

Supplementary Information For A Maneuverable Underwater Vehicle for Near-seabed Observation

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This file includes:

Supplementary Notes

Supplementary Note 1. Hydrostatic data acquisition.

Supplementary Note 2. Stability of robots under transverse constant load.

Supplementary Note 3. The ratio of forward distance to depth change.

Supplementary Note 4. Convergence proof for depth controllers.

Supplementary Note 5. Robot Low Disturbance Design.

Supplementary Note 6. Control Algorithm Comparison.

Supplementary Note 7. Robot structure parameters.

Supplementary Note 8. Disturbance observation platform.

Supplementary Note 9. Control parameters.

Supplementary Figures

Supplemental Fig. 1. Robot dynamics model parameter identification.

Supplemental Fig. 2. Stability under Constant Load.

Supplemental Fig. 3. Robot structure optimization.

Supplemental Fig. 4. Effect of thruster tilt angle on low perturbation ascent velocity, propulsive efficiency, and control torque.

Supplemental Fig. 5. Effectiveness of different algorithms against interference.

Supplemental Fig. 6. Anti-disturbance ability of the three algorithms.

Supplemental Fig. 7. Structural dimensions of NS-MUV.

Supplemental Fig. 8. Modification of robot structure.

Supplemental Fig. 9. Disturbance Observation Platform.

Supplementary Tables

Supplementary Table 1. Robot body parameters.

Supplementary Table 2. Sensor parameters.

Supplementary Table 3. Control parameters.

Supplementary Notes

Supplementary Note 1. Hydrostatic data acquisition

We applied torque commands to the robot in a hydrostatic environment, varying them according to a sinusoidal cycle. We collected information on angular acceleration, attitude angle, and angular velocity. Independently, we gathered data for the three attitude angles, the rotational data were collected within the time intervals of 140s~160s for each attitude angle, and 7000~8000 angular acceleration data points were collected for each degree of freedom, serving as input for a kinetic model fitting for the robot. The fitting results are shown in Supplementary Fig.1.

Supplementary Note 2. Stability of robots under transverse constant load

The motion data of the robot under constant load are depicted in the following figure. We decreased the recovery torque of the robot to minimize thrust usage for attitude control. However, this adjustment resulted in decreased stability. Under a constant load of 3 kg, with no control force output, the robot's attitude angle changed by 0.432 radians in 0.5 seconds, and the angular velocity increased to -0.47 rad/s within 0.1 seconds (Supplementary Fig.2).

Supplementary Note 3. The ratio of forward distance to depth change

The ratio of forward distance to depth change in AUR is solely dependent on the angle formed between the propeller center axis clamp angle and the fuselage center axis, when the wake aligns parallel to the seabed, the ratio of depth change to forward distance is $\tan(\delta) = 0.363$. The underactuated vehicles equipped with rudder-propeller devices rely on rudder lift for depth adjustments. A depth change of 70m at a forward speed of 3m/s over a period of 750s¹, the ratio is 0.031. A depth change of 1m at a forward speed of 1.5m/s over a period of 13s², the ratio is 0.0513. It is worth noting that in the analysis of underactuated vehicles, their wake streams are not precisely parallel to the seabed, with deviation of 6°~8°, the ratio may be smaller under ideal conditions where the wake is parallel to the seabed. Although not all underactuated vehicles were enumerated, the result suggests that relying solely on rudder effects for depth adjustments necessitates longer forward distances for depth changes, thereby limiting its application in rough terrain.

Supplementary Note 4. Convergence proof for depth controllers

The velocity of the robot along the z-axis in the world coordinate system is denoted as $v_z = -n_x \sin(\theta)$. The position of the robot along the z-axis in the world coordinate system can be regulated by adjusting the robot's pitch angle θ . Initially, the desired depth is defined as z_d , and the current actual depth is denoted as z^* . Define the depth error along the z-axis as $d_{error} = z^* - z_d$, construct a function $S = d_{error}^2 / 2$ based on depth error, and subsequently derive the derivative of S .

$$\dot{S} = d_{error} \dot{d}_{error} = d_{error} (-n_x s\theta) \quad (9)$$

For the algorithm that employs the pitch angle to regulate depth, the equation for θ is given as Eq. 10.

$$\theta = \arctan(kd_{error}) \quad (10)$$

Due to $\sin(\arctan(\theta)) = \theta / \sqrt{1 + \theta^2}$. Equation (10) is substituted into Equation (9) to yield Equation (11).

$$\dot{S} = d_{error} (-n_x \theta / \sqrt{1 + \theta^2}) \quad (11)$$

In Eq. (10), due to the $\arctan$ function is monotonic, meaning $\theta d_{error} \geq 0$. When the robot's speed $n_x > 0$, it can be assured that $\dot{S} < 0$. Consequently, the depth error is guaranteed to converge to zero, it can be demonstrated that our depth control rate ensures the depth error converges to zero.

During the speed planning process, $n_x = n_x^* + \Delta v$, where n_x^* denotes the initial velocity of the robot, and Δv represents the speed increment derived from the real-time depth error adjustment. When a disturbing force acts upon the robot along the z-axis of the global coordinate system, it creates an unknown velocity v^* . Subsequently, Eq. (11) can be expressed as follows.

$$\dot{S} = d_{error} (-n_x^* \theta / \sqrt{1 + \theta^2} + v^*) \quad (12)$$

Owing to the existence of v^* , the occurrence of $-n_x^* \theta / \sqrt{1 + \theta^2} + v^* > 0$ becomes feasible, therefore, it is not possible to rigorously ensure $\dot{S} < 0$, necessitating the

additional planning for Δv . By employed for the planning of Δv into Eq. (12), we can get Eq. 13.

$$\begin{aligned}\dot{S} &= d_{error} \left(-n_x^* \frac{\theta}{\sqrt{1+\theta^2}} - (k_p d_{error} + k_i \int_0^t d_{error}(t)) \frac{\theta}{\sqrt{1+\theta^2}} + v^* \right) \\ &= \frac{d_{error} \theta}{\sqrt{1+\theta^2}} \left(-(n_x^* + k_p d_{error} + k_i \int_0^t d_{error}(t)) - v^* \right)\end{aligned}\quad (13)$$

In Eq. 13, v^* denotes the unknown rate of depth change. By integrating the depth error, we can get $k_p d_{error} + k_i \int_0^t d_{error}(t) - v^* > 0 \quad t \rightarrow \infty$. Consequently, it can be

ensured that $\dot{S} < 0$, thereby guaranteeing the convergence of the depth error to zero.

