

A Maneuverable Underwater Vehicle for Near-seabed Observation

Corresponding Author: Professor Gang Wang

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

This study proposes a new design for remotely operated vehicles performing environmental sampling tasks in shallow waters.

One of the main challenges that often arise when collecting near-seabed images in rapidly changing environments is the turbidity caused by the robot's thrusters, which affects image quality. The authors propose a new design that maintains maneuverability while ensuring that the thrusters generate significantly less turbidity; hence, enabling the collection of higher quality near-seabed images. Through real-world experiments, they also demonstrate that their design achieves good disturbance rejection properties.

The video showcasing the results of the experiments is very helpful for better understanding the paper.

While the results of the experiments are significant, the theoretical contribution of the paper is not adequately addressed. The design is briefly discussed, but the design aspects and the rationale for the design choices are not sufficiently explained. In addition, the writing of the paper can be significantly improved.

In the control section (starting with line 373), instead of a PID controller, a more rigorous control approach (e.g., adaptive control methods), which is often used in similar studies, could be employed for comparison. Also, a mathematically rigorous assessment of the designed control approach in Eq. 7 should be included.

Reviewer #2

(Remarks to the Author)

This manuscript describes the design of a maneuverable underwater vehicle for underwater observation. Its results show the robot's capability to maintain a distance from the seabed and reduce its impact when moving away from it. I believe this work holds significance for underwater robotics research; however, the author's investigation is not sufficiently comprehensive. Some aspects of the work support its conclusions and claims, yet additional evidence is required. The authors' data analysis lacks more complex or real-world scenarios. The proposed solution represents an idealized model. Providing a modeling scheme based on the design platform would be more beneficial for researchers to explore. The followings are my concerns regarding the article:

1. The author fails to clearly articulate the research questions and core contributions of the paper in the abstract, the first paragraph of the background description, and the discussion section. For instance, the significance of separately describing floating, legged, and wheeled robots is not elucidated. While the author posits that they all cause interference underwater, it remains unclear whether separate delineation is necessary. Besides, could the author provide the negative effects (evidence) from current underwater vehicles for near-seabed observations such as the blurred vision data collected by the common platforms?
2. The author's description of the structural design lacks sufficient detail. For instance, the robot's body length is not clearly explained. The author could provide detailed descriptions of the robot via CAD/FBX/3D Models or relevant documents, along with the original purpose and dynamic analysis.

3. Apart from Figure 1, all other scenarios tested are static. However, I believe the near-seabed conditions are far more complex than static tests. Could the author provide simulation or actual test results to substantiate this? Figure 1 does not adequately demonstrate the characteristics of the robot in dynamic underwater environments.
4. The experimental setup in Figure 3 is considered one of the core experiments. However, the author provides insufficient information regarding experimental conditions and explanations, such as the pose and direction of those robots. Modifying the structure designed by the author to resemble other types of underwater vehicles and conducting comparative experiments may better illustrate the advantages of the author's design.
5. The high flexibility of this structure also appears to be one of the contributions of the manuscript. A slowly ascending underwater vehicle can also reduce its impact on the seabed. Therefore, the author should provide information on the impact on the surrounding environment during significant changes in posture/acceleration/etc.
6. Some language within the article appears redundant. The caption for Figure 3(E) is missing. On page 13, line 419, "NS-NS-MUV" appears. In the background section on page 3, only references [39] and [40] are listed (closely related), and [40] pertains to an earlier research report. The meanings of the parameters in Equation 7 also need to be clarified.

Reviewer #3

(Remarks to the Author)

This paper proposes an underwater vehicle, which is able to perform complex maneuvers while being close to the seabed.

The proposed design and control strategy are promising; however, the manuscript presets several flaws which critically hinder the overall paper quality.

- The Authors goal seems to be to design a vehicle for near-seabed observation, specifically, (L14-15) "[...] to gather detailed information on species, habitats, and ecological dynamics [...]. However, it is not clear the direct relationship between the measurements the robot is able to gather (i.e., seabed videos and images) with the actual habitat conservation status. How biologists typically perform seabed status assessments? Which Key Performance Indicators (KPIs) do they use? How does the proposed robot meet the quality requirements for these observations? From the Abstract and Introduction, I was expecting a deeper discussion and analysis on the application of this robot, while, at the moment, the main contribution of this paper seems to be a nice underwater robot, with no straightforward relation with its ecological function.
- It is not clear if the robot is autonomous or not. This point is not discussed in the paper, despite it is crucial.
- The terrain tracking experiments does not seem precise from Fig. 4C. What is the actual reference? How does the robot localize itself?
- The video is nice and informative, but I was expecting to see all the experiments reported in the manuscript, while they are different. This limits the paper clarity. For instance, it would be nice to see the video of the experiments in Fig. 3.
- In Sec. "Resistant to Strong Disturbances", the proposed algorithm is compared to a PID controller. This comparison is not fair. PID is a very simple controller, whose performance are heavily dependent on the selected gains. The slow response (L391) of the PID could be affected by a poor gain selection. How did you tune the gains?
- The Results section contains paragraphs which are more suited for a Discussion section (e.g., L486-495). Conversely, the Discussion section is poor, and it contains paragraphs which are more an introduction than a discussion (e.g., L513-541).
- The Methods section is not particularly solid. Vectors are sometimes defined as columns and sometimes as rows, is it intentional or a typo? The whole "offline learning part" is vague, and it misses important explanation. Variables are used multiple times with different meanings. For instance, H in (5) is a model, in (6) it becomes a transformation matrix. k is a gain, then it becomes a time instant. Several variables are not defined. In (7) there is a X symbol never used before.
- The supplementary material does not contain deeper information on the methods. The parameters tables are not discussed, and the control gains are not reported.
- Figures are not cited in the correct order.
- The paper is not always clear. There are a few typos (e.g. L88, L373), and unclear sentences (L79-80, L108-110, L543-546).

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

Thank you for your revisions and the detailed explanations provided. I appreciate the effort you've put into addressing all the comments and suggestions from the previous round.

Reviewer #2

(Remarks to the Author)

I thank the authors for their detailed responses to the previous review comments and the revisions made. After careful review, I believe the authors have adequately addressed the concerns I raised, and the quality of the current version has improved significantly compared to the previous one. The paper's content is clearer, the logic is more rigorous, and the overall depth and breadth of the research have been enhanced.

Therefore, I have no further comments on the current version and recommend that the paper proceed to the next stage.

Reviewer #3

(Remarks to the Author)

The Authors improved the manuscript's quality. A few issues still remain.

-) \beta is still not defined.

-) A few limitations mentioned in the rebuttal file (autonomy and localization ability) are not mentioned in the manuscript (Reviewer#3 Concern #2; Reviewer#3 Concern #4).

-) The novel videos are nice, but it would be better to have some commentary/explanation like in the first video.

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Point-to-Point Response to the Reviewers

Manuscript ID: NCOMMS-24-15186A

“A Maneuverable Underwater Vehicle for Near-seabed Observation.”

by Kaixin Liu, Mingxuan Ding, Biye Pan, Peiye Yu, Dake Lu, Siwen Chen,
Shuo Zhang, Gang Wang

We sincerely appreciate the editor and reviewers' valuable and insightful comments. We have revised and improved our manuscript as suggested. In the following, we provide a point-to-point response to each question raised, and substantial revisions to address the issues presented by the reviewers. Please refer to the revised manuscript (Revised manuscript clean.pdf, Revised manuscript.pdf).

