# An Unmanned Aerial-Surface Vehicle Hybrid Outfitted with a Transformable Housing

Chung Hsuan Tsai, Armagan Elibol, and Nak Young Chong

***Abstract*—Waterborne vessels have advanced in many ways over the last two decades. However, their usage and deployment are still labor and expertise-intensive. They need to be transported by a surface vessel to the deployment area, which causes a substantial increase in transportation and logistics costs. In this paper, a modular design approach to the universal robotic housing is presented for off-the-shelf UAVs that enable them to operate on the water surface using the thrust force transferred from the UAV rotors through a clutch mechanism. The transformable robotic housing is outfitted with a waterproof cover sliding back and forth on its frame by a servo motor integrated link mechanism. The waterproof cover opens and closes depending on whether the UAV unit is airborne or on the water surface. Compared to the custom-built UAV-USV hybrid vehicle or collaborative operations of two individual vehicles, the proposed housing, which is easily reproducible and disposable, can be straightforwardly scaled to accommodate off-the-shelf UAVs of any size. Initial experiments have been conducted in an in-lab testbed and demonstrated a promising validation toward its practical applications.**

## I. INTRODUCTION

Increased research efforts within unmanned aerial vehicles (UAVs) seek to expand their presence in a variety of applications, such as entertainment (*e.g.*, complex missions beyond aerial video and image capture [1], entertainment show [2]), commercial delivery (*e.g.*, Amazon's Amazon Prime Air UAV delivery business), natural disaster and environmental monitoring, land use survey, and topographic mapping, mostly in terrestrial areas [3], [4]. On the other hand, there has lately been an increase in unmanned vehicle-assisted tasks in the aquatic environment [5], [6], [7], [8] including territorial defense, marine science and oceanography, pipeline laying and maintenance, offshore structure inspection, and seabed survey, and many similar others. The need for multi-mission/purpose transformable platforms in various environmental media remains high, especially the vehicles capable of operating both in the air and water (*e.g.*, UAV-based inspection tasks for offshore wind turbines). Although many robotic vehicles are available for consumer use operating in water media (*e.g.*, Unmanned Surface Vehicles (USVs), Autonomous Surface Vehicles (ASVs)) and in the air separately (UAVs), a limited amount of research has been conducted to develop a multi-medium unmanned vehicle. Such a vehicle deserves more attention and significantly reduces deployment and logistical issues such as transportation, deployment, and human intervention.

All authors are with the School of Information Science, Japan Advanced Institute of Science and Technology, Nomi, Ishikawa 923-1292, Japan `{s2010070, aelibol, nakyoung}@jaist.ac.jp`

The main objective of this research is to design a transformable housing that enables an off-the-shelf UAV to move and navigate autonomously on the water surface. In addition, the housing provides the UAV with exploration capabilities performing a number of data collection tasks (collecting water samples, optical data collection, and many others) in a water environment. The housing is designed to open and close autonomously by a servo motor depending on whether the UAV is airborne or lands on water. During the opening and closing, the housing-mounted propeller is automatically connected and separated from the UAV rotor shaft. The housing propellers will be connected to the UAV rotor shaft, turning the force of the UAV propeller into the thrust so that the housing can move to different locations without carrying additional motors, which significantly reduces the overall payload. It is also possible to control the housing by controlling the speed of rotation of the UAV propeller. Moreover, the power required to move on the water is also less than that required by the UAV flying in the air. The battery life of the UAV can be increased when moving from one location to another on the water surface.

A basic operational principle is shown in Fig. 1, where the waterproof housing in yellow color remains open in the UAV mode, allowing the vehicle unit to fly with being least affected by aerodynamics. Then, reaching the designated location, the UAV will descend to and float on the water surface and its motor will be turned off. After the UAV motor has come to a complete stop, the housing servo motor turns to close the frame and connect the housing propeller to the UAV propeller automatically. Once the housing propeller is connected to the UAV propeller, the UAV motor starts to rotate the housing propeller, generating the thrust force. At the end of the mission, the UAV motor is turned off and the servo motor turns to open the housing frame whose propellers will be disconnected from the UAV propeller. This mode transition brings the vehicle unit back to the UAV mode, allowing it take off and return onshore. Surface navigation is a compelling extension to existing competencies of UAVs.