The aforementioned proof demonstrates that, even in the presence of an unknown disturbing force on the depth, the controller still ensure the convergence of the depth control error.

Supplementary Note 5. Robot Low Disturbance Design

When underwater robots operate near the seabed, the primary issue is the resuspension of sediments due to the propeller wake. A direct solution entails ensuring the wake does not move towards the seabed. In this way, the core objective of this paper's low-disturbance design is to facilitate the robot's ascent without the wake impacting the seabed.

When the force generated by the propeller is also parallel to the seabed, it typically dose not induce a tendency for the robot to move away from the seabed. However, by tilting the propeller at an angle with the robot, this parallel force can be decomposed into the two planes of the robot. As depicted in Fig. 3I, the force from the bottom propeller, parallel to the seabed, is resolved to the x-direction and z-direction of the robot. The x-direction force propels the robot away from the seabed, while the z-direction force draws it closer. By adjusting the damping in these two directions, we can maneuver the robot away from the seabed while maintaining the wake parallel to the seabed.

We examine the impact of the robot's hydrodynamic coefficients in the forward (x) and upward (z) directions on its acceleration during the ascent. Following the kinetic formulation presented in Eq. 3, the motion of the robot in the x and z degrees of freedom can be expressed as follows.

$$\begin{bmatrix} m + X_{\dot{u}} & 0 \\ 0 & m + Z_{\dot{w}} \end{bmatrix} \begin{bmatrix} \dot{u} \\ \dot{w} \end{bmatrix} + \begin{bmatrix} X_u + X_{|u|u}|u| & 0 \\ 0 & Z_w + Z_{|w|w}|w| \end{bmatrix} \begin{bmatrix} u \\ w \end{bmatrix} = \begin{bmatrix} \tau_x \\ \tau_z \end{bmatrix} \quad (14)$$

In the equation above, $X_{\dot{u}}$ and $Z_{\dot{w}}$ denote the additional mass in the x and z

directions, respectively. The coefficients X_u, Z_w and $X_{|u|u}, Z_{|w|w}$ represent the linear and quadratic damping, respectively. Among these parameters, the additional mass and damping coefficients, apart from the robot's inherent mass, are only influenced by its shape.

We define the distance at which the robot move away from the seabed as Z_1 (positive in the direction away from the seabed) and the distance at which the robot closer to the seabed as Z_2 (positive in the direction toward the seabed). Since the quadratic damping associated with the velocity quadratic term is caused by turbulence³, during the low-speed phase, the quadratic damping coefficient can be disregarded. Consequently, we can employ the following equations to derive the expressions for Z_1 and Z_2 .

$$Z_1(t) = \int_0^t u \sin(\delta) dt \quad u = \frac{\tau_x - (m + X_{\dot{u}})\dot{u}}{X_u} \quad (15)$$

$$Z_2(t) = \int_0^t w \cos(\delta) dt \quad w = \frac{\tau_z - (m + Z_{\dot{w}})\dot{w}}{Z_w} \quad (16)$$

Where $\tau_x = F_1 \cos(\delta) - F_2 \cos(\delta)$, $\tau_z = F_1 \sin(\delta) + F_2 \sin(\delta)$.

In the equation above, F_1 and F_2 represent the thrust generated by the lower and upper propellers, respectively. We establish the relationship between F_1, F_2 and Z_1, Z_2 .

$$Z_1(t) = \frac{\sin(2\delta)(F_1 - F_2)}{2X_u} \left(t - \frac{(m + X_{\dot{u}})}{X_u} (1 - e^{\frac{-X_u t}{(m + X_{\dot{u}})}}) \right) \quad (17)$$

$$Z_2(t) = \frac{(F_1 + F_2) \sin(2\delta)}{2Z_w} \left(t - \frac{(m + Z_{\dot{w}})}{Z_w} (1 - e^{\frac{-Z_w t}{(m + Z_{\dot{w}})}}) \right) \quad (18)$$

We should ensure that $Z_1 > Z_2$ is sufficient for the robot to move away from the seabed, and $F_1 \geq 0, F_2 \geq 0$ is maintained the wake does not towards the seabed.

Based on the expression for Z_2 , when the robot and the seabed are at a certain angle, the thrust from the propeller must be balanced with the restoring moment of the robot, satisfying the following equation.

$$F_1 + F_2 = \frac{\tau_{recover} \tan(\delta)}{B} \quad (19)$$

Where $\tau_{recover}$ represents the recovery torque of the robot. Subsequently, Z_2 can be

expressed in the following manner.

$$Z_2(t) = \frac{\tau_{recover} \sin^2(\delta)}{Z_w B} \left(t - \frac{(m + Z_{\dot{w}})}{Z_w} \left(1 - e^{\frac{-Z_w t}{(m + Z_{\dot{w}})}} \right) \right) \quad (20)$$

Once the robot's structure is established, the distance Z_2 is independent of the control force selection. To optimize $Z_1 - Z_2$, we set $F_2 = 0$, and Z_1 will be maximized. Therefore, we set $F_2 = 0$ to evaluate the impact of structural parameters on the outcome of $Z_1 - Z_2$, to avoid the influence of different control force choices.