We are grateful for the reviewers' recognition of our work, and in response to these queries, we have added more field experiments to demonstrate the robot's maneuverability in more complex undersea environments. Additionally, we included further comparative tests of control algorithms to address the reviewers' concerns regarding insufficient algorithm comparisons in the initial submission. We also provided a detailed description of the robot's design principles in the supplementary information to clarify the questions raised by Reviewer 1 and Reviewer 2 about the robot's design principles.

The authors sincerely thank all the reviewers for their valuable suggestions. We hope the revised manuscript can meet the publication criteria of Nature Communications. We appreciate your time and look forward to your response again.

Reviewer#1

Reviewer#1 Overall comment: This study proposes a new design for remotely operated vehicles performing environmental sampling tasks in shallow waters. One of the main challenges that often arise when collecting near-seabed images in rapidly changing environments is the turbidity caused by the robot's thrusters, which affects image quality. The authors propose a new design that maintains maneuverability while ensuring that the thrusters generate significantly less turbidity; hence, enabling the collection of higher quality near-seabed images. Through real-world experiments, they also demonstrate that their design achieves good disturbance rejection properties. The video showcasing the results of the experiments is very helpful for better understanding the paper.

Thank you for the positive evaluation of our paper and your recognition of the contributions made in developing the NS-MUV. We are pleased to hear that the manuscript's experimental videos have been well received. We value the reviewer's constructive feedback and diligently addressed the points the reviewer raised to enhance the paper.

Reviewer#1 Concern #1: While the results of the experiments are significant, the theoretical contribution of the paper is not adequately addressed. The design is briefly discussed, but the design aspects and the rationale for the design choices are not sufficiently explained.

Thank you for your feedback regarding the lack of design aspects and the rationale for the design choices. In this study, we present a design concept for the low-disturbance ascent of a levitating robot. Specifically, when the force generated by the propeller is also parallel to the seabed, it typically does 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 have included a new section in the **Supplemental Information (Section 5, L73-164; Fig. S3)** that discusses the design aspects of the robot in detail, including the rationale behind our design choices.

Reviewer#1 Concern #2: In addition, the writing of the paper can be significantly improved.

Thank you for your comment. We have thoroughly reviewed the entire manuscript and corrected grammatical errors. We sincerely appreciate your assistance in enhancing the clarity and readability of our work. The manuscript has been updated by checking and correcting entire sentences to ensure better readability.

Reviewer#1 Concern #3: In the control section (starting with line 373), instead of a PID controller, a more rigorous control approach (e.g., adaptive control methods), which is often used in similar

studies, could be employed for comparison.

Thank you for your valuable feedback regarding the inclusion of a comparison algorithm. We conducted additional comparative tests using the adaptive algorithm which incorporates both an adaptive term and tanh-sigmoid-surface control laws to enhance the controller's anti-disturbance capabilities. In the supplementary comparative test, it was observed that the adaptive algorithm reacted more rapidly than the PID algorithm in response to disturbances affecting the robot; however, it resulted in substantial fluctuations in the pitch angle. We extrapolate that the pitch angle oscillations induced by the adaptive algorithm are due to the NS-MUV's indirect depth control approach, which makes it more difficult to resist disturbances. 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. 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 indirect control method for the depth of NS-MUV necessitates a control algorithm capable of rapid interference resistance to stabilize both the depth and pitch angle when the NS-MUV faces disturbances. The algorithm in this paper successfully solves the anti-disturbance problem of NS-MUV on depth control, showing its fast response to external disturbances.

Detailed data pertaining to the comparative tests of control algorithms are provided in the **Supplementary Information (Section: 6, L166-230; Fig. S5, S6)**.

Revised manuscript (L559-582) Section: Resistant to Strong Disturbances (Removal highlighted in red, addition highlighted in blue):

The disturbance resistance algorithm presented in this paper is based on a PD controller that utilizes the estimated value of external disturbances as a feed-forward component to enhance the controller's ability to counteract disturbances.

We conducted additional comparative tests using the adaptive algorithm⁵⁵ and the PID controller, respectively. The adaptive algorithm utilizes both an adaptive term and tanh-sigmoid-surface control laws to enhance the controller's anti-disturbance capabilities. The experimental results indicate that its response speed is significantly superior to that of the PID controller; specifically, with the adaptive controller, the time required for the pitch angle to stop decreasing after the disturbance was applied decreased from 1.23 s with the PID controller to 0.55 s. Additionally, the depth control error was also reduced. However, during the subsequent weight block stabilization stage, the adaptive algorithm exhibited substantial fluctuations in the pitch angle, ranging from -0.416 rad to 1.021 rad. In contrast, the algorithm presented in this paper showed much smaller fluctuations in pitch angle during the weight block 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. Detailed data and an in-depth analysis of the experimental results are provided in the supplementary material.

It is evident that, although the PD controller chosen for the disturbance resistance algorithm

in this paper exhibits a slower control response compared to the tanh-sigmoid-surface control laws of the adaptive algorithm, it offers significant advantages in control stability by swiftly detecting and effectively compensating for external disturbances. The disturbance resistance algorithm described in this paper effectively stabilizes the pitch angle soon after exposure to transient strong disturbances, significantly reducing fluctuations in pitch angle and depth.

Reviewer#1 Concern #4: Also, a mathematically rigorous assessment of the designed control approach in Eq. 7 should be included.

Thanks for your feedback on the lack of a convergence proof for Eq. 7. We apologize for the omission of this section in the previous manuscript. To address this, we have included a dedicated section on the proof of stability for the depth control rate in the **Supplementary Information (Section 4, L37-71)**. The supplement offers a mathematically rigorous evaluation of the formulation of Eq. 7 to ensure its convergence.

Reviewer#2

Reviewer#2 Overall comment: This manuscript describes the design of a maneuverable underwater vehicle for underwater observation. Its results show the robot's capability to maintain a distance from the seabed and reduce its impact when moving away from it. I believe this work holds significance for underwater robotics research; however, the author's investigation is not sufficiently comprehensive. Some aspects of the work support its conclusions and claims, yet additional evidence is required. The authors' data analysis lacks more complex or real-world scenarios. The proposed solution represents an idealized model. Providing a modeling scheme based on the design platform would be more beneficial for researchers to explore. The followings are my concerns regarding the article:

Thank you for recognizing the significance of our work. We have thoroughly read and considered the feedback provided by the reviewer. We understand that the reviewer has identified some flaws or concerns in our manuscript, and we have addressed these concerns and made the necessary changes to enhance the overall quality of our work. We have added more field experiments in the **Revised manuscript (Section: Field experiment, L594-649; Fig. 8, 9)**, as well as added a modeling scheme for the robot in the **Supplemental Information (Section 5, L73-164; Fig. S3)**.

Reviewer#2 Concern #1: The author fails to clearly articulate the research questions and core contributions of the paper in the abstract, the first paragraph of the background description, and the discussion section.

Thank you for your feedback regarding the main contributions and research questions of the article. In seafloor observations, robots situated close to the seabed can capture clearer image data; however, floating robots can disrupt the visibility by stirring up sediment as they navigate near the seafloor. Although benthic robots can reside directly on the seafloor to capture images, they struggle to get through the rugged terrain. The primary contributions of this paper include a robotic design solution that enables closer proximity to the seabed, thereby reducing light refraction and scattering distances, and enhancing image quality. This design leverages the benefits of floating robots navigating rugged seafloor terrain while mitigating the impact on bottom sediments during near-seabed activities, especially in the ascent phase.

