IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received January 5, 2019, accepted January 21, 2019, date of publication January 25, 2019, date of current version February 12, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2895335

Unmanned Water-Powered Aerial Vehicles: Theory and Experiments

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ABSTRACT Water-powered jetpacks have become a well-known recreational product in water theme parks. It requires a large number of skills to operate them. And it is difficult for visitors, particularly for kids and elders, to master these skills in a limited period of time. This paper designed several unmanned water-powered aerial vehicles (UWAVs) to deal with this dilemma. Two types of actuating mechanism are proposed, each of which is applied in different UWAVs. The dynamics of the two types of UWAV is modeled and analyzed. Several UWAV prototypes, including airframes, actuators, controllers with PD algorithm, and inertial sensors, are fabricated. Under the control of the onboard controllers, the prototypes can achieve attitude stabilization. One can use a remote control to drive a prototype to perform specific tasks. The experimental results are provided, and the experimental mission demonstrations show that the UWAVs could be used in recreation as well as other fields, such as fire extinguishing, salvage, fast transportation on water, and underwater detection.

INDEX TERMS Water-powered, actuating mechanism, unmanned aerial vehicle.

I. INTRODUCTION

Water-powered jetpacks have become a commercial product since 2010 [1]. Jetlev-Flyer flight package [2], Jetovator [3], and Jetboard [4] are typical cases, as shown in Fig. 1. The Jetboard system, for instance, consists three components: a Jetboard, a flexible water hose and a power unit. The power unit, which is usually a powerful Jet Ski, is an essentially pump floating in water. As the power unit starts up, the robust stream of water it creates is channeled into the long hose, which in turn, propels the pilot on the Jetboard high up into the sky and allows him/her to perform a variety of maneuvers like flips and spins. There are three rotary joints in the Jetboard to adjust the direction of two nozzles and prevent the hose from twisting.

However, this kind of jetpacks has not become as popular as other recreational water crafts such as motorboats due to following restrictions. First of all, it requires a large amount of skills to operate a jetpack. And it is difficult for visitors, particularly for kids and elders, to master these skills in a limited period of time. Secondly, it takes a long time for preparation. One should get swimsuits on and deposit personal belongings before operate the jetpack. It takes much longer time than that for driving a motorboat. Finally, it must be in a warm or hot weather to operate this product because the pilot wearing swimsuits always immerses himself in water during operating the jetpack.

FIGURE 1. Some kinds of water powered jetpacks.

This paper is aiming towards the development of Unmanned Water-powered Aerial Vehicles (UWAVs), which could fly autonomously with the help of the onboard controllers and could execute remote control instructions. A semi-autonomous water-powered jetpack has been designed in [1] to reduce the skills required to flight the jetpack. But it still needs a pilot on the craft to steer it. Besides

The associate editor coordinating the review of this manuscript and approving it for publication was Nishant Unnikrishnan.

the jetpack, water reaction is also used on another kind of aircraft, known as the water rocket, usually for entertainment or education. [5]–[7] focused on hydrodynamics and thrust characteristics of the water rocket. The water rocket can work as a booster to launch an aquatic micro air vehicle, shown in [8] and [9]. The booster could work only 0.4 second and therefore couldn't provide continuous thrust. Anyhow, to the best of the authors' knowledge, no UWAV has been released to date.

Once water-powered aerial vehicles could fly autonomously, they could be used in many fields besides recreation. The Dubai government's official Media Office shared a video on Twitter showcasing its new jetpack-powered firefighting system [10]. They hope that the Dolphin, as the setup is called, will aid firefighters in putting out boat and shoreline fires. The device has a nozzle attached to a pair of boots, which allows the user to hover dozens of feet in the air and pump water at a target. Whereas the UWAV could put fire out and allow the user keep a safe distance from the fire site. The UWAV could also dive into water. This would enable a fast underwater detection and salvage to emergency scenarios such as a stricken ship. The UWAV could move beneath a drowning man and lift him out of water, without a second injury.