$$\begin{aligned} & Z_1(t) - Z_2(t) \\ &= \frac{\sin(2\delta)F_1}{2} \left(\frac{t}{X_u} - \frac{t}{Z_w} + \frac{(m + Z_{\dot{w}})}{Z_w^2} \left(1 - e^{\frac{-Z_w t}{(m + Z_{\dot{w}})}} \right) - \frac{(m + X_{\dot{u}})}{X_u^2} \left(1 - e^{\frac{-X_u t}{(m + X_{\dot{u}})}} \right) \right) \end{aligned} \quad (21)$$

In Eq. 21, when $t = 0$, $Z_1(t) - Z_2(t) = 0$ is satisfied. By differentiating Equation (21), we derive Eq. 22, which help us to understand the ascent process.

$$\dot{Z}_1(t) - \dot{Z}_2(t) = \frac{\sin(2\delta)F_1}{2} \left(\frac{1 + e^{\frac{-X_u t}{(m + X_{\dot{u}})}}}{X_u} - \frac{1 + e^{\frac{-Z_w t}{(m + Z_{\dot{w}})}}}{Z_w} \right) \quad (22)$$

From the Eq. 22, it is evident that to satisfy $\dot{Z}_1 - \dot{Z}_2 > 0$, we must first ensure $\delta \in (0, \pi/2)$. Subsequently, we analyze the conditions for making Equation (23) positive and explore how to maximize its value.

$$UP_v = \frac{1 + e^{\frac{-X_u t}{(m + X_{\dot{u}})}}}{X_u} - \frac{1 + e^{\frac{-Z_w t}{(m + Z_{\dot{w}})}}}{Z_w} \quad (23)$$

We observe that the value of UP_v is independent of the thruster's tilt angle and the control force, only depends on the robot's shape. By analyzing UP_v , we can determine which shape is more conducive to the robot's low-perturbation ascent. As depicted in Supplementary Fig.3E, the side view of the robot's sealing shell showcases a design based on a sphere. By adjusting the distance between points OA, the top and bottom of the sphere are spliced together to form a sealing shell. Adjusting the value of OA could change the damping coefficient and the additional mass factor. We conducted hydrodynamic simulations to model the damping and added mass coefficients of the sealing shell at various values of OA.

The simulation results indicate that the robot can ascend with low disturbance if the damping in the XOY plane exceeds that in the XOZ plane. Moreover, a smaller OA distance corresponds to a larger value of Eq. 23 in this design approach. Therefore, we reduced the OA distance to 80mm, ensuring that the components could still be accommodated within the chamber.

Next, we analyze $\sin(2\delta)$, which affects the value of Eq. 22. This enables us to clarify how to choose the tilt angle of propellers. We note that when δ is in the range of $(0, \pi/4)$, when δ increases $\sin(2\delta)$ also increases. However, this increase in tilt angle results in a decrease in propulsive efficiency. We quantified this loss of propulsive efficiency through experiments (Supplementary Fig.3D). By measuring the relationship between thrust and power at different tilt angles, we define propulsive efficiency as the ratio of the power required to produce the same thrust at various tilt angles to the power required to generate that thrust at a zero tilt angle. Our findings revealed that at tilt angle of 20° , the robot's low-disturbance ascent speed reaches 64% of its maximum value, while the thruster efficiency during advancement decreases by only 4.3%. Additionally, the maximum pitching moment associated with depth control decreases by just 6.25% (Supplementary Fig.4). Notably, the maximum roll moment increases and is approximately equal to the magnitude of the maximum pitch moment, which is well-aligned with the hydrodynamic shape of the robot's disk. Moreover, Other tilt angles could be selected or actively controlled in future work to optimize the NS-MUV for specific environments.

Supplementary Note 6. Control Algorithm Comparison

We have evaluated the performance of various algorithms against disturbances by employing a 3 kg weight block as a disturbance in our comparative analysis.

In the control algorithm proposed in this paper, a PD controller is employed as the based control algorithm, utilizing the observed magnitude of external disturbances as feed-forward input to reject disturbance. For comparative analysis, a PID controller is selected, as it shared the PD controller with the controller that we proposed, differing only in its approach to reject disturbances. Using this comparison, we could demonstrate the superiority of the proposed disturbances resistance logic over the integral term's role in the PID controller for disturbances mitigation.

In this paper, the pitch angle control algorithm is $\tau_q = -K_2(\tilde{\theta} + \hat{\theta}) - K_{D2}\dot{\tilde{\theta}}$. By normalization the control parameters, we get $\tau_q = -K_{gain2}(K_{p2}(\tilde{\theta} + \hat{\theta}) + K_{d2}\dot{\tilde{\theta}})$, where $K_2 = K_{gain2}K_{p2}$, $K_{D2} = K_{gain2}K_{d2}$, the PID controller is Eq. 24.

$$\tau_{q_PID} = -K_{gain2}(K_{p2}\tilde{\theta} + K_{d2}\dot{\tilde{\theta}} + K_{i2}\int \tilde{\theta}) \quad (24)$$

The K_{p2} and K_{d2} of both controllers are maintained identically during the comparison. We selected various integral coefficients K_{i2} to incorporate into the PID controller. As illustrated in Supplementary Fig.5A, varying integration parameters yield distinct control effects. Supplementary Fig.5A demonstrates that the depth error does not diminish with the integration coefficient increase. Specifically, when the integration coefficient is 0.8, the robot's depth decreases more rapidly compared to when the coefficient is 0.4. We surmise that this discrepancy arises because the integration coefficient accumulates error from the period prior to disturbance application, thereby continuing to influence the robot's control effect during instantaneous disturbances. The disturbance resistance of the PID controller is optimal at K_{i2} equal to 0.6, and we use this set of experimental data in the subsequent analysis.