We have revised the Abstract, Introduction, and Discussion sections to more clearly articulate the research focus and the primary contributions of the paper.

Revised manuscript (L23-37) Section: Abstract (Removal highlighted in ~~red~~, addition highlighted in ~~blue~~):

However, these robots face limitations in delicate ecosystems, such as coral reefs and anemone beds, because of their inevitable contact with their surroundings. We propose a maneuverable underwater vehicle for near-seabed observations to address these challenges. This configuration significantly ~~minimizes~~ ~~reduces~~ sediment disturbance by the robot ~~during near-seabed movement compared with traditional setups~~ when it's away from the seabed, enhancing its ability to closely observe the seabed (approximately 20 cm), thereby reducing light refraction and scattering distances, contributing to producing higher-quality images. It enables the rapid detection of intense disturbances, such as turbulence and wall effects, allowing real-time planning to prevent the robot from bottoming. ~~Over ten sets of practical swimming observation tests were~~

~~successfully conducted within a 20 cm proximity to various observation subjects, including coral reefs and sandy gravel terrains.~~ We conducted multiple tests in various marine environments, such as sandy areas, coral reefs, and sheer rock, successfully verifying the robot's low sediment disturbance and adaptability to rugged underwater terrains.

Revised manuscript (L40-63) Section: Introduction (Removal highlighted in ~~red~~, addition highlighted in ~~blue~~):

Seabed detection plays a crucial role in safeguarding marine ecosystems. Effective management and protection of seabed ecosystems are facilitated by meticulously identifying and documenting the distribution and abundance of vital ecosystems, such as seabed organisms, coral reefs, and seagrass beds. High-definition visual information enables the capture of both color and texture nuances of the seabed, thereby facilitating the identification of biota distribution. Furthermore, clearer and more detailed images can serve as valuable supplements to traditional large-scale ocean observations. ~~However, the clarity of visual information is contingent on the visibility of the water column.~~ In current oceanographic research, image data is extensively utilized across various fields for environmental monitoring, such as the Pigmentation Reaction Score (PRS), which is crucial in assessing coral reef health¹. Additionally, the video data were essential to add value and create relationships between the morphology of the seabed, the composition of the sediments, and the geochemistry of the gases². Moreover, high-quality images are essential for constructing accurate topographic maps, aiding in ecological assessments³.

Despite many efforts to enhance underwater image clarity^{4,5}, obtaining sharper raw images remains the optimal solution. However, the clarity of visual information depends on the visibility of the water column and the distance to the target. Refraction and scattering caused by water image quality, and this effect intensifies with distance⁶. Therefore, positioning the robot closer to the seabed directly improves the quality of the captured images. However, the robot's activities may disturb seabed sediment, causing them to suspend and consequently impairing the field of view. Additionally, the rugged topography of the seabed poses challenges to the robot's mobility, hindering objective achievement.

Revised manuscript (L682-708) Section: Discussion (Removal highlighted in ~~red~~, addition highlighted in ~~blue~~):

With the ongoing advancement of ocean observation, the significance of image information in seabed exploration has grown considerably. The richness of image data offers significant value for a variety of applications, including the detection of hydrothermal vents on the seabed⁵⁶, the detection of minerals on the seabed⁵⁷, environmental protection⁵⁸, high-precision measurements of coral reef structure³, and the detection of plant health¹.

The use of image information has significantly enhanced our understanding of the undersea world, and with the continuous advancement of technology, it is expected to play an even more central role in underwater observation in the future. However, we cannot overlook the impact of water refraction and scattering on image contrast and color accuracy, particularly for seabed state analysis based on image data. For example, in the coral reef pigmentation response, the attenuation of red light by the water column makes it challenging to detect PRS lesions, which typically appear bright pink¹. Furthermore, water turbidity hampers the creation of high-precision topographic images through imagery³. The resolution decreases as smaller targets occupy fewer pixel dots due to large distance from the target⁵⁹. Additionally, the autonomous classification of biota based on underwater imagery results in diminished accuracy as the altitude of the imaging

robot increases⁶⁰. The primary factor influencing the extent of light refraction and scattering in water is distance. As the distance increases, the effects become more pronounced⁶. Therefore, a practical approach to mitigating these challenges is to minimize the robot's distance from the seabed.

Among existing ocean observation robots, wheeled and legged types encounter significant challenges in rough terrains, where obstacles and sloped surfaces can hinder their functionality. In contrast, floating robots can navigate above challenging seabed terrain, but their operations near the seabed, especially during ascent could disturb sediment. This disturbance often results in sediment resuspension, which obscures visibility.

Reviewer#2 Concern #2: For instance, the significance of separately describing floating, legged, and wheeled robots is not elucidated. While the author posits that they all cause interference underwater, it remains unclear whether separate delineation is necessary.

Thank you for your feedback. Based on your comments, we have emphasized the robots' contributions and highlighted the main challenges of near-seafloor exploration in the Abstract, Introduction, and Discussion sections of the paper. In the near-seafloor environment, robot activity often causes resuspension of sediments, and the rugged terrain challenges the robots' maneuverability. Floating, legged, and wheeled robots are all limited by the issues mentioned above when exploring near the seafloor.

The purpose of our introduction to benthic robots is to highlight their importance, as many seabed exploration studies rely on these robots, which should not be overlooked in the background introduction. The purpose of categorizing legged and wheeled robots is based on that have study shows that legged robots cause very little disturbance to seafloor sediments [13], their main challenge lies in improving terrain traversal capabilities, which is different from wheeled robots.

And the introduction of benthic robots can highlight the advantages of floating robots in terrain passage capability, as long as we solve the problem of disturbance to the seafloor sediments, then we can significantly improve the ability of the robot near the seafloor exploration of terrain passage, which can be more prominent in this paper, the advantages and significance of the research.

[13] G. Picardi, M. Chellapurath, S. Iacoponi, S. Stefanni, C. Laschi, M. Calisti, Bioinspired underwater legged robot for seabed exploration with low environmental disturbance. *Science Robotics*, 5. (2020). doi: 10.1126/scirobotics.aaz1012.

Reviewer#2 Concern #3: Besides, could the author provide the negative effects (evidence) from current underwater vehicles for near-seabed observations such as the blurred vision data collected by the common platforms?

Following your suggestion, we collected data on the blurred vision experienced by several underwater vehicles due to the sediment churn from propellers at the seabed.

(1) Fig. R1 (<https://www.bilibili.com/video/BV1Kt4y1T7Zg>).

(2) Fig. R2 (<https://youtu.be/2kWmDtXF8kQ>).

From the vision data, it is clear that the primary challenge for conventionally constructed robots navigating near the seabed is the propensity of the propellers to turbid the water column by stirring up sediment.