The paper is organized as follows. Section II addresses two types of actuating mechanism for the UWAV. Section III contains dynamic models and characteristic analysis. UWAV prototypes and experiment results are presented in Section IV, followed by conclusions in Section V.

II. ACTUATING MECHANISM

For an aircraft, no matter it is a quadrotor, a rocket, or a satellite, in order to adjust or stabilize its attitude, it is necessary to generate three control torques by the actuating mechanism. These three torques are generally orthogonal, and the water-powered aerial vehicle is no exception. The principle of generating torques for a Jetboard is essentially by changing the thrust directions. Based on this idea, we can design an actuating mechanism which can change the nozzles in all directions. This mechanism is similar to the vector nozzle mechanism of a rocket. The UWAV that uses this mechanism is named Nozzle-gimbaled UWAV. The control torque can also be generated by changing the magnitude of the thrust from different nozzles. This idea is similar to the quadrotor, whose pitching and rolling torques are generated by changing the magnitude of the lift from different rotors. We can design an actuating mechanism which can regulate the water flow going through the nozzles to adjust the magnitude of the thrust. The UWAV that uses this mechanism is named Flow-regulated UWAV.

A. NOZZLE-GIMBALED UWAV

Each nozzle is connected to the airframe through a short flexible hose. Two actuators drive the nozzle through the connecting rods, as shown in Fig. 2. Actuator 1 and actuator 3 drive two nozzles to deflect left and right in the same direction, producing the rolling torque. Actuator 2 and actuator 4 drive two nozzles to deflect forwards and backwards in the same direction, producing the pitching torque. Actuator 2 and actuator 4 drive two nozzles to deflect backwards and forwards in the opposite direction, producing the yawing torque.

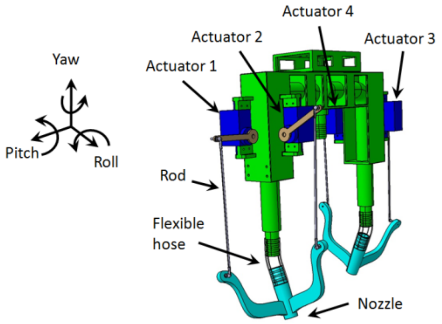
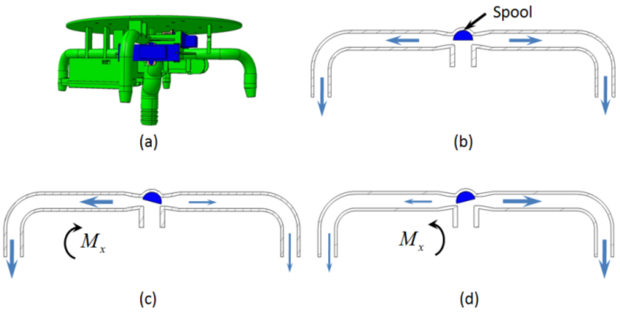


FIGURE 2. Nozzle-gimbaled mechanism.



(a) (b) (c) (d)

FIGURE 3. Flow-regulated mechanism.

B. FLOW-REGULATED UWAV

The UWAV consists of two sets of orthogonal flow-regulated mechanisms, as shown in Fig. 3(a). Each mechanism has two nozzles and one spool, and the spool is driven by an actuator. The sectional drawing of any mechanism is shown in Fig. 3(b). At this point, the spool is not deflected. The flow rate of the two nozzles is equal, and no torque is generated. When the spool deflects clockwise, as shown in Fig. 3(c), the flow rate of the left nozzle is greater than that of the right nozzle, generating clockwise torque. When the spool deflects counterclockwise, as shown in Fig. 3(d), the flow rate of the right nozzle is greater than that of the left nozzle, generating counterclockwise torque. These two sets of orthogonal mechanisms can produce pitching torque and rolling torque, respectively. No yawing torque can be generated in this UWAV. The UWAV can fly with the yaw angle uncontrolled, as demonstrated in section IV.

Of course, the UWAV can use both mechanisms at the same time. For example, the flow-regulated mechanism can be used to generate the rolling and pitching torques, while the nozzle-gimbaled mechanism can be used to generate the yawing torque.