Subsequently, we implemented an adaptive algorithm for the comparative experiment⁴. This algorithm utilizes both an adaptive term and tanh-sigmoid-surface control laws to enhance the controller's ability to resist external disturbances.

Initially, we adhered to the control parameters recommended in the referenced article⁴. Although stability in static water is ensured, the robot rapidly destabilizes when a disturbance is applied. Then we make the parameter adjustments, in the parameter tuning of the adaptive algorithm, we found that integration time Δt and integral coefficients have the most significant impact on control performance. We conducted a dozen parameter adjustments, with the results displayed in Supplementary Fig.5.

In the depth control effects, the adaptive algorithm has significantly enhanced the control efficiency ($\Delta t = 2s, K_{i2} = 0.4$). Specifically, following disturbance application, the adaptive algorithm decreased the maximum descent depth from 0.86m (observed using PID control, $K_{i2} = 0.6$) to 0.46m. Moreover, the time required for pitch angle stop falling after disturbance was reduced from 1.23 s in the PID controller to 0.55 s. This proves that the adaptive algorithm highlighted the efficacy of rejecting external disturbances by using the adaptive term and the tanh-sigmoid surface control rate.

However, from the data on the pitch angle, during the subsequent weight block stabilization stage, the adaptive algorithm resulted in substantial fluctuations in the pitch angle (ranging from -0.416 rad to 1.021 rad). In contrast, the algorithm presented in this study exhibited much smaller fluctuations in the pitch angle during the subsequent stabilization stage (ranging from -0.025 rad to 0.198 rad), with the fluctuation amplitude of the adaptive algorithm being 7.16 times larger than that of our algorithm.

Due to the NS-MUV's method of indirectly controlling depth through pitch angle adjustments, when an external force disturbs the pitch angle direction, the controller

must rapidly counteract this disturbance to stabilize the pitch angle. If the controller lacks the aforementioned capability, two problematic scenarios can arise. Firstly, with a slow-reacting algorithm (PID), the robot's pitch angle adjusts gradually to stop depth reduction. However, during this adjustment, significant depth decrease occurs (Supplementary Fig.5A). Secondly, while a fast-response algorithm (adaptive algorithm) swiftly adjusts the pitch angle, this rapid change does not directly stabilize the depth but instead causes depth fluctuations, these fluctuations in depth consequently prompt further affects the planning of pitch angle. This cycle of changes exacerbates the instability in the pitch angle; although it reduces depth errors, it results in substantial pitch angle fluctuations that could adversely affect the robot's navigation near the seabed. Pitch angle fluctuations could lead to collisions with the seabed.

Overall, the robot proposed in this paper employs an effective depth control strategy for anti-interference, enabling the controller to rapidly identify disturbances and provide swift feedback, this approach stabilizes depth while minimizing fluctuations in pitch angle.

Supplementary Note 7. Robot structure parameters

The structural dimensions of the robot are illustrated in Fig.S7A, B and C. The design principle of the Sealing shell is depicted in Supplementary Fig.7D. In this design, a portion of the sphere is removed to leave an 8 cm high shell. This shell is then assembled by splicing the upper and lower sections. By cutting 1 cm from the lower shell, a flat base is created to placement. The spacing between the thrusters' center axes is maintained at 16 cm, aligning with the theoretical height of the waterproof shell. When including the thruster shells, the overall height reaches a maximum of 24.5 cm.

Supplementary Note 8. Disturbance observation platform

We have designed two types of perturbation observation platforms: planar and trapezoidal. Detailed dimensional information for these platforms is provided in Supplementary Fig.9. Each platform features an arrangement of plastic spheres intended to observe the effects of the thruster wake on the surface below. Both platforms were configured with three rows of plastic spheres, with the spacing between the spheres in the outermost rows matching that of the NS-MUV's thrusters (0.76 m). Additionally, the arrangement of the plastic spheres is set with a spacing of 10 cm, and each sphere is secured to the platform using a thin wire that is 15 cm in length. During the test, we let the plastic spheres remain below the thrusters to sense disturbance from propeller wake.

Supplementary Note 9. Control parameters

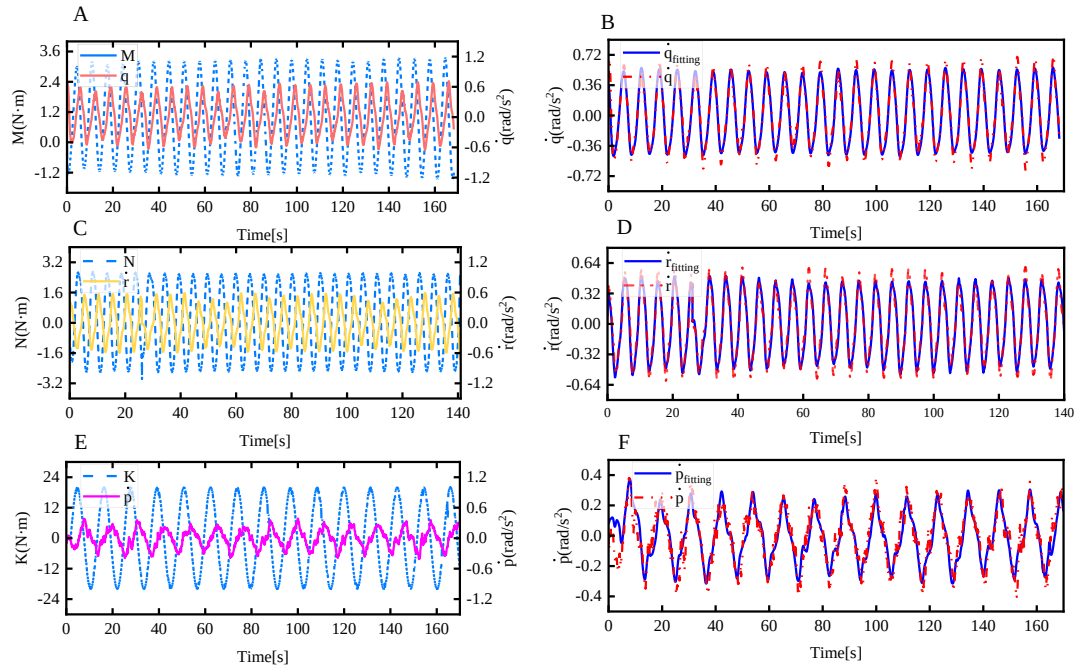
The control parameters are shown in Table 3. The control algorithm proposed in this paper incorporates several parameters, tuning those related to the basic Proportional-Derivative (PD) controller to ensure effective control in a static water environment. Notably, the pitch angle control parameter is larger than the roll angle control parameter, as the pitch angle directly influences depth control, whereas changes in the roll angle do not affect depth. The gain for the bow angle control is set slightly lower because the bow rotation offers greater flexibility compared to the other two degrees of freedom.