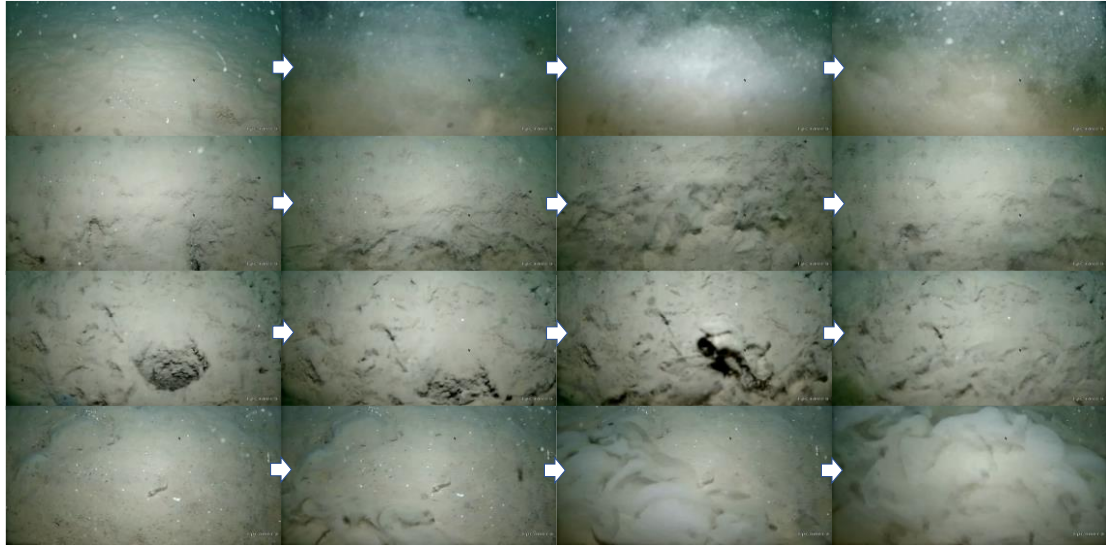


Fig. R1. Blurred vision data.

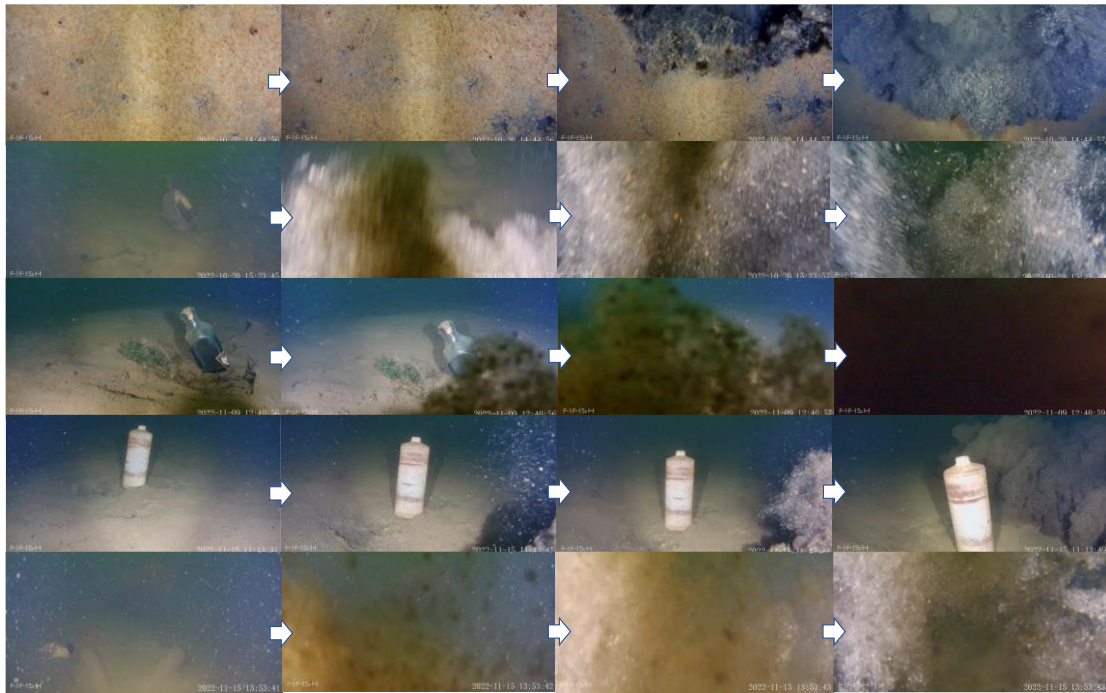


Fig. R2. Blurred vision data.

Reviewer#2 Concern #4: The author's description of the structural design lacks sufficient detail. For instance, the robot's body length is not clearly explained. The author could provide detailed descriptions of the robot via CAD/FBX/3D Models or relevant documents, along with the original purpose and dynamic analysis.

We apologize for the oversight in not introducing the length of the robot body previously. We have provided the detailed dimensional information in the **Supplementary Information (Section 7, L232-240; Fig. S7)**. Furthermore, we conducted a detailed analysis of the impact of the robot hull's shape on the performance of its low-disturbance ascent in **Supplementary Information (Section 5, L73-164; Fig.S3)**, which helps to illustrate the rationale behind the design choices made

in this paper.

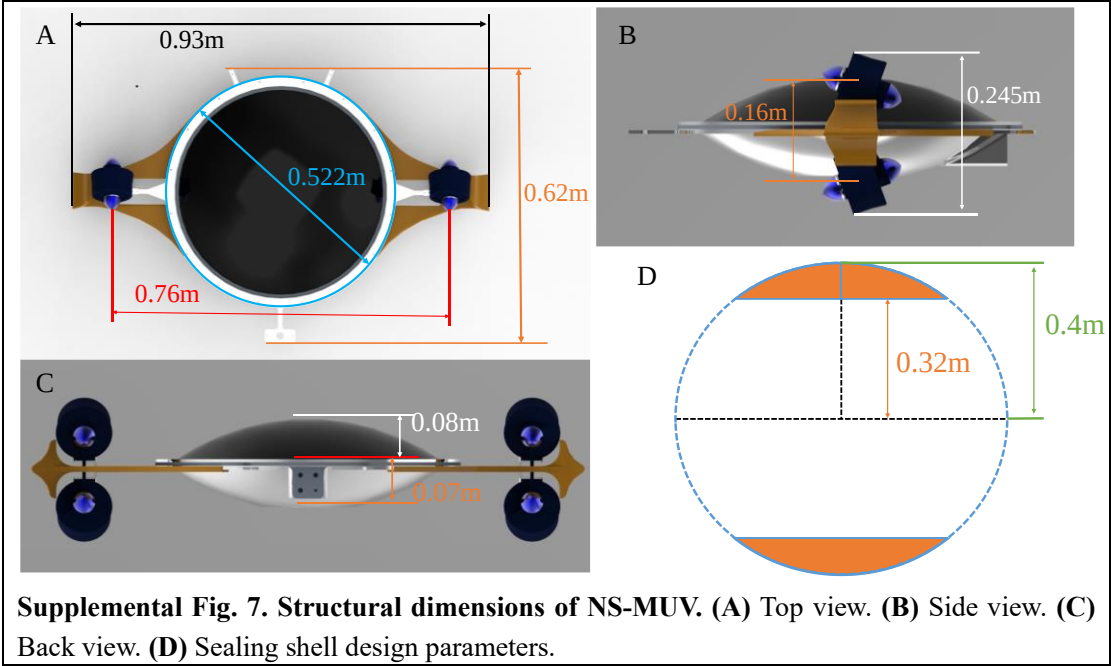
Revised manuscript (L198-200) Section: Robotic Systems Overview (Removal highlighted in red, addition highlighted in blue):

The NS-MUV mass is 16.3 kg. ~~with a disk surface diameter of 68 cm,~~ the robot's overall length is 0.62m, a maximum width of ~~93 cm~~ 0.93m at the fuselage, ~~and a height of 16 cm~~ and the highest point of the robot structure is 0.245m.