## II. RELATED WORK

All of the existing waterborne vessels face difficulty in managing one or more of the following issues: linkage to a mother vessel with an umbilical cable, remote transportation, launch and recovery, storage, and human intervention for failure response. Over the past few years, various methods have been tried to confront the aforementioned issues. A ballast system was designed for submersible UAVs to control buoyancy with the same set of motors and propellers for both

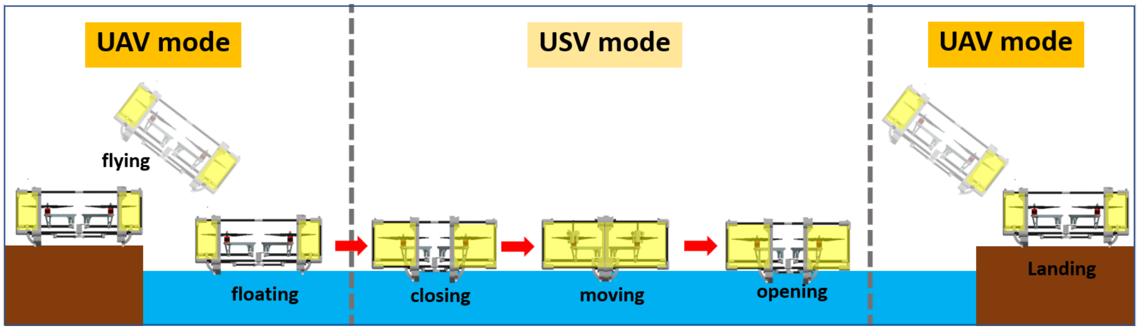


Fig. 1. An exemplary deployment scenario of a VTOL (vertical take-off and landing) UAV-USV hybrid vehicle outfitted with the transformable housing: flying offshore in UAV mode, navigating on the water surface in USV mode, and returning onshore in UAV mode.

airborne flight and underwater maneuvering [9]. For seamless transition between water and air, a reversible double-layer propeller system was proposed [10]. Additive manufacturing and fabrication and sealing techniques were applied to UAV that can stay underwater for months and launch into the air [11]. A customized waterproof hull casing with complex geometry was proposed for an aquatic UAV [12]. An affordable solution to water quality monitoring was demonstrated that a UAV flied to the sampling location and descended to the prespecified altitude, then a water sampler was submerged to a specific depth [13], [14], [15]. On the other hand, in UAV-USV collaborative operation setups, a UAV can land on the deck of a USV that moves to a designated location [16], or a USV can be installed beneath a heavy lift payload UAV [17]. To summarize, the trans-medium UAV is a technically viable solution to the multi-domain operation. However, building such a hybrid UAV is considered technically difficult, costly, and time-consuming. A disposable, low-cost, simple, and easy-fabricable hybrid vehicle deserves more attention.

Most of the existing hybrid vehicle designs are tailored to meet specific functional needs, leading to a highly sophisticated and labor-intensive platform. In contrast, this research aims to propose a universal design process of hybrid vehicles, outfitted with a single motor driven waterproof housing easily scalable to fit into commercial off-the-shelf aerial vehicles. The robotized housing endows a commercial aerial vehicle with the capability of being transformed to a surface configuration. When the vehicle is on a maritime mission, the waterproof housing also can be used a sample container, keeping the vehicle upright and safe from the waves. This research is an unprecedented attempt to provide transformability of the unmanned vehicle without using any mechanisms for reconfiguring the vehicle platform itself.

## III. HOUSING DESIGN

The housing can be transformed back and forth between the UAV mode and the USV modes as shown in Fig. 2, enabling an off-the-shelf UAV to operate both in air and on water. The housing body consists of the carbon tube rectangular cuboid frame and 3D printed slider parts.

### A. Main Body

The main body is composed of

- a rectangular cuboid frame,
- a pair of coupled sliders,
- two sets of the waterproof sleeve that can be folded,
- two housing propellers, and
- one servo motor.

The housing can be divided into three parts as shown in Fig. 3. The first part is to connect the housing-mounted propeller and the UAV propeller, allowing the housing to move on the water surface using the thrust of the housing-mounted propeller in the USV mode. The second part keeps the UAV upright and safe from the waves. And the third part is for opening and closing the housing with a servo motor integrated two-link mechanism.

### B. Housing Propellers

In order to transform an UAV to its USV mode, the sliders move to the center of the housing from their initial position and make the housing closed. The housing propeller is then connected to the UAV propeller axis moving downwards along a parabolic trajectory as shown in Fig. 4. This novel design of a simple mechanism allows for automatically positioning and connecting the housing propeller to the UAV propeller. The housing propeller is placed above the UAV propeller along the same vertical axis in the USV mode to ensure that the maximum power can be transmitted. The misalignment of two axes results in power losses, vibration, and an impediment to the UAV propeller rotation.