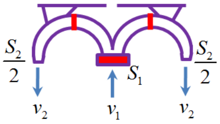


FIGURE 4. Water flow in the UWAV.

III. MODELING AND DYNAMIC ANALYSIS

Similar as UAVs and rockets, the attitude dynamic model of the UWAV can be obtained using Newton equations. It is the same as that of other aircrafts, particularly as that of quadrotors (see [11]–[14] for an overview). But due to the influence of the hose and the water flow, the composition of the forces and torques is different from that of quadrotors.

The forces applied to the airframe include the active control force F_w produced by the nozzles and the interference force F_h from the hose. The torques applied to the airframe include the active control torque from nozzles, Coriolis torque from water flow in the airframe, and the interference torque from the hose.

The calculation of the interference force and torque of the hose is very complicated. Many articles focus on the dynamics of the underwater hose. Its application background is deep sea mining (see [15]–[20] for an overview). These studies show that the hinge force and torque of the hose cannot be expressed explicitly by simple formulas. Therefore the interference force and torque of the hose to the airframe will be simplified in the following analysis.

A. LONGITUDINAL MOTION CHARACTERISTICS

Assuming that the water is incompressible flow, Conservation of Mass gives

$$q = v_1 S_1 = v_2 S_2 \tag{1}$$

where S_1 and S_2 are the total cross-sectional area of the airframe inlet and that of outlets, respectively. v_1 and v_2 are the flow velocity at the inlet and outlet, respectively. $q > 0$ is the volume flow rate of the whole water supply system (including the pump, the hose and the internal flow channel of the airframe).

Suppose $h > 0$ is the pump lift, that is, the flying altitude of the UWAV. P is the power of the pump, determined by the throttle. For an ideal pump, when the pump power is constant, the greater the lift is, the smaller the flow. Thus,

$$\frac{\partial q}{\partial h} < 0 \tag{2}$$

The flow is related to power and lift. So q can be marked as $q = q(h, P)$.

Since $S_1 \gg S_2$ (in the later prototype, $S_1 = 12.96 S_2$), then $v_2 \gg v_1$. Regardless of the flow velocity at the inlet of the airframe, the reaction force generated by the nozzles is

$$\begin{aligned} F_w &= \frac{d m_w v_w}{dt} \\ &= \rho q(h, p) v_2 \\ &= \rho q^2(h, p)/S_2 \end{aligned} \tag{3}$$

where, ρ is the density of water.

When there is only vertical motion, the hinge force of the hose is assumed as

$$F_h = -\lambda_1 h - \lambda_2 L \dot{v} - \lambda_3 (L - h)\, |v|\, v \tag{4}$$

where, $v = \dot{h}$ is the velocity in the vertical direction. $-\lambda_1 h$ is the gravity of the hose part above the water. It is proportional to h. Assume that the gravity of the hose underwater is the same as the buoyancy. $-\lambda_2 L \dot{v}$ represents the inertia force of the whole hose when it accelerates. $-\lambda_3 (L - h)\, |v|\, v$ is the drag force during the movement of the underwater hose. It is proportional to v^2 and contrary to the direction of v. $L - h$ is the length of the hose underwater and $L - h > 0$. The Coriolis force caused by the rotation of the hose is negligible. $\lambda_i\ (i = 1, 2, 3) > 0$ are the related force coefficients, which are related to the characteristic parameters of the hose.

Thus, the longitudinal motion equation of the UWAV can be written as

$$m\dot{v} = F_w + F_h - mg \tag{5}$$

That is

$$\begin{aligned} \ddot{h} = \rho q^2(h, P)/(m S_2) - \lambda_1 h/m \\ - \lambda_2 L \ddot{h}/m - \lambda_3 (L - h)\, |v|\, \dot{h}/m - g \end{aligned} \tag{6}$$