Supplementary Information (L232-240) Section 7:

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 Fig. S7D. 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 Information Fig. S7:



Reviewer#2 Concern #5: Apart from Figure 1, all other scenarios tested are static. However, I believe the near-seabed conditions are far more complex than static tests. Could the author provide simulation or actual test results to substantiate this? Figure 1 does not adequately demonstrate the characteristics of the robot in dynamic underwater environments.

Thank you for your feedback regarding the lack of real near-seabed environmental testing. In the **Revised manuscript (Section: Field Experiment, L594-649)**, we have included additional out-of-field experiments to demonstrate the robot's proficiency in moving through complex terrains.

These tests comprise the following:

Fig. 8A: Demonstrating the NS-MUV's capability to ascend steep terrain.

Fig. 8B: Showcasing the NS-MUV's ability to use roll motion to closely approach sloped terrain.

Fig. 8C: The NS-MUV traversal over undulating terrain through successive pitching motions.

Fig. 8D: The NS-MUV use of roll motions to navigate around obstacles without changing its forward direction.

Fig. 8E: Re-deploying the scanning experiments originally conducted in Fig. 4C within a real undersea environment.

We have incorporated these details into the **Revised manuscript (Section: Field experiment, L594-649; Fig. 8, 9)**.

The primary reasons for conducting multiple static environment tests during the submission process are as follows:

(1) The main objective of the test shown in Fig. 3, conducted in a static scenario, was to eliminate environmental factors that could influence the results. This approach allowed for a clearer comparison between the NS-MUV and traditional configurations concerning bottom disturbance.

(2) In the test illustrated in Fig. 6B, the goal was to evaluate the robot's resistance to disturbances caused by strong external disturbances. To ensure that the external environment did not affect the comparison, we performed the test in a static setting. This enabled us to analyze the performance of different algorithms under disturbed conditions and identify variations in control effectiveness through data analysis.

Revised manuscript (L607-646) Section: Field experiment (Removal highlighted in red, addition highlighted in blue):

We assessed the robot's capability to move through the various terrains in the real-world setting. The robot is equipped with one degree of freedom for forward motion and another for steering, complemented by two additional degrees of freedom for rotation (pitch and roll). Our field experiments demonstrated that increasing these rotational degrees of freedom significantly enhances the robot's ability to traverse rugged undersea terrains. The experiments were conducted with the driver utilizing camera feedback from the user interface to adjust the robot's pose (Fig. 8A, B, C and D).

The pitch degrees of freedom enable the robot to regulate its depth and facilitate rapid diving and ascent to a designated depth. During seafloor observation missions, encountering elevated terrain is inevitable. By leveraging these pitch degrees of freedom, the robot can ascend steep terrain (Fig. 8A). Additionally, the ability to pitch is crucial for navigating continuous undulating terrain. As illustrated in Fig. 8C, the robot rapidly approaches the terrain and avoids obstacles within the undulating landscape through continuous pitching motions.

The robot's roll degree of freedom enables it to navigate along inclined seabed walls by keeping its plane as parallel as possible to the terrain through roll motion (Fig. 8B). Additionally, this feature alters the collision relationship between the robot and the obstacle, enabling it to bypass the obstacle ahead without changing its forward direction. As illustrated in Fig. 8D, the robot avoids obstacles in its path through continuous rolling motions without altering its forward direction.

Simultaneously, we executed the scanning task in a real undersea environment by pre-programming the speed (constant forward force) and direction, with the driver providing the desired altitude through camera feedback. As depicted in Fig. 8E, the primary challenge faced by

the robot during task execution is the presence of undulating terrain. It is evident that the robot effectively utilizes its pitching degree of freedom to navigate and mitigate the impact of the undulating terrain on the task execution process. We analyzed the data from the scanning motion, identifying a maximum angular velocity of 0.91 rad/s when the robot encountered the undulating terrain shown in Fig. 8E. Furthermore, according to the pitching moment data in Fig. 9C, the peak pitching moment used by the robot during the scanning process was only 21.3% of the maximum pitching moment it can deliver. This indicates that the robot retains considerable pitch control force, which is sufficient for handling more complex terrains.

Revised manuscript Section: Field experiment, Fig. 8, 9 (Removal highlighted in ~~red~~, addition highlighted in blue):

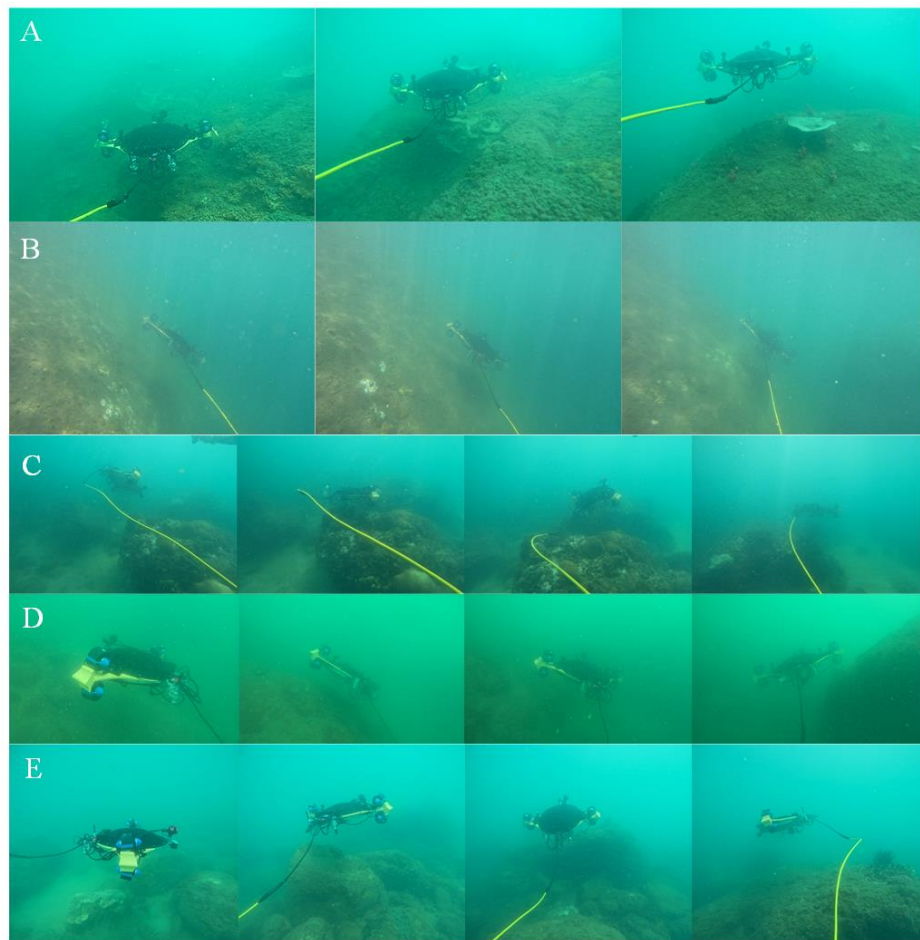
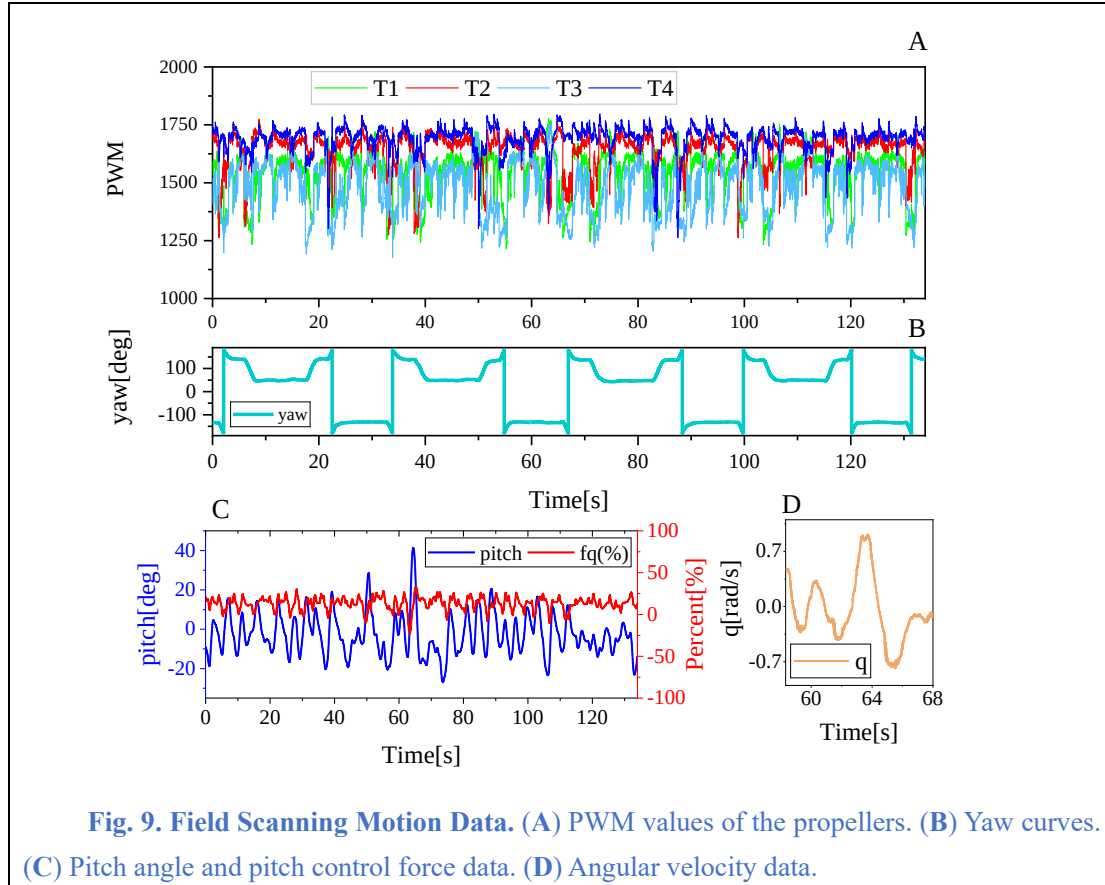