The housing propeller has two linkages: one is connected to the cuboid frame and the other is connected to the slider, denoted by $LF$ and $LS$, respectively in Fig. 4 (b). When the slider moves, the housing propeller unit moves in the same direction and descends. This allows for a smooth connection to the UAV propeller without affecting the operation of UAV propeller in both the UAV and USV modes.

The exploitation of power source of the UAV is one of the most important issues. In order to transmit the UAV rotor torque to the housing propellers with a minimum loss, we design the quadruplet grip that can move up and down according to the horizontal movement of the slider. Since the orientation of the UAV propeller cannot be pre-determined when the UAV motor is stopped, the quadruplet grip subject to gravity ensures a secure connection between the housing

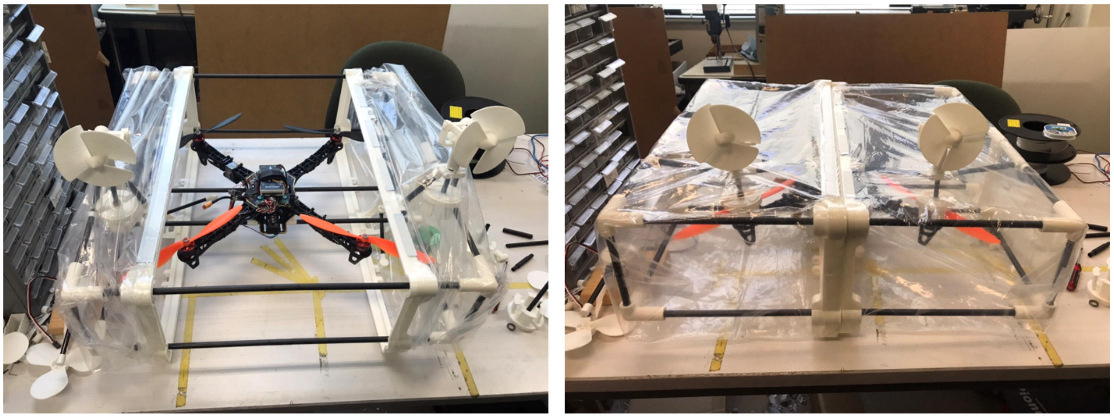

Fig. 2. A hybrid vehicle prototype in UAV mode (left) and USV mode (right).

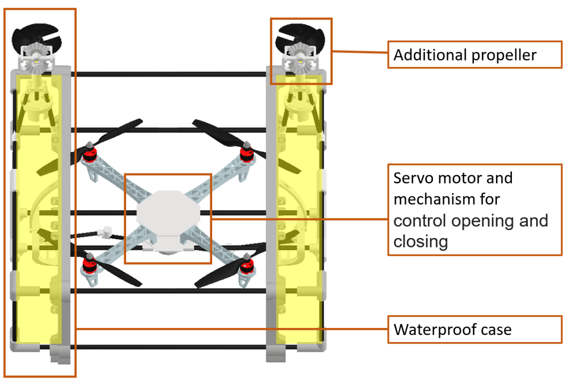


Fig. 3. Main body design of the transformable housing.

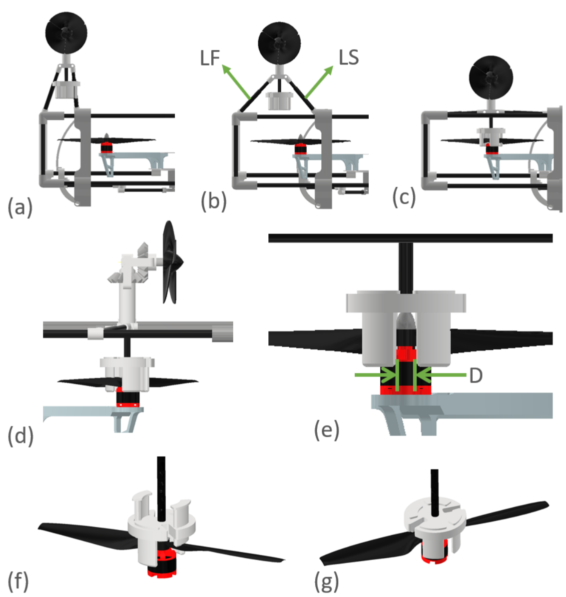


Fig. 4. Power transfer process through the proposed clutch (quadruplet grip) mechanism: (a)-(c) a sequence of steps in connecting the housing propeller unit to the UAV rotor shaft as the slider closes the housing, (d) the housing propeller is positioned perpendicular to the UAV rotor axis, (e) an enlarged view of the grip, and (f)-(g) the grip slides down into the space due to gravity.