Equation (6) can be simplified as

$$\ddot{h} + k_1 \dot{h} + k_2 h - k_3 q^2 (h, P) + k_4 = 0 \tag{7}$$

where,

$$\begin{aligned} k_1 &= \lambda_3 (L - h)\, |v| \,/(m + L\lambda_2) > 0, \\ k_2 &= \lambda_1/(m + L\lambda_2) > 0, \\ k_3 &= \rho/(m S_2 + L\lambda_2 S_2) > 0, \\ k_4 &= mg/(m + L\lambda_2) > 0. \end{aligned}$$

Assuming that the UWAV is just under force balance and keeps still when $h = \bar{h}$. Then,

$$k_2 \bar{h} - k_3 q^2 \left(\bar{h}, P\right) + k_4 = 0 \tag{8}$$

Thus, a disturbance equation can be obtained by introducing the disturbance Δh to (7),

$$\Delta \ddot{h} + c_1 \Delta \dot{h} + c_2 \Delta h = 0 \tag{9}$$

where,

$$c_1 = k_1 > 0, \quad c_2 = k_2 - 2 k_3 q \left(\bar{h}, P\right) \left.\frac{\partial q\,(h, P)}{\partial h}\right|_{h=\bar{h}}.$$

Since $q\,(h, P) > 0$ and $\partial q\,(h, P)/\partial h < 0$, so $c_2 > 0$. Equation (9) is a second-order homogeneous equation. Due to $c_1 > 0$ and $c_2 > 0$, according to mathematical knowledge, Δh will quickly converge to zero.

In fact, it is not difficult to understand that the higher the altitude of the UWAV, the smaller the thrust of the nozzle, while the greater the gravity of the hose above the water surface, and vice versa. So, there must be a unique altitude where these two forces get balanced. If the UWAV vibrates

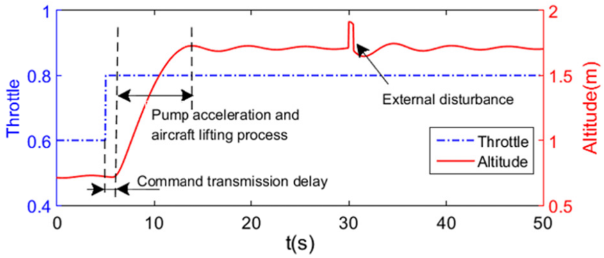


FIGURE 5. Numerical simulation of longitudinal motion.

TABLE 1. Parameters of longitudinal simulation.

Symbol	Description	Value
m0	Mass of aircraft	1Kg
L	Length of hose	7m
λ_1	Weight of hose per meter(water included)	4N/m
λ_2	Mass of hose per meter(water included)	0.4Kg/m
λ_3	Resistance coefficient	3.3Kg/m^2
K_pump	Reaction force coefficient	4.4×10^{-5}N/Pa
T_pump	Time constant of the pump	2s
τ_pump	Command transmission delay	0.5s

up and down at this equilibrium position, the vibration will soon disappear under the damping of the underwater hose.

A numerical simulation is performed to show the longitudinal dynamic performance of the aircraft, as shown in Fig. 5. The simulation parameters are shown in TABLE I.

Fig. 5 shows that for a throttle step input, the altitude response of the aircraft is as follows. First, there is a command transmission time delay. Then the pump starts to accelerate and the thrust increases. The flight altitude gradually increases and finally stabilizes to a new value. At this time, a disturbance is applied to the altitude, which increases the altitude by 0.2 meters. When the disturbance disappears, the altitude of the aircraft will quickly return to its original value. Fig. 5 indicates that the altitude channel of the aircraft is self-stable and has certain robustness.

B. LATERAL MOTION CHARACTERISTICS

1) NOZZLE-GIMBALED UWAV

For the convenience of analysis and expression, only the dynamics within the rolling plane is considered, as shown in Fig. 6.

In the figure, γ is the roll angle and δ is the nozzle deflection angle. It is assumed that the water hose is vertically downward. The hose force on the aircraft is also vertical and downward. And its component in horizontal direction is 0. Thus the horizontal acceleration of the UWAV is

$$a_x = F_w \sin(\delta - \gamma)/m \approx F_w(\delta - \gamma)/m \tag{10}$$

Since the connecting point between the hose and the aircraft is at the center of mass of the aircraft, there is no torque generated by the hose force. So there is only one restoring torque from the hose, which is produced by the elasticity of the hose.