A smaller value for parameter $\dot{\omega}_{\min}$ increases the sensitivity of the robot to external disturbances, allowing even minor disturbances to trigger the observation of these external factors. Theoretically this value should be as small as possible, but will be limited by the limitations suffered by the sensor. We adjust $\dot{\omega}_{\min}$ to be large than the noise level detected by the sensors when the robot is stationary.

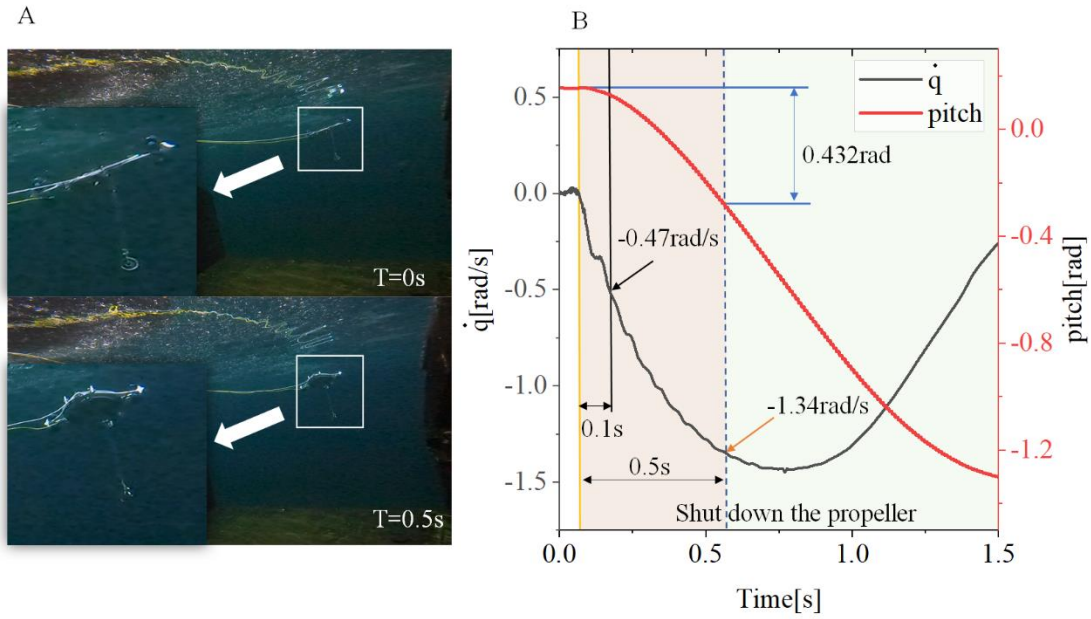
The choice of parameter $\eta_{\max}$ will affect the observation time for external disturbances. As outlined in Eq. 8 of this paper, the algorithm employs two approaches for observing external disturbances: one approach waits until a maximum observation time is reached before updating the disturbance estimates, while the other updates the estimates when the observed value over a short time period exceeds $\eta_{\max}$. It is important not to set $\eta_{\max}$ too high; otherwise, it may result in the robot becoming unresponsive to external transient disturbances.

The establishment of threshold β is essential, and the fundamental rationale for setting this threshold to initiate observations is that when the robot's depth error falls below β , it can be assumed that the robot is in a steady state with current speed, eliminating the need for further adjustments. Subsequently, it is only necessary to plan the pitch angle of the robot to reduce the depth error and avoid frequent changes in the running speed.