propeller and the UAV propeller. Moreover, the spacing $D$ in Fig. 4 (e) between two adjacent fingers was designed by taking into account the dimension of the UAV propeller blade root. Regardless of the orientation of the UAV propeller, at least two of the four fingers can be connected with the UAV propeller. Once the propeller starts to rotate, remaining two fingers automatically slide down into the space available under the influence of gravity. In the USV mode, the housing propellers move the housing by turning the UAV propeller torque into a horizontal thrust via the 90-degree bevel gear as shown in Fig. 4 (d).

### *C. Opening and Closing Link Mechanism*

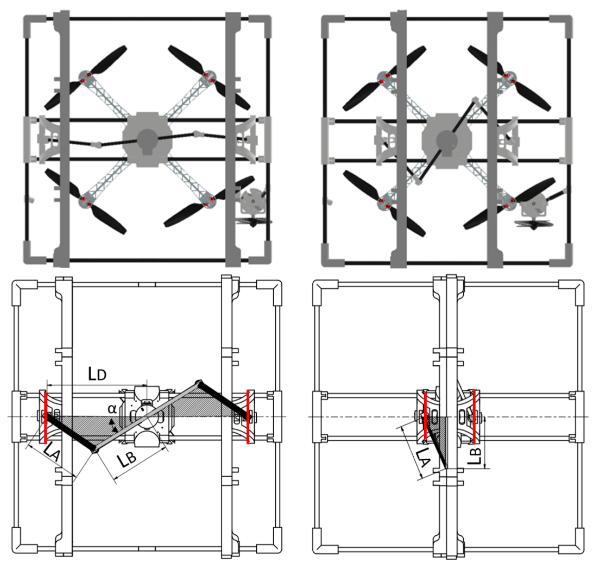


Fig. 5. A servo motor-integrated link mechanism for opening and closing the housing. The top figure shows a sequence of closing, and the bottom figure shows the link lengths of the two-link mechanism and stroke length of the slider.

We only use one servo motor to control the housing opening and closing mechanism. This housing endows a UAV with the capability of transforming between the UAV mode and the USV mode with a low payload as shown in Fig. 5. The length of the two-link mechanism was determined such that a minimum rotation angle of the servo motor is required to achieve the slider travel distance for opening and closing the housing. Let us consider the area of the shaded triangle shown in the bottom left subfigure of Fig. 5, where the distance $L_D$ for the maximum slider stroke is set to $260mm$. Assuming that $L_A$ and $L_B$ are equal in length, they must satisfy the triangle inequality, $260 < L_A + L_B$. Given an offset angle $\alpha$ to avoid the singular configuration, we can calculate the link length using trigonometry, $L_A = L_B = \frac{130}{\cos(\alpha)}$. The bottom right subfigure of Fig. 5 shows the same triangle when the housing is closed, where $\alpha$ can reache its maximum value of $90°$. Here if $L_B$ is greater than $L_A$, the housing will not close completely. Therefore, $L_A$ must be greater than or equal to $L_B$.

Using the two-link mechanism, the rotation of the servo motor can be converted into horizontal linear motion, and the additional payload appended is reduced compared to its alternatives such as a rack-and-pinion mechanism. With the limited rotation angle of the motor, and the two sliders connected to the servo motor via the two-link mechanism travel the same distance. When the housing needs to be transformed to the UAV mode, the mechanical linkage connected to the servo motor starts to rotate and moves the housing to be open. It converts the torque of the servo motor into a lateral force. When the housing needs to be transformed to the USV mode, the servo motor will rotate in the opposite direction, moving the sliders toward the center of the housing.

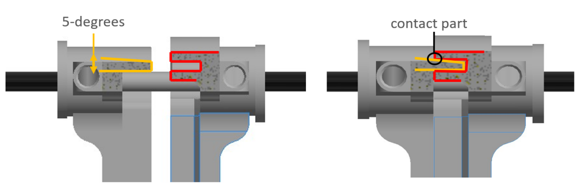

Fig. 6. Locking mechanism of two sliders.