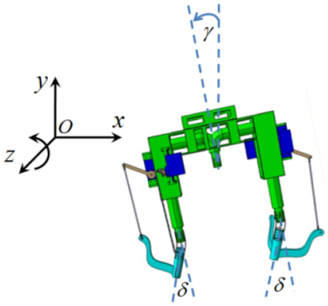


FIGURE 6. Dynamics in the rolling plane for a nozzle-gimbaled UWAV.

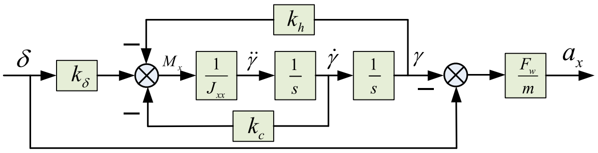


FIGURE 7. Block diagram of the transfer function from δ to a_x.

$$M_h = -k_h \gamma \tag{11}$$

where, $k_h > 0$ is a restoring torque coefficient, which is related to the material, diameter and pressure of the hose.

During the rotation of the aircraft, the water flowing in the aircraft generates Coriolis force, which produces a damping torque,

$$M_c = -k_c \dot{\gamma} \tag{12}$$

$k_c > 0$ is the Coriolis torque coefficient, which is related to the size of the aircraft and the flow rate of water.

The deflection of the nozzles produces a control torque,

$$M_\delta = k_\delta \sin(\delta) \approx k_\delta \delta \tag{13}$$

where, $k_\delta = F_w l$. l is the vertical distance from the center of mass to the nozzle gimbals.

It should be noted that the control torque should be much larger than the interference torque, and the control torque generated by the unit deflection angle should be greater than the recovery torque generated by the unit roll angle. That is

$$k_\delta > k_h \tag{14}$$

Therefore, the total torque applied to the vehicle is

$$M_x = k_\delta \delta - k_h \gamma - k_c \dot{\gamma} \tag{15}$$

The block diagram of the transfer function from δ to a_x is shown in Fig. 7.

The transfer function can be derived as

$$\frac{a_x(s)}{\delta(s)} = \frac{F_w}{m} \frac{J_{xx}s^2 + k_c s + (k_h - k_\delta)}{J_{xx}s^2 + k_c s + k_h} \tag{16}$$

There is a positive zero point in the system due to $(\mathrm{k_h} - \mathrm{k_\delta}) < 0$ and therefore it is a non-minimum phase

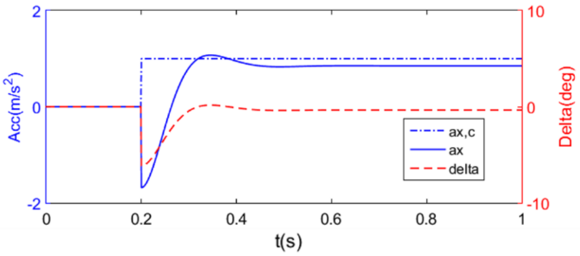


FIGURE 8. Lateral motion of nozzle-gimbaled UWAV.

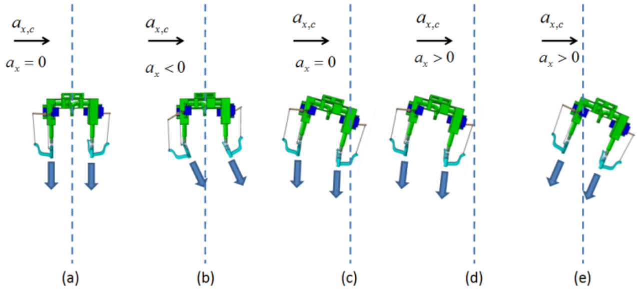


FIGURE 9. Time domain demonstration of non-minimum phase characteristics.

system. Here, a PD controller is selected to control this non-minimum phase system. The closed loop response is shown in Fig. 8. In this simulation, the dynamics of the actuator is considered to be an inertia element with a time constant of 0.02s. The red curve is the deflection angle of the nozzle.