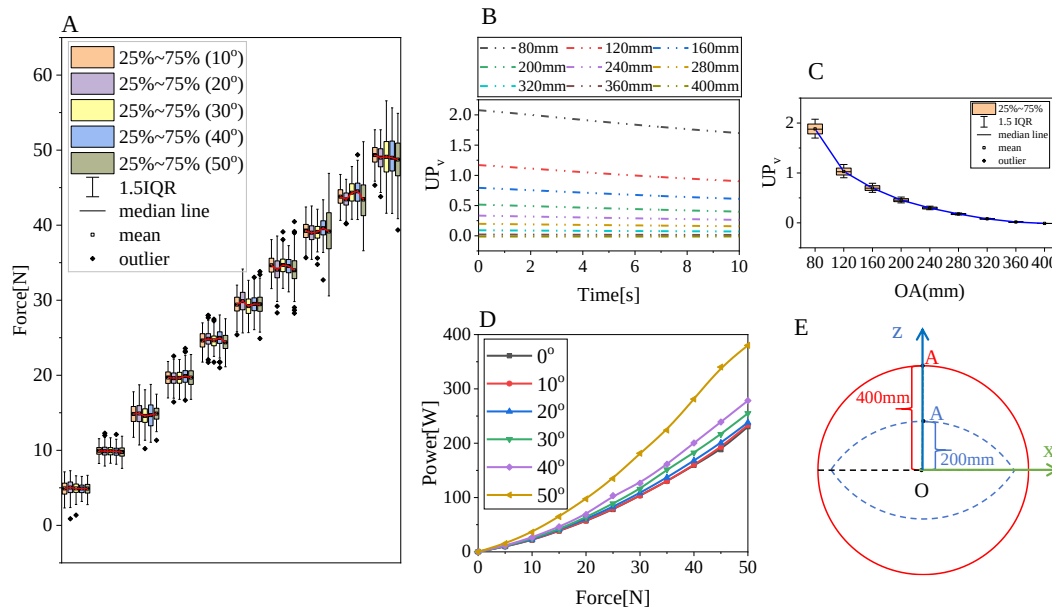
Supplementary Figures



Supplementary Fig. 1. Robot dynamics model parameter identification. (A) Pitch torque and angular acceleration. (B) Pitch angular acceleration fitting curve. (C) Yaw torque and acceleration. (D) Yaw angular acceleration fitting curve. (E) Roll torque and angular acceleration. (F) Roll angular acceleration fitting curve. Source data are provided as a Source Data file.

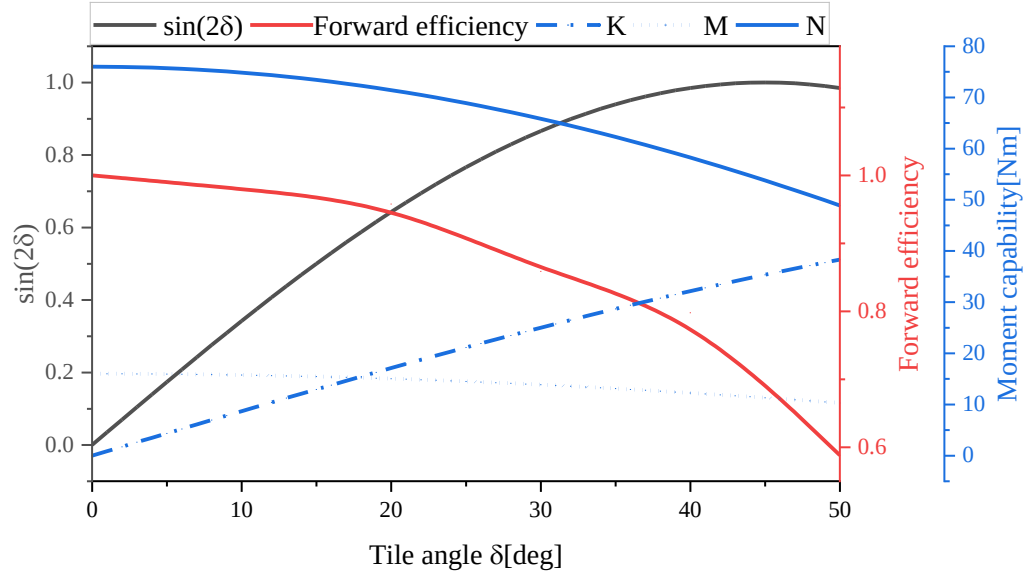


Supplementary Fig. 2. Stability under Constant Load. (A) Response of the robot under a constant load of 3 kg after propeller shutdown. (B) Angular velocity and angle data of the robot under constant load. Source data are provided as a Source Data file.

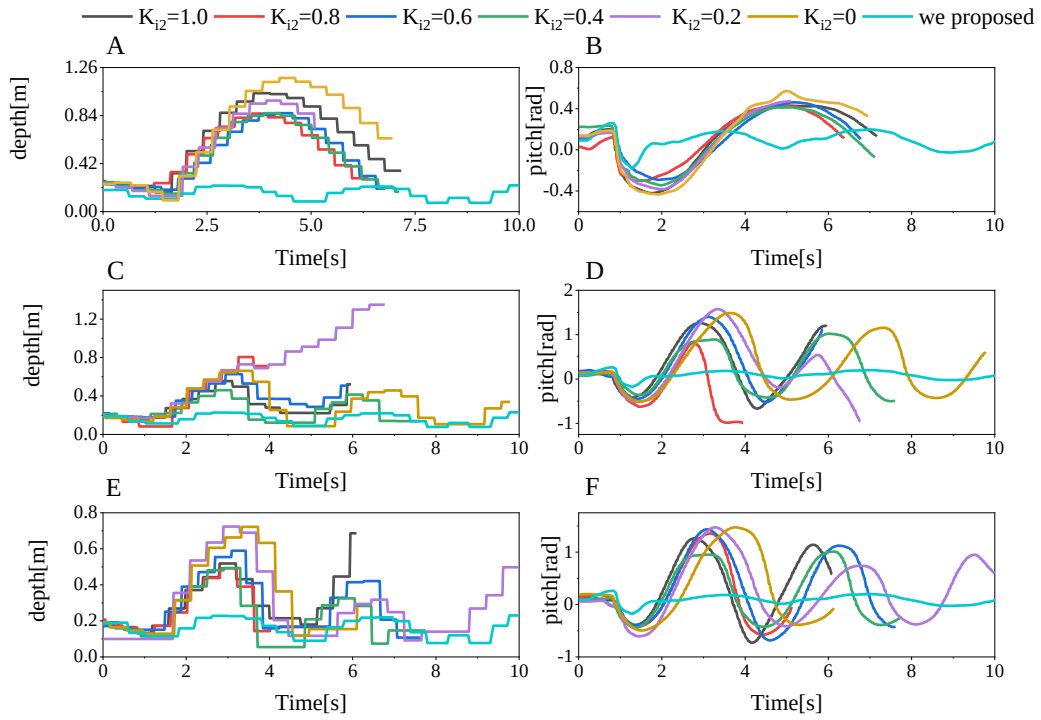


Supplementary Fig. 3. Robot structure optimization. (A) Thrust statistics at different tilt angles (number of data: 200), (Mann-Whitney U test: median, mean, and 25th to 75th percentiles). (B) Values of UP_v for different OA values. (C) Statistics of UP_v . (D) Power vs Force for different tilt angles. (E) Schematic of the robot's structure.

