houses the hull of Sea-U-Foil, two thrusters, batteries, a control box, and antennas. Conversely, the lower section contains a fuselage, a front wing (or hydrofoil), and two elevons, each controlled by one servo.

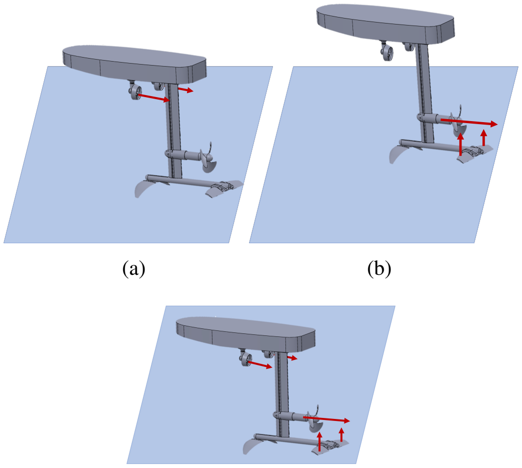
(a)
(b)
(c)

Fig. 3: The actuators and control surfaces used in different locomotion modes. The red arrows stand for the forces generated by the actuators and control surfaces. The length of arrows means the relative scales of forces. (a): Displacement mode; (b): Foilborne mode; (c): Submarine mode

In the upper part, almost all the electronics are sealed in the control box, which is affixed to the upper surface of the hull. To mitigate electromagnetic interference from seawater, the antennas for GPS and telecommunication, as well as the receiver for the remote controller, are elevated on a stick measuring $70\,\mathrm{cm}$ in length. The thrusters located beneath the hull can produce both forward and backward thrusts and are independently controlled by PWM signals. The design of the lower part is similar to flying-wing structures [19] [20]. The front wing, akin to those on flying-wing aircraft, features a longer upper surface and a shorter lower surface. As per Bernoulli's principle, an upward lift is generated as the hydrofoil traverses the water [21] [22]. The elevons function similarly to those on flying-wing designs, adjusting or maintaining Sea-U-Foil's attitudes. The propulsion system, encompassing a motor and a propeller, powers Sea-U-Foil's forward movement.

Depending on the hull's position relative to the water surface and the actuators in use, three motion modes including displacement, foilborne, and submarine modes can be identified.

1) Displacement mode: The displacement mode is the simplest, safest, and most stable motion mode of Sea-U-Foil. In this mode, Sea-U-Foil operates similarly to a catamaran, which utilizes differential thrusts. This configuration affords Sea-U-Foil three degrees of freedom (DOFs): surge, sway, and yaw. Generating forward thrusts propels Sea-U-Foil forward, while backward thrusts enable rearward movement. The yaw angle is adjusted through differential thrusts. The actuators employed in the displacement mode are illustrated in Fig. 3(a). When the thrusters produce entirely opposing thrusts, Sea-U-Foil can execute sharp turns within confined spaces, allowing for navigation in narrow environments with a minimal turning radius.

2) Foilborne mode: In foilborne mode, Sea-U-Foil's hull is lifted out of the water by the hydrodynamic lift force generated by the wing, while the propulsion system and the lower part of Sea-U-Foil are still submerged in the water.

The lift L generated by the front wing is described as follows:

$$L = \frac{1}{2}\rho V^2 S C_L, \tag{1}$$

where ρ is the density of the seawater, V represents the velocity of the wing through the water, S stands for the planform area of the wing, and C_L is the lift coefficient which is affected by the profile of the wing [23]. As inferred from (1), the lift is directly proportional to the velocity squared. In the foilborne mode, the lift should approximately match Sea-U-Foil's weight. Hence, the foilborne mode is typically achieved when Sea-U-Foil attains a predefined speed.

In the foilborne mode, Sea-U-Foil possesses 6 DOFs: surge, sway, heave, roll, pitch, and yaw. The elevons stabilize Sea-U-Foil's attitudes in a manner analogous to the elevons on flying wings. The surge, heave, and sway motions of Sea-U-Foil are achieved through the regulation of motor rotation, pitch angle adjustment, and roll angle control, respectively. The actuators and control surfaces utilized in the foilborne mode are depicted in Fig. 3(b).

When compared to traditional USVs, such as mono-hulls and catamarans, Sea-U-Foil offers several advantages in the foilborne mode. In this mode, the contact area between Sea-U-Foil and the sea is substantially reduced, leading to diminished water drag. This reduction in drag allows Sea-U-Foil to achieve higher speeds and greater energy efficiency than conventional USVs. Additionally, when Sea-U-Foil works in foilborne mode, the increased speed may indirectly contribute to a greater payload, as suggested by (1).