As can be seen from Fig. 8, for a positive step acceleration command, the aircraft first produces a negative acceleration. Then acceleration gradually becomes larger, moving closer to the command. To explain this process more clearly, the process can be divided into five states, as shown Fig. 9.

When the aircraft is in equilibrium (a), it receives a positive acceleration command and immediately deflects the nozzles to generate a negative torque (state (b)). At this moment, a negative acceleration is generated. And then a negative roll angle is generated, reaching the state (c) and (d). The acceleration becomes positive, but a negative displacement has been generated. And finally it reaches state (e), producing a positive displacement. From the process of (a) to (e), the center of mass of the aircraft has a left shifting process, which is a time domain representation of the non-minimum phase system. Due to this reverse movement characteristic, the nozzle-gimbaled UWAV is not suitable for approaching a vertical surface (such as a wall) during flight. Once approached, it will not be able to leave. Forcibly leaving will result in impacting the vertical surface, possibly damaging the aircraft.

It should be noted that this reverse movement characteristic of the aircraft is independent of the form of the controller. The controller cannot change the closed loop system to a minimum phase system.

In addition, this type of nozzle-gimbaled UWAV is not suitable for load. The external load on the aircraft would make the center of mass of the entire system higher. Equation (13) $M_\delta = F_w l\delta$ shows that the control torque produced by the nozzle will increase. Therefore the external load will enlarge the open-loop gain of the whole system and brings difficulties to the design of the control system.

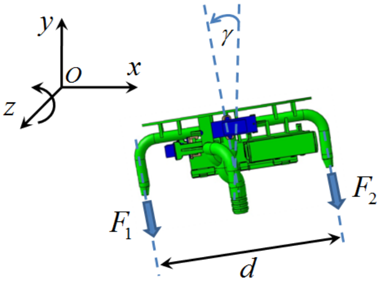


FIGURE 10. Dynamics in the rolling plane for a flow-regulated UWAV.

2) FLOW-REGULATED UWAV

Flow-regulated UWAV generates torque by adjusting the flow rate of the two nozzles. The rolling plane is still used as an example, as shown in Fig. 10.

Let δ be the deflection angle of the spool, and

$$\begin{cases} F_1 = F_w(1-\delta)/2 \\ F_2 = F_w(1+\delta)/2, \end{cases} \quad \delta \in [-1, 1] \tag{17}$$

Then,

$$M_\delta = F_2 d/2 - F_1 d/2 = F_w d\delta/2 \tag{18}$$

where, d is the distance between the two nozzles.

The horizontal acceleration of the aircraft is

$$a_x = -(F_1 + F_2)\sin(\gamma)/m \approx -F_w\gamma/m \tag{19}$$

The transfer function from δ to a_x can be derived as

$$\frac{a_x(s)}{\delta(s)} = -\frac{F_w^2 d}{m}\frac{1}{J_{xx}s^2 + k_c s + k_h} \tag{20}$$

It is a minimum phase system. And there will be no reverse movement characteristic. Equation (18) shows that the control torque is independent of the position of the center of mass. And external load has no effect on the control torque.

Remark: the flow-regulated UWAV is suitable for the load and can be close to a vertical surface. It is suitable for docking. However, due to its large area in the xz plane, it has large resistance and low speed during underwater movement, so it is suitable for water rescue, fast transportation, entertainment, fire extinguishing, etc. The nozzle-gimbaled UWAV is not suitable for load, cannot be close to a vertical plane. But due to its small area in the xz plane, it has low resistance and high speed during underwater movement. So it is suitable for underwater detection and flight performance.

IV. UWAV PROTOTYPES

A. SYSTEM SCHEME

The UWAV system scheme is shown in Fig. 11.

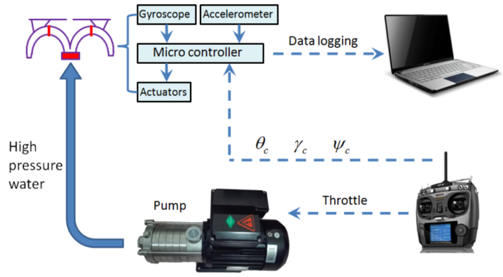


FIGURE 11. UWAV system diagram.