Fig. 8. Field terrain tracking. (A) Ascending along a sloping terrain. (B) Using roll motion to closely approach a sloped terrain. (C) Executing continuous pitch maneuvers to traverse undulating terrain. (D) Performing roll maneuvers to evade obstacles ahead. (E) Field Scanning Motion.



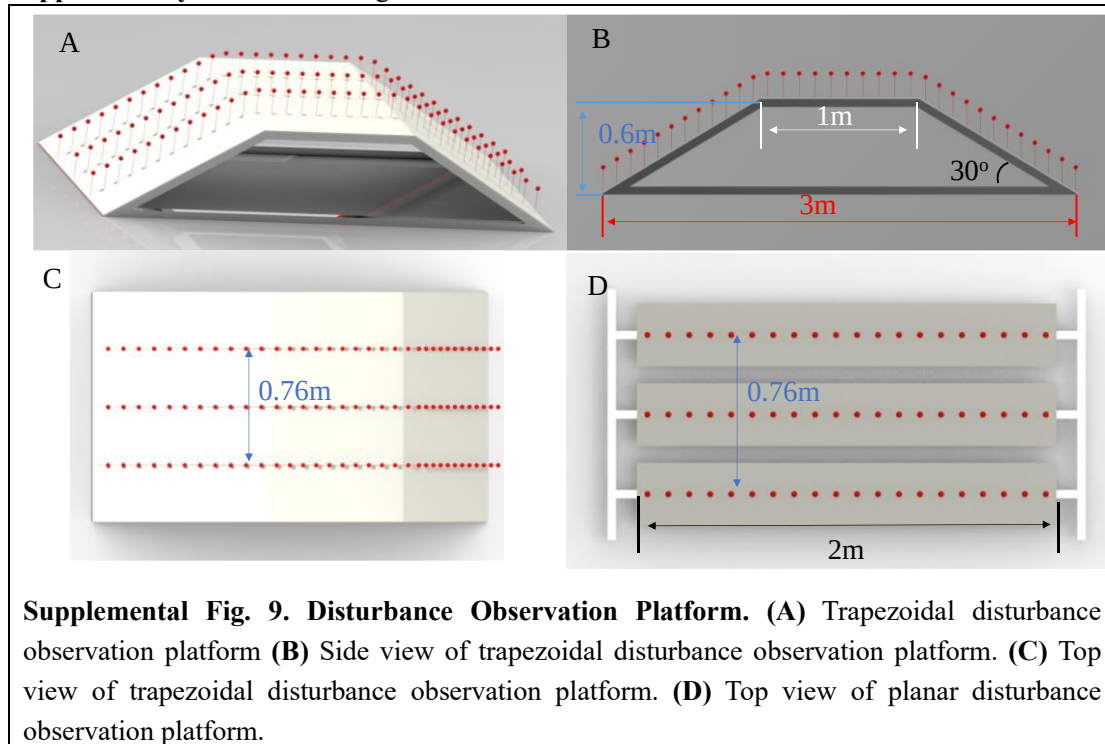
Reviewer#2 Concern #6: The experimental setup in Figure 3 is considered one of the core experiments. However, the author provides insufficient information regarding experimental conditions and explanations, such as the pose and direction of those robots.

Thank you for your feedback on the test details. We have provided a detailed description of the test platform structure and the position of the plastic spheres in the **Supplementary Information (Section 8, L242-252; Fig. S9)**. The perturbation observation platform has three rows of plastic spheres. The spacing of the outermost two rows matches the distance between the robot's propellers (0.76m). During the test, we let the plastic spheres remain below the thrusters to sense disturbance from propeller wake. Additionally, the effects of the motions from both robots on the plastic spheres are shown in our **Supplementary Video (Bottom Disturbance.mp4)**.

Supplementary Information (L242-252) Section 8:

We have designed two types of perturbation observation platforms: planar and trapezoidal. Detailed dimensional information for these platforms is provided in Fig. S9. 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 Information Fig. S9:



Reviewer#2 Concern #7: Modifying the structure designed by the author to resemble other types of underwater vehicles and conducting comparative experiments may better illustrate the advantages of the author's design.

Thank you for your feedback on modifying the structure of the robot. Modifying the existing robot structure prevents the comparison results from being influenced by variations in the robot's shape and mass. This allows the test results to be more directly influenced by the thruster layout and the method of depth control. We have modified the NS-MUV's structure to resemble the underwater vehicles shown in Fig. R3[48]. The robot depicted in Figure R3, designed for seabed exploration, resembles our body in shape and possesses the same number of thrusters. This similarity in application scenarios and robot appearance is the reason why we chose this structure for modification.