There are many ways to fasten the two sliders together in the center to close the housing. However, when the fastening becomes loose, water may seep through the contacting surface as shown in Fig. 6 into the housing. To overcome this problem, we designed the left and right sides of the fastener in different shapes as shown in Fig. 6 and with an additional 5-degree inclination on the left side. This provides a better sealing when the two sliders are closed, allowing the contacting surface to be closed more tightly.

### *D. Slider on a frame*

The sliders on a frame are prone to stick at certain points as shown in Fig 7 during the opening and closing movement. Since the servo motor controlling opening and closing is placed underneath the UAV, the slider receives not only horizontal forces but also vertical forces at the same time. Therefore, when the direction angle of the forces exceeds the limit that the slider can withstand, the slider will stick.

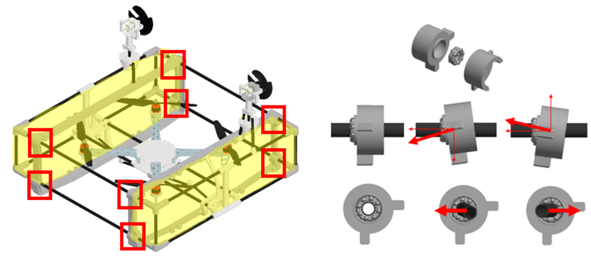
Fig. 7. Self-aligning ball bearing design.

Initial experimental tests revealed that the slider interaction area is subject to longitudinal upward/downward forces and transversal forces, and a standard bearing is not being able to tolerate the angular displacement. In order to deal with this problem, we designed a self-aligning ball bearing. This type of bearing has two rows of balls. The outer ring has a common spherical track. Therefore, the bearing can be self-aligned and not easily affected by the angular displacement or misalignment between the shaft and the bearing housing. This self-aligning ball bearing allows the sliders to have enough movement angles while opening and closing.

## IV. EXPERIMENTAL RESULTS

### *A. Propeller Rotation Comparison*

When the external propellers mounted on the housing are connected to the UAV propellers in the USV mode, we confirmed through extensive tests that both propellers are perfectly synchronized at the same speed in the range of $5,000rpm$ to $6,000rpm$. This means that there is no need for additional motors for the housing propellers in order to move the USV forward. Therefore, the USV movement can be controlled only using the motors built in to an off-the-shelf UAV body without causing rotational speed loss. This control method is considered very effective and cost-efficient.

### *B. Propeller Thrust*

To test the performance of the propellers mounted on the housing, a simplified experimental testbed was built in-house to measure the thrust force generated by the housing propellers at different speeds and the rate of movement as shown in Fig. 8. A number of UAV-USV mode transition tests were conducted. The figure shows snapshots in the process of transforming an off-the-shelf UAV outfitted with the proposed housing to a USV that moves forward on the water surface in our testbed. The results of the experiment are shown in Fig. 9 and Fig. 10. The obtained results support the fact that the higher the rotational speed, the greater the thrust force generated by the housing propeller as expected.

Starting from a minimum of $5,000rpm$ of the UAV motor, we measure in units of $100rpm$ as shown in Fig. 9 and Fig. 10. At speeds above $6,300rpm$, the thrust generated by the UAV propeller inside the housing starts causing the housing to wobble. It is likely to disrupt the stability of the housing on the water surface, which in turn causes the housing to fail to

Fig. 8. Vehicle mode transition and movement test in a laboratory testbed: (top) snapshots of the transition from the UAV mode to the USV mode, (bottom) the USV mode moving on the water surface.

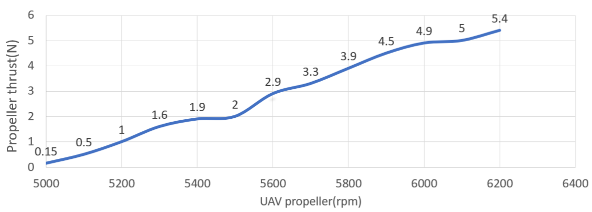


Fig. 9. The thrust of the housing propeller in the USV mode for different UAV rotor speeds. The data in this graph was measured by putting a thrust-meter in front of the housing.