3) Submarine mode: By adjusting the pitch angle upwards or downwards, flying wings can either climb or dive vertically while airborne. Given its structural similarities to flying wings, Sea-U-Foil can also submerge and operate as a submarine when its pitch angle is directed downwards. This is the submarine mode of Sea-U-Foil.

Like the foilborne mode, Sea-U-Foil's submarine mode encompasses 6 DOFs. Upon submersion, two thrusters located beneath the hull are activated, facilitating a more intuitive control strategy. These thrusters not only generate forward propulsion but also modify Sea-U-Foil's yaw angle, mirroring the approach used in the displacement mode. The remaining DOFs are managed using methods akin to those in the foilborne mode. The actuators and control surfaces employed in the submarine mode are illustrated in Fig. 3(c).

Operating underwater expands Sea-U-Foil's range of applications, including covert surveillance, potential offensive operations, and serving as a signal relay for submarine sensors.

TABLE I: Machinery elements design

	Materials	Specifications
Hull	EPP & Al alloy	$167 \times 73 \times 16\,\mathrm{cm}$ $110\,\mathrm{L}$ $12.6\,\mathrm{kg}$
Wing	Carbon fiber	$69.5 \times 22.4 \times 4.4\,\mathrm{cm}$ $0.9\,\mathrm{kg}$
Propeller	Stainless Steel	$7.25 \times 6\,\mathrm{in}$
Strut	Al alloy (CNC)	$80\,\mathrm{cm}$
Fuselage	Al alloy (CNC)	$90\,\mathrm{cm}$
Elevon	Al alloy (CNC)	NACA 66
Motor Cover	Al alloy (CNC)	\
Screw	316 SS	Use with grease
Total weight	$50\,\mathrm{kg}$	
Dimensions	$170 \times 73 \times 90\,\mathrm{cm}$	

III. PROTOTYPE DESIGN

A. Mechanical Design

The mechanical components of Sea-U-Foil encompass the hull, wing, propeller, strut, fuselage, elevons, and motor cover. In this subsection, we elaborate on the design details of these mechanical elements, as presented in Table I.

The hull is fabricated from expanded polypropylene (EPP) material, reinforced with an internal framework of aluminum alloy. Its dimensions are $167\,\mathrm{cm}$ in length, $73\,\mathrm{cm}$ in width, and $16\,\mathrm{cm}$ in height, boasting a displacement of $110\,\mathrm{L}$. The front wing, constructed of carbon fiber, is a commercially sourced product. It spans $69.5\,\mathrm{cm}$ in length, $22.4\,\mathrm{cm}$ in width, and $4.4\,\mathrm{cm}$ in thickness, with a weight of $0.9\,\mathrm{kg}$. The propeller, made from stainless steel, has a diameter of $7.25\,\mathrm{inches}$ and a pitch of $6\,\mathrm{inches}$.

We designed the other components of Sea-U-Foil using Solidworks software, and they were manufactured using computer numerical control (CNC) techniques. In the foilborne mode, the water plane area of Sea-U-Foil is dependent on the cross-sectional dimensions of the strut. To minimize the effects of waves and water on Sea-U-Foil, we designed the strut with a drop-shaped cross-section. The fuselage is shaped like a long cylinder with a bullet-shaped head, which further reduces water drag. Additionally, it has a customized tail to house the servos. Sea-U-Foil's elevons are based on the NACA 66 airfoil profile, chosen for its excellent lift coefficient and ease of manufacturing and installation.

The self-designed components are made of Al alloy. Al alloy is widely favored in various industries for its low density, good formability, and high strength. Additionally, aluminum alloy inherently resists corrosion in salt water, thanks to a thin, protective oxide layer on its surface. All components are assembled using screws made of 316 stainless steel (316 SS) and are further secured with grease. This particular stainless steel variant is chosen for its superior strength and resistance to seawater corrosion, while the grease acts as a barrier between the seawater and the screw threads, offering additional protection.