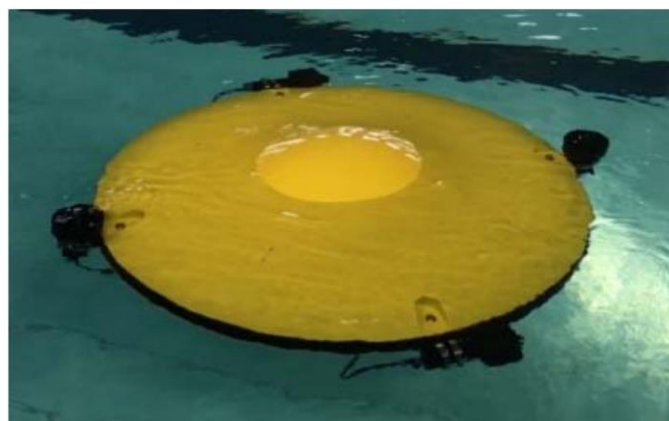


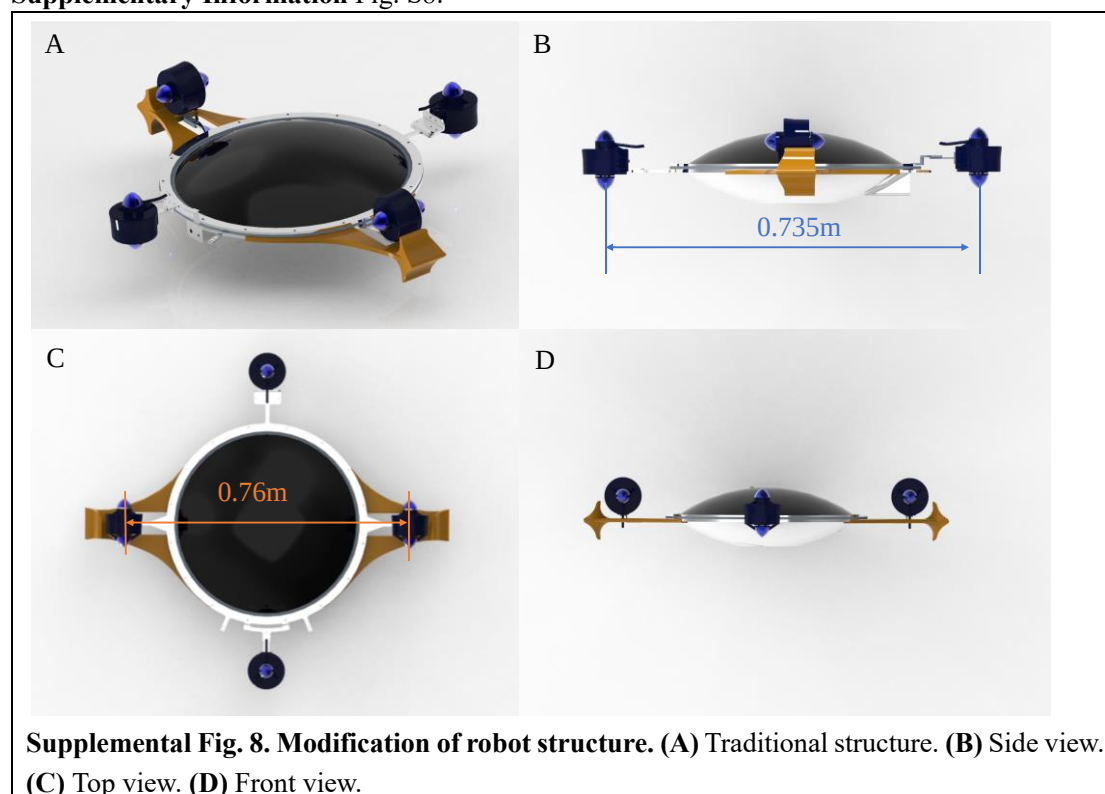
Fig. R3. AUH.

[48] C. Chenwei, Y. Ningmin, Prediction of Added Mass for an Autonomous Underwater Vehicle Moving Near Sea Bottom Using Panel Method, *2017 4th International Conference on Information Science and Control Engineering (ICISCE)*.

Revised manuscript (L320-328) Section: Vehicle Disturbance to the Bottom (Removal highlighted in red, addition highlighted in blue):

The analysis reveals that variations in bottom disturbance are primarily attributed to differing wake distributions during the robot's ascent. To effectively emphasize the advantages of the structure presented in this paper and to mitigate the impact of shape and mass discrepancies on the comparison results, the thruster layout of the existing NS-MUV structure was modified to resemble those of other underwater vehicles designed specifically for seabed exploration⁴⁸. For clarity, the structure depicted in Fig. 3A will be referred to as the NS-MUV, while the structure shown in Fig. 3B will be designated as the traditional structure. Detailed modifications are elaborated upon in the supplementary information.

Supplementary Information Fig. S8:



Reviewer#2 Concern #8: The high flexibility of this structure also appears to be one of the contributions of the manuscript. A slowly ascending underwater vehicle can also reduce its impact on the seabed. Therefore, the author should provide information on the impact on the surrounding environment during significant changes in posture/acceleration/etc.

This comment is highly valuable as it highlights the effectiveness of a slowly rising underwater vehicle in reducing its impact on the seabed. As previously mentioned, our underwater vehicle

underwent modifications, and we assessed the effects of two different configurations on bottom disturbance during the ascent process.

The depth and acceleration data indicate that, during the initial acceleration phase, both the traditional structure and the NS-MUV exhibited similar behavior in the early stages of depth change (Fig. 3G). However, the NS-MUV experienced a more rapid acceleration, allowing the robot to ascend more quickly compared to the traditional structure (Fig. 3F, G). The final effects on the plastic spheres revealed that the ascent of the traditional structure significantly increased the propellers' impact on the bottom spheres (Fig. 3B).

Furthermore, we compared the impact of the two configurations on the seabed during ascent in a real sandy environment. The traditional structure caused re-suspension of sand and gravel (Fig. 3K), whereas the NS-MUV showed no significant disturbance to the sand during its ascent (Fig. 3J).

Revised manuscript (L329-341) Section: Vehicle Disturbance to the Bottom (Removal highlighted in red, addition highlighted in blue):

We conducted experiments with robots equipped with two distinct thruster structures, allowing them to ascend on the planar platform. Fig 3A and 3B illustrate that the NS-MUV exerts significantly less disturbance on the bottom plastic balls during ascent compared to the traditional structure. Fig 3F and 3G reveal that there is no substantial difference in the initial rate of depth change between the two robot types. However, the NS-MUV demonstrates greater speed and acceleration in the subsequent ascent phase, while causing less disturbance to the bottom than the traditional structure. To assess the environmental impact of the two designs, we performed experiments in a natural sandy environment. In Fig. 3J, resuspension of seabed sediments is not observed due to the ascent of NS-MUV. In contrast, the traditional structure stirs up considerable sand, resulting in turbid water (Fig. 3K). Field experiments have confirmed that the NS-MUV is capable of minimizing seabed sediment disturbance when the robot is moved away from the seabed.