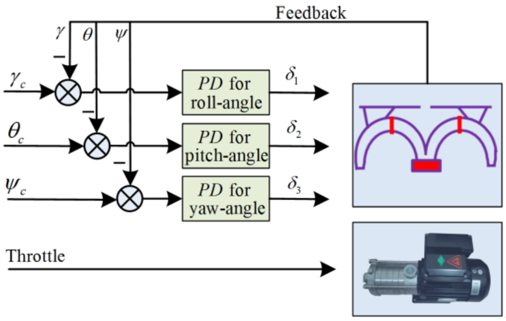


FIGURE 12. UWAV control architecture.

The pump delivers high pressure water to the aircraft through the hose. The aircraft is equipped with a micro controller, gyroscopes, accelerometers, actuators, a battery, communication modules, etc. The remote controller sends the throttle command to the water pump to control the altitude of the aircraft, and sends attitude angle commands to the aircraft to control the lateral movement. The computer communicates wirelessly with the aircraft to record the flight data of the aircraft.

B. CONTROL ALGORITHM

Although there are many advanced control algorithms, such as fractional-order sliding mode control (see [21], [22] for an overview), this paper focuses on the feasibility of the scheme and does not emphasize the advancement of the control algorithm. Therefore, the mature control algorithm which is simple, reliable and easy to implement is preferred. For the control of three attitude angles, PD control algorithm is adopted, as shown in Fig. 12.

Because of the self-stabilization of the longitudinal motion, the altitude control could be open-looped. It should be noted that the distance between the pump and nozzles results in a large delay between an increase in throttle and the increase in thrust. If closed-loop control of altitude is required in future work, the controller should be able to handle the system lag.

C. EXPERIMENT RESULT

Two UWAVs have been fabricated, one of which is nozzle-gimbaled and the other flow-regulated. The flight test screenshots are shown in Fig. 13.

The attitude angles of the flow-regulated UWAV when it is hovering are shown in Fig. 14.

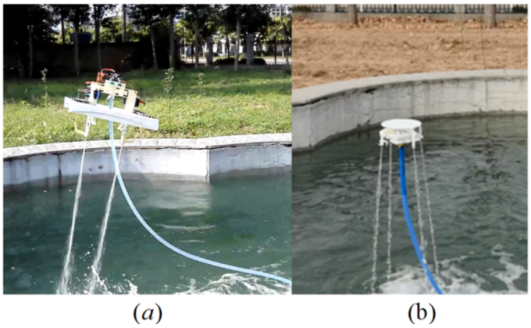

(a) (b)

FIGURE 13. (a)Nozzle-gimbaled UWAV when maneuvering (b) Flow-regulated UWAV when hovering.

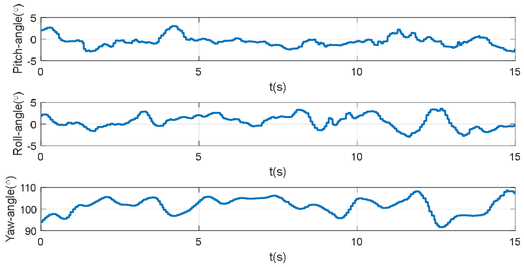


FIGURE 14. Attitude angles when hovering.

FIGURE 15. Taking off from water.

The pitch angle and roll angle are controlled in ±5 degrees. There is no control torque in the yaw direction. But the yaw angle is constrained in ±10 degrees by the hose.

D. MISSION DEMONSTRATION

1) TAKING OFF FROM WATER

The nozzle-gimbaled UWAV was equipped with a floating landing gear. So it can float on water when the pump is off. And it can take off from water, as shown in Fig. 15. Of course it also can land on water.

2) WATER SALVAGE

The flow-regulated UWAV has been modified to be waterproof. It can move beneath a drowning man (or other floating objects) and lift him out of water, without a second injury. This function could be used for water salvage, as shown in Fig. 16.