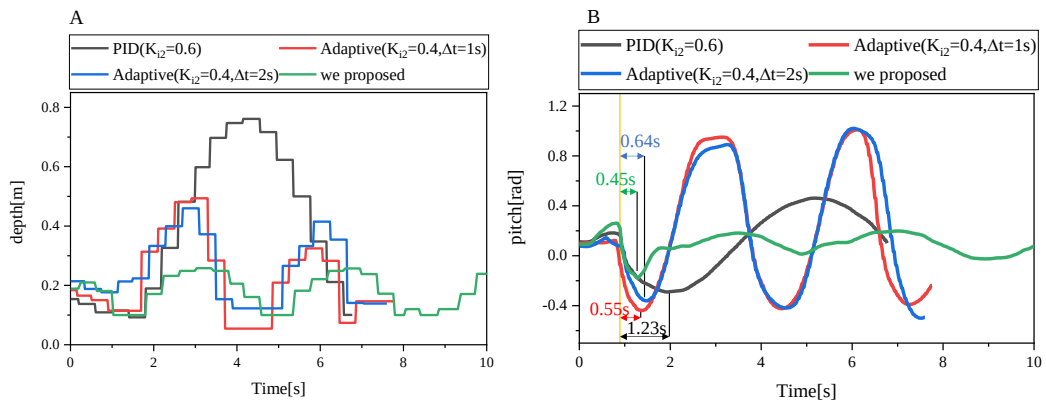
UP_v values for different OA values in 0-10s (number of data: 1000), (Mann-Whitney U test: median, mean, and 25th to 75th percentiles). **(D)** Thrust and power curves for different tilt angles of the thruster. **(E)** Side view of the robot's sealing shell. Source data are provided as a Source Data file.



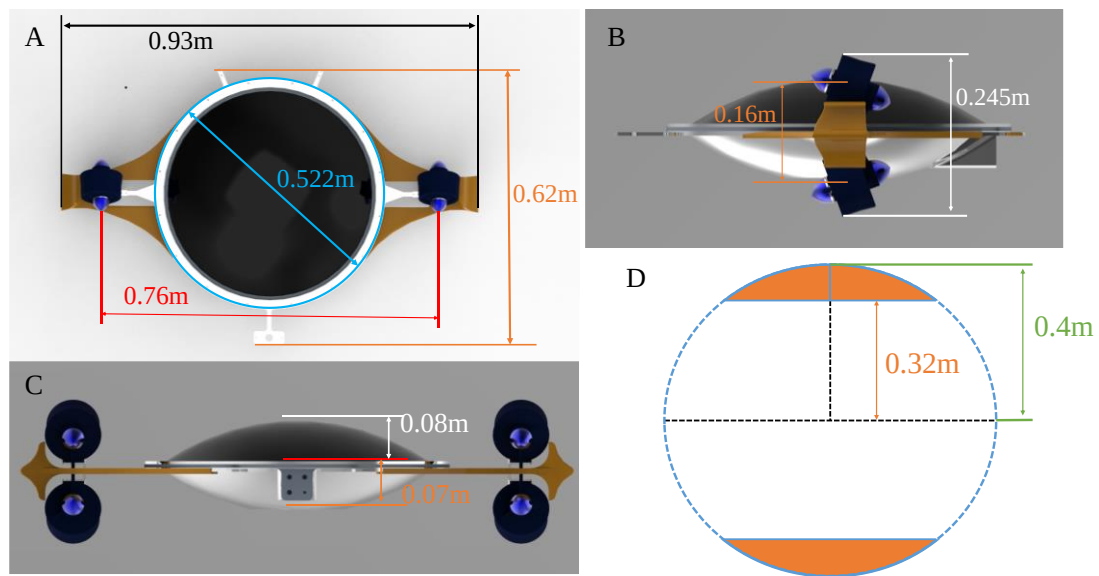
Supplementary Fig. 4. Effect of thruster tilt angle on low perturbation ascent velocity, propulsive efficiency, and control torque. Source data are provided as a Source Data file.