TABLE II: Component selections

Component	Model and specifications
Controller	CUAV-V5+
Batteries	58V 44AH /LiPo6S 10000mAh
Motor	Maytech MTI65162 $10\,\mathrm{N\,m}$
ESC	MT300A-WP 300A
Thruster	SP-TH80 $7.5\,\mathrm{kg}/5.3\,\mathrm{kg}$
Servos	kingmaxS180 $180\,\mathrm{kg\,cm}$
Receiver	R7008BS

B. Electronics

The electronics design of Sea-U-Foil is illustrated in Fig. 4. The controller employed in Sea-U-Foil is CUAV V5+, designed in accordance with the Pixhawk FMUv5 design standard and is fully compatible with both PX4 and ArduPilot firmware. The CUAV V5+ is equipped with a magnetometer, a barometer, and three 6-axis inertial measurement units, each combining a 3-axis gyroscope and a 3-axis accelerometer. Data from these sensors are utilized to estimate the attitudes of Sea-U-Foil. Additionally, GPS data are fused to determine the precise positions of Sea-U-Foil.

Sea-U-Foil is equipped with five actuators: a propulsion system (comprising a motor and propeller), two servos, and two thrusters. All of these are controlled by PWM signals from CUAV-V5+. For the propulsion system, a critical consideration is its ability to provide sufficient forward force for Sea-U-Foil. We choose a commercial propulsion system capable of propelling an eFoil forward and lifting an adult above the sea surface. This propulsion system offers a maximum torque of about $10\,\mathrm{N\,m}$. In foilborne and submarine modes, two servos control the rotation of the attached elevons. To ensure agile maneuvers, the servos must produce output torques robust enough for the elevons to counter the substantial water resistance due to Sea-U-Foil's weight and speed. For this purpose, we select KingmaxS180, known for its impressive stall torque of $180\,\mathrm{kg\,cm}$ and a rapid response speed of $0.11\,\mathrm{s}/60°$. To facilitate flexible operations in confined spaces during displacement mode, we choose thrusters capable of producing a maximum forward thrust of $7.5\,\mathrm{kg}$ and a backward thrust of $5.3\,\mathrm{kg}$.

Electromagnetic interference originating from inductive loads can adversely affect the system's performance. In Sea-U-Foil's electronics system, the motor serves as the primary source of this interference. To mitigate these effects and enhance system stability, two separate batteries are employed. Battery 1 powers the propulsion system, while Battery 2, housed within the control box, supplies energy to the other electronic components. Additionally, a DC-DC module, connected to Battery 2, is utilized to isolate interference originating from the servos and thrusters.

Furthermore, the Xavier NX is employed to manage complex tasks such as motion planning, obstacle avoidance, and localization. A summary of the chosen components can be found in Table II.

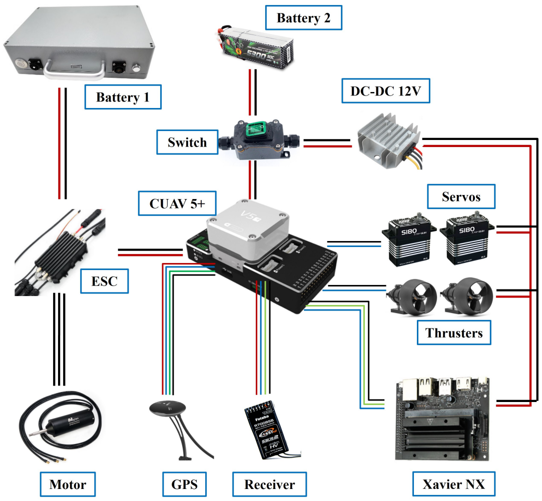

Fig. 4: Electronics design of Sea-U-Foil

C. Waterproof design

Ensuring a high level of water resistance is of paramount importance for Sea-U-Foil. To address the water-tightness issue and mitigate saltwater corrosion, the following waterproof measures are taken. First, wires are interconnected using waterproof connectors, with their internal cavities further sealed with epoxy resin for enhanced protection. Next, the electronics discussed in the previous subsection are housed within a control box constructed from acrylic sheet material. O-rings, in conjunction with grease, are employed to bolster the water-tightness of the control box. Although the manufacturer asserts that Kingmax180 servo possesses IPX8 waterproof performance, this does not take into account the unique challenges posed by seawater conditions, leading to suboptimal waterproofing in marine environments. To augment the waterproof performance of the servos, we apply silicone grease and dielectric oil, adopting the methodology outlined in [24].

D. Software Design

State estimation and controller design constitute the primary components of software design. We directly employ the EKF2 module in PX4 for state estimation, given its robustness and accuracy, which have received independent validation from numerous researchers and engineers. In this subsection, our emphasis is on the controller design for Sea-U-Foil.