3) SHORE LANDING

Two parallel rods were installed on the flow-regulated UWAV as a landing gear. Another pair of rods was installed on

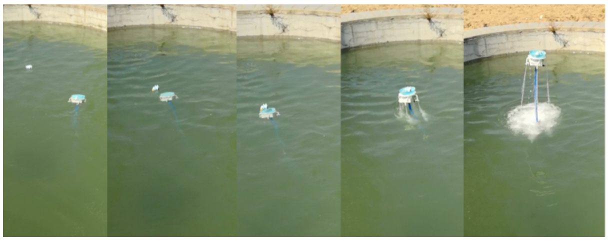


FIGURE 16. **Water salvage.**

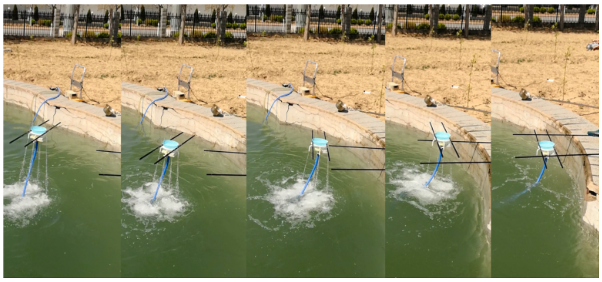


FIGURE 17. **Landing by the shore.**

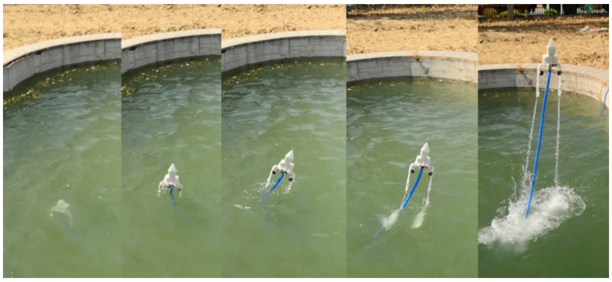


FIGURE 18. **Taking off from under water.**

the shore as a landing facility. The aircraft can land by the shore under the help of the landing gear and landing facility, as shown in Fig. 17. Of course it also can take off from the landing facility. This demonstration shows that the UWAV could land by the deck of a ship. One can use the UWAV as a fast conveyance to transport goods or passengers from one ship to another one, or from in the water to a ship after a water salvage.

4) UNDERWATER MOVEMENT

A third UWAV, which is a hybrid of two kinds of actuating mechanism, has been fabricated. It is nozzle-gimbaled in pitching and yawing planes while flow-regulated in rolling plane. Due to its small area in the xz plane, it has low resistance and high speed during underwater movement. And one can use it for underwater detection. This UWAV can move underwater, surf on water surface and fly in the air. So it could be used for performance. The process of taking off from underwater is shown in Fig. 18.

V. CONCLUSION

This paper focuses on the development of unmanned water-powered air vehicles. Two kinds of actuating mechanism are proposed. The dynamic characteristics of the UWAVs using different actuating mechanism are analyzed. It is found that the nozzle-gimbaled UWAV is not suitable for approaching a vertical surface due to the reverse movement characteristic. External load on this type of UWAV would make the center of mass higher and therefore bring difficulties to the design of the control system. But the nozzle-gimbaled UWAV can move quickly underwater because the area in the xz plane is small. The flow-regulating UWAV suffers no reverse movement characteristic and therefore can dock by the shore. It is suitable for loading.

Compared with helicopters, quadrotors and other aircraft that can hover, the UWAV has no rotor and does not rely on air. So it is more resistant to the wind. Several flight tests have shown that the UWAV can be used for fast transportation, water salvage, underwater detection, flight performance and so on.

At present, the control commands come from the remote controller. And one needs to control the aircraft to complete the salvage, landing or other missions. In the future work, we will study the guidance law so that the flight can automatically complete a specific flight mission. In order to improve the control performance of the UWAV, it is also necessary to study flexible hose modeling, robust control for coupling problems and uncertainties.

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