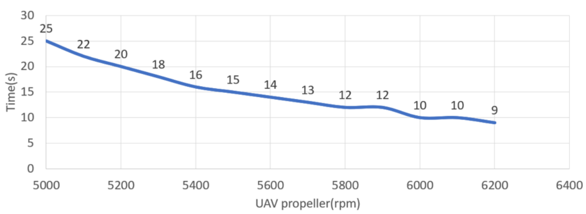


Fig. 10. The total amount of time needed for traveling a distance of $125cm$ for different UAV rotor speeds.

move in the intended direction. Therefore, it can be concluded from the experimental tests that the operational range of the housing propeller speed is between $5,000rpm$ and $6,200rpm$ for the UAV used in the experiments.

### C. Slider Test for Mode Transition

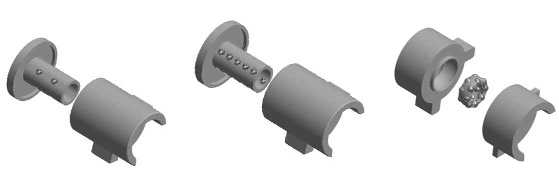

Fig. 11. Two column, five column, and self-aligning ball bearing.

TABLE I
BEARING TEST FOR SLIDING

| Angle(°) | ball bearing | | |
|---|---|---|---|
| | Two columns | Five columns | Self-aligning |
| 0 | 100% | 100% | 100% |
| 1 | 100% | 100% | 100% |
| 2 | 80% | 80% | 100% |
| 3 | 80% | 80% | 100% |
| 4 | 70% | 60% | 100% |
| 5 | 70% | 60% | 100% |
| 6 | 60% | 40% | 100% |
| 7 | 50% | 30% | 100% |
| 8 | 50% | 20% | 100% |
| 9 | 40% | 10% | 100% |
| 10 | 30% | 10% | 100% |
| 11 | 30% | 0% | 100% |
| 12 | 20% | 0% | 100% |
| 13 | 20% | 0% | 100% |
| 14 | 20% | 0% | 90% |
| 15 | 10% | 0% | 90% |
| 16 | 0% | 0% | 90% |
| 17 | 0% | 0% | 90% |
| 18 | 0% | 0% | 80% |
| 19 | 0% | 0% | 80% |
| 20 | 0% | 0% | 80% |

A servo motor is set underneath the UAV that drives the two-link mechanism for the opening and closing motion of the slider. In the experiments, we tested two-column ball bearing, five-column ball bearing, and self-aligning ball bearing as shown in Fig. 11. Experiments were carried out for different angular displacements, each of which was tested ten times to obtain the success rate provided in Table I. From the experimental results, the shaft alignment tolerance angle of the two and five columns ball bearing is less than 10 degrees, and that of the self-aligning ball bearing is between 0 to 13 degrees. We have confirmed that the self-aligning ball bearing can be adaptable to angular changes in all directions.

### D. Fabrication and Specification

We used Arduino Single Board PC for the control of the servo motor, and developed necessary software in the Python programming language environment. We used Inventor and SolidWorks softwares to design the proposed housing, which was 3D printed with $15\%$ infill density and full honeycomb patterns using Polylactic Acid (PLA) material. The weight of the housing is $2.2kg$, while the off-the-shelf UAV used weighs $1.0kg$. Therefore, most off-the-shelf or custom-built UAVs with a minimum payload of $3.0kg$ can be outfitted with our robotic housing unit.

## V. CONCLUSIONS

This paper presented a universal housing design method that allows an off-the-shelf UAV to go from air to water surface, and vice versa, with minimal logistics costs. The presented design comprises a pair of coupled sliders moving on a rectangular cuboid frame, covered with the waterproof material. Notably, only one servo motor was used to switch between the UAV and USV modes. In the USV mode, motion is generated by the housing propeller thrust transmitted from the UAV propeller, without requiring any additional motors. A single servo motor-integrated mode change mechanism helps keep the housing light-weight and preserve the battery endurance.

In order to demonstrate the feasibility of the proposed design, we built a pool with a length of $160cm$ and a width of $70cm$. Using this pool, we performed a variety of tests on the robotic housing mode transition and movement on the water surface. We have experimented with the relationship between the propeller rotational speed when an additional housing propeller is connected to a UAV propeller. The housing propeller provides the thrust at different rotational rates when the housing is floating on the water. The time taken for different thrusts at the same distance were presented. The design would make a UAV accomplish a variety of surface explorations in an efficient way such as rescue and salvage missions, underwater topographic surveys, and many other similar purposes. The robustness and structural integrity issues of the proposed hybrid vehicle remain to be studied in field trials under real-world conditions.

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