The primary objective of this paper is to demonstrate the feasibility of Sea-U-Foil's various locomotion modes, and thus, straightforward control techniques are adopted. In the displacement mode, feasibility is illustrated using an open-loop controller, where two distinct PWM channels independently control the two thrusters. For the foilborne and submarine modes, feasibility is evident only when the attitudes are stabilized. Consequently, closed-loop controllers are designed for these two modes, as depicted in Fig. 5.

The controllers are adapted from [17] and the attitude controller in PX4 [25]. In the controller diagram, the com-

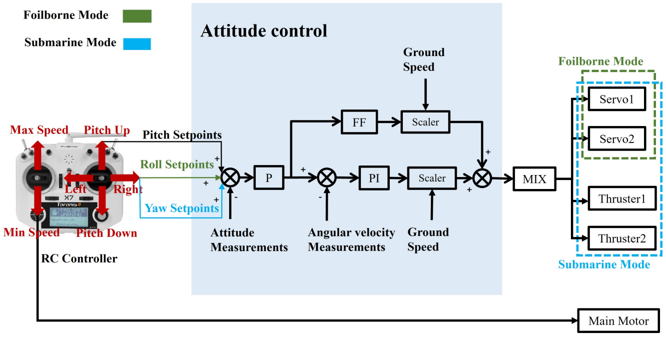

Fig. 5: Controller diagram of foilborne and submarine modes

Fig. 6: Test results of Sea-U-Foil in displacement mode

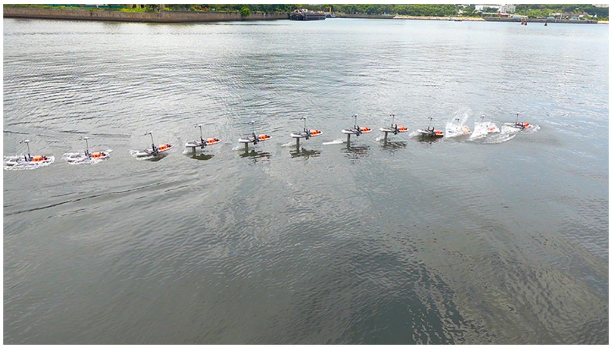

Fig. 7: Test results of Sea-U-Foil in foilborne mode

mands originate from the remote controller. The thruster channel of the remote controller outputs the control signal for the main motor, while the right stick of the remote controller provides the attitude setpoints. The error between attitude setpoints and measurements is fed into a cascade PID controller, where an outer loop employs a P controller and an inner loop utilizes a PI controller. To compensate for hydrodynamic damping, a feedforward controller is implemented. Given that the effectiveness of control surfaces varies at different speeds, two scalars associated with ground speed measurements are employed to address this issue. The output from the cascade PID controller undergoes further processing by a mixer, which allocates the control commands to specific actuators. The speed of Sea-U-Foil is managed using an open-loop method, meaning the control signal from the remote controller is directly relayed to the electronic speed controller (ESC) of the main motor.

In the foilborne mode, the Left/Right channel of the controller provides roll setpoints. Two primary reasons dictate this choice: First, the configuration with two elevons lacks control surfaces to regulate the yaw angle. Second, the yaw rate is coupled with the roll angle [20]. Contrastingly, in the submarine mode, the Left/Right stick of the controller outputs yaw angle setpoints. This is because the two differential thrusters can directly control Sea-U-Foil's heading. Furthermore, the actuators employed in the foilborne and submarine modes differ. Specifically, the mixer allocates control commands from the PID controller to two servos in the foilborne mode, but in the submarine mode, it allocates to both two servos and two thrusters.

IV. EXPERIMENTAL RESULT

To validate the effectiveness of the three distinct locomotion modes of Sea-U-Foil, we conducted an extensive series of field experiments.

A. *Displacement mode*

To investigate the feasibility of Sea-U-Foil's displacement mode, we directed Sea-U-Foil to navigate the 2D sea surface using two differential thrusters independently. The test results, depicted in Fig. 6, demonstrate that Sea-U-Foil can move smoothly on a 2D surface, underscoring the practicality of the displacement mode.