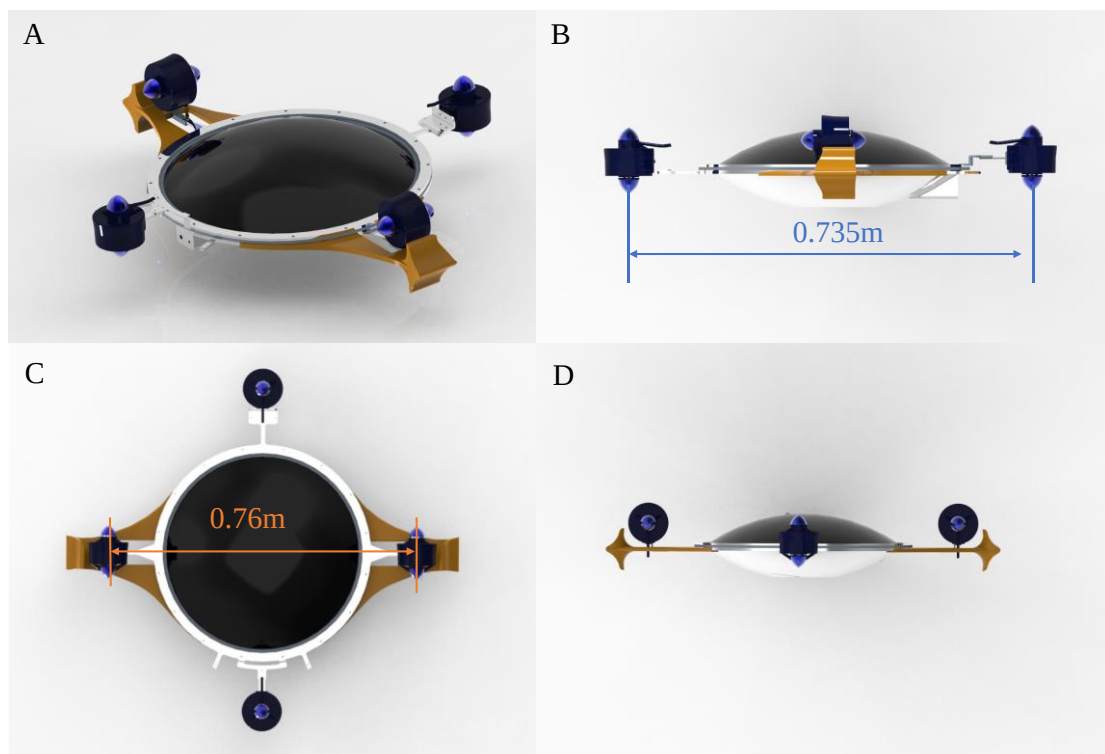
Supplementary Fig. 5. Effectiveness of different algorithms against interference. (A) Depth control effect of different integral coefficients of PID algorithm. (B) Effectiveness of PID algorithm for pitch angle control with different integration coefficients. (C) The effect of varying integration coefficients on depth control effect of adaptive algorithm ($\Delta t = 2s$). (D) The effect of varying integration coefficients on pitch angle effect of adaptive algorithm ($\Delta t = 2s$). (E) The effect of varying integration coefficients on depth control effect of adaptive algorithm ($\Delta t = 1s$). (F) The effect of varying integration coefficients on pitch angle effect of adaptive algorithm ($\Delta t = 1s$). Source data are provided as a Source Data file.



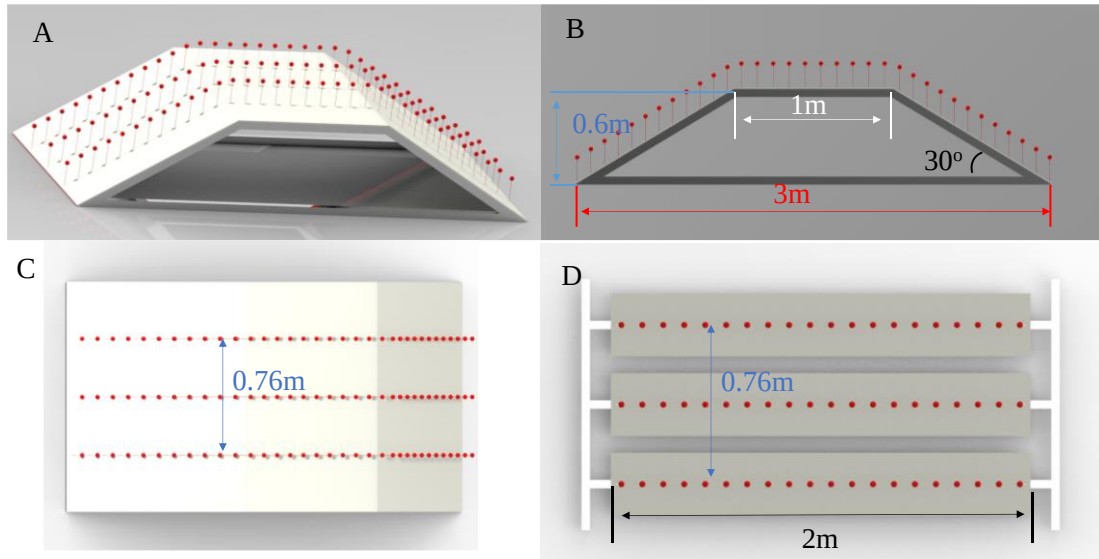
Supplementary Fig. 6. Anti-jamming ability of the three algorithms. (A) The depth control effects. (B) The pitch angle control effects. Source data are provided as a Source Data file.



Supplementary Fig. 7. Structural dimensions of NS-MUV. (A) Top view. **(B)** Side view. **(C)** Back view. **(D)** Sealing shell design parameters.



Supplementary Fig. 8. Modification of robot structure. (A) Traditional structure. **(B)** Side view. **(C)** Top view. **(D)** Front view.



Supplementary Fig. 9. Disturbance Observation Platform. (A) Trapezoidal disturbance observation platform (B) Side view of trapezoidal disturbance observation platform. (C) Top view of trapezoidal disturbance observation platform. (D) Top view of planar disturbance observation platform.

Supplementary Tables

λ	0.25m
D	0.32m
Mass	16.3kg
δ	20°
B	0.16m

Supplementary Table 1. Robot body parameters.

Accelerometer	Bias Stability	<0.4mg
	Noise Density	75ug/ $\sqrt{\text{Hz}}$
	Resolution	<0.5mg
Gyroscope	Bias Stability	2°/hr
	Noise Density	0.0028°/s/ $\sqrt{\text{Hz}}$
	Resolution	<0.001°/s
Depth sensor	Resolution	<0.002m

Supplementary Table 2. Sensor parameters.

k	1.5	k_i	0.5
k_p	0.1	$\dot{\omega}_{\min}$	0.08 rad s ⁻²
β	0.05m	η_1	0.1
ρ	1.9	η_2	0.1
K_1	30	η_3	0.1
K_2	60	$t_{\max}$	0.1s
K_3	15	K_{D1}	15
K_{D2}	20	K_{D3}	7.5

Supplementary Table 3. Control parameters

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