B. *Foilborne mode*

As indicated by equation (1), the lift generated by the wing is proportional to the square of the velocity. Therefore, the lift can counterbalance Sea-U-Foil's gravity and facilitate effective operation in foilborne mode when the speed exceeds a specific threshold. Through extensive experimentation, this speed threshold is determined to be approximately $4\,\mathrm{m/s}$. After arming the system, we initially increase the throttle, and once Sea-U-Foil reaches the speed threshold, we set a positive pitch angle to level the hull above the sea surface. The hull's altitude above the sea surface can be maintained by fine-tuning the pitch angle manually. The landing process is achieved by setting a negative pitch angle or reducing the throttle. The entire foilborne mode process, including take-off, gliding over the water, and landing, is depicted in Fig. 7. The attitude control results of Sea-U-Foil in foilborne mode are illustrated in Fig. 8, indicating that Sea-U-Foil can approximately follow the attitude setpoints. Discrepancies between measured results and setpoints may arise due to wave influences.

A distinguishing feature of Sea-U-Foil in foilborne mode is its capability to attain higher speeds than typical USVs. This is attributed to the reduced water drag experienced when gliding over the sea surface. We conducted a series of experiments to determine Sea-U-Foil's maximum speed, and the highest recorded velocity to date is approximately $8\,\mathrm{m/s}$. This speed surpasses that of most small surface vessels with dimensions or propulsion system power comparable to Sea-U-Foil. A detailed comparison can be found in Table III.

TABLE III: Maximum speeds of different USVs

Model	APACHE6 [26]	SZ40 [27]	Q-Boat 1800 [28]	Catarob [29]	Sea-U-Foil
Max Speed (m/s)	5	3	5	2	**8**

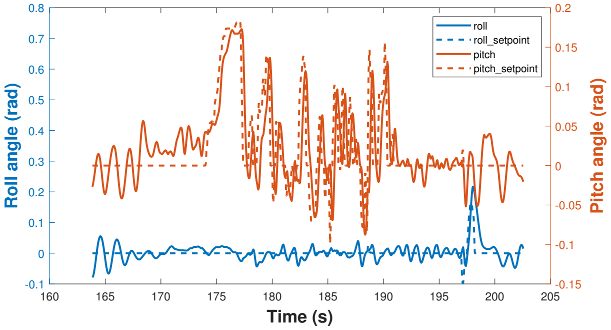

Fig. 8: Test results when working in foilborne mode

C. Submarine mode

Data connectivity is a primary concern for many underwater vehicles, as water significantly impedes the data transmission of telemetry, remote control, and GPS. Without a reliable data connection, determining the precise location of Sea-U-Foil and controlling the vessel effectively becomes challenging.

While the primary focus of this article is to evaluate the effectiveness of Sea-U-Foil's three locomotion modes, we employ a straightforward method to address the data transmission issue, as illustrated in Fig. 2. The receiver of the remote controller, along with the antennas for GPS and telemetry, are affixed to an aluminum stick, positioned 70 cm away from the hull. In the submarine mode, when Sea-U-Foil is submerged, this stick extends above the water surface, ensuring data connectivity. Although the stick's length limits Sea-U-Foil's submersion depth, it doesn't hinder the testing of the submarine mode. Future endeavors may focus on developing a dedicated underwater positioning and data connection system for Sea-U-Foil's submarine mode, aiming to increase operational depth and enhance data transmission capabilities.

The control methods of diving into the water, surging underwater and emerging from the water in submarine mode are similar to the methods in foilborne mode. When reaching the speed threshold, Sea-U-Foil can dive into the water by setting a negative pitch angle setpoint. The depth of Sea-U-Foil underwater can be controlled by adjusting the pitch angle. Emerging from the water is performed by setting a positive pitch angle or reducing the speed of Sea-U-Foil. The field test performance is shown in Fig. 9.

V. CONCLUSION

In this paper, we introduce Sea-U-Foil, a novel hydrofoil marine vehicle designed to offer innovative solutions for marine missions. Distinguished by its three locomotion modes: displacement, foilborne, and submarine modes, Sea-U-Foil boasts versatile maneuverability, high-speed and high-load capacities, and exceptional concealment. This design allows Sea-U-Foil to operate both above and below the water surface, catering to a diverse range of marine tasks. Notably, its ability to dive in submarine mode and its superior performance in foilborne mode stand out as key features. Until now, we just design the attitude controller of Sea-U-Foil, and the attitudes commander comes from remoter controller. Future research will focus on the development of robust attitude controllers, position controller, trajectory tracking algorithms for all three locomotion modes. Besides that, seamless transition between foilborne and submarine modes is also our key research point.

Fig. 9: Test results of Sea-U-Foil in submarine mode

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