Revised manuscript Fig .3 (Removal highlighted in red, addition highlighted in blue):

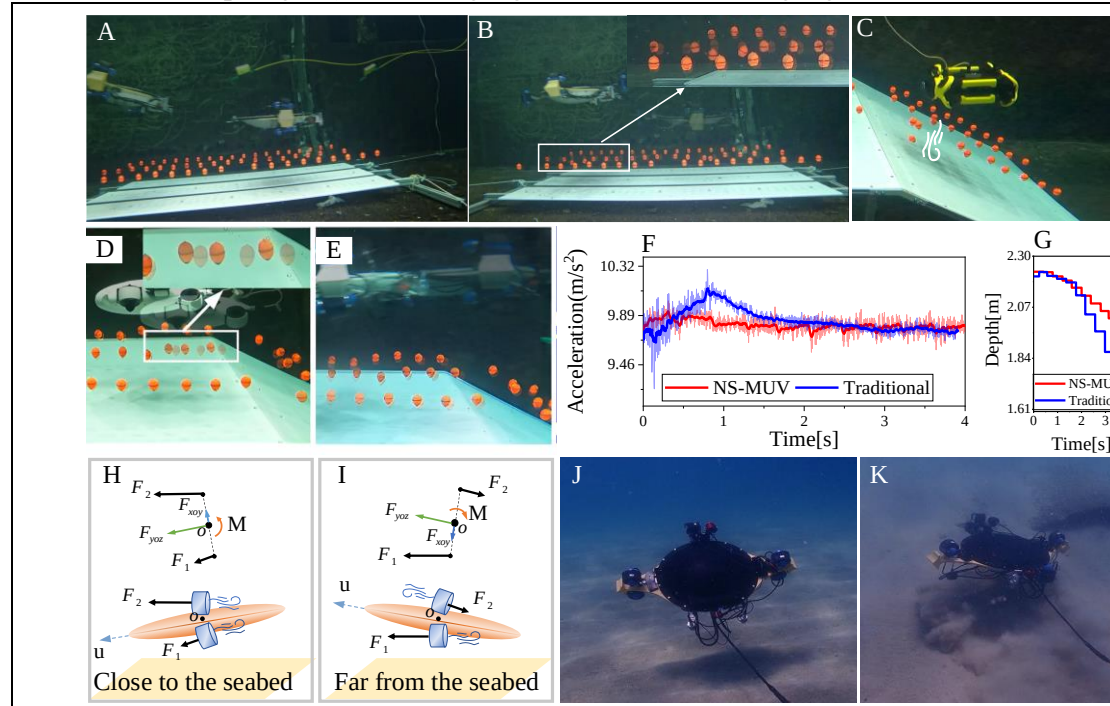


Fig. 3. Bottom Disturbance. ~~(A) NS-MUV moves through a trapezoidal terrain. (B) Bottom disturbance by 3.9kg vehicle. (C) Bottom disturbance by NS-MUV. (D) 4.5 kg vehicle using propellers to directly disturb the small balls at the bottom. (F) Schematic of the wake as NS-MUV moves closer to the seabed. (G) Schematic of the wake as NS-MUV moves away from the seabed. (H) NS-MUV moving away from the seabed with low disturbance in a real environment.~~ (A) NS-MUV moving away from the planar platform. (B) Traditional structure moving away from the planar platform. (C) vehicle (4.5kg, yellow) using propellers to directly disturb the small balls at the bottom. (D) Bottom disturbance by vehicle (3.9kg, white). (E) Bottom disturbance by NS-MUV. (F) Acceleration curves during the ascent of robots with different structures. (G) Depth curves during the ascent of robots with different structures. (H) Schematic of the wake as NS-MUV moves closer to the seabed. (I) Schematic of the wake as NS-MUV moves away from the seabed. (J) NS-MUV moving away from the seabed in a real environment. (K) Traditional structure moving away from the seabed in a real environment.

Reviewer#2 Concern #9: Some language within the article appears redundant. The caption for Figure 3(E) is missing.

Thank you for your detailed review of the figures. we have revised the title of Figure 3.

Revised manuscript (L304-318) Section: Vehicle Disturbance to the Bottom, Fig. 3(Removal highlighted in ~~red~~, addition highlighted in blue):

Fig. 3. Bottom Disturbance. ~~(A) NS-MUV moves through a trapezoidal terrain. (B) Bottom disturbance by 3.9kg vehicle. (C) Bottom disturbance by NS-MUV. (D) 4.5 kg vehicle using propellers to directly disturb the small balls at the bottom. (F) Schematic of the wake as NS-MUV moves closer to the seabed. (G) Schematic of the wake as NS-MUV moves away from the seabed. (H) NS-MUV moving away from the seabed with low disturbance in a real environment.~~ (A) NS-MUV moving away from the planar platform. (B) Traditional structure moving away from the planar platform. (C) Vehicle (4.5 kg, yellow) using propellers to directly disturb the small balls at the bottom. (D) Bottom disturbance by vehicle (3.9kg, white). (E) Bottom disturbance by NS-MUV. (F) Acceleration curves during the ascent of robots with different structures. (G) Depth curves during the ascent of robots with different structures. (H) Schematic of the wake as NS-MUV moves closer to the seabed. (I) Schematic of the wake as NS-MUV moves away from the seabed. (J) NS-MUV moving away from the seabed in a real environment. (K) Traditional structure moving away from the seabed in a real environment.

Reviewer#2 Concern #10: On page 13, line 419, "NS-NS-MUV" appears.

Thank you for your careful review of the manuscript.

Revised manuscript (L491-492) Section: Resistant to Strong Disturbances (Removal highlighted in ~~red~~, addition highlighted in blue):

Consequently, we replaced the control of the bottom distance with that of the ~~NS~~-NS-MUV depth

during the experiment.

Reviewer#2 Concern #11: In the background section on page 3, only references [39] and [40] are listed (closely related), and [40] pertains to an earlier research report.

Thank you for your careful review of the manuscript. We expanded our research to include more related types of robots.

In searching the literature related to buoyancy regulation, it was found that its main use is in underwater gliders [44], this is because this robot does not have a high requirement for the speed of buoyancy adjustment, as it takes several hours before it needs a buoyancy adjustment.

we also find a mechanical fish equipped with a buoyancy adjustment device [45]. However, using a vacuum to create a cavity within the body becomes increasingly difficult as the robot dives deeper. This is because there is always a pressure difference between the cavity and the external water. The deeper the robot dives, the greater the force required to adjust the buoyancy, which leads to greater energy loss.

We reviewed the literature on positively buoyant robots [47], which is very scarce. To our knowledge, this approach has not been used to minimize disturbance to bottom sediments during near-seafloor movements. Furthermore, there is a natural disadvantage: when these robots are fully submerged, they require additional energy to maintain depth. Moreover, increasing the rate of upward dive necessitates greater positive buoyancy, which in turn, demands even more energy to keep the robot at a constant depth.

[44] Wang, Shuxin, et al. "Dynamic modeling and motion analysis for a dual-buoyancy-driven full ocean depth glider." *Ocean Engineering* 187 (2019): 106163.

[45] Du, Sheng, et al. "Design and control of a two-motor-actuated tuna-inspired robot system." *IEEE Transactions on Systems, Man, and Cybernetics: Systems* 51.8 (2019): 4670-4680.

[47] W. Zhiguang, W. Zhaoyu, Y. Caoyang, C. junjun, Dynamic modeling and optimal control of a positive buoyancy diving autonomous vehicle. *Brodogradnja: An International Journal of Naval Architecture and Ocean Engineering for Research and Development*. 74.1, 19-40. (2023). doi: 10.21278/brod74102.

Reviewer#2 Concern #12: The meanings of the parameters in Equation 7 also need to be clarified.

Thank you for your careful review of the equation. We provided a detailed explanation of each parameter in Equation 7.

Revised manuscript (L890-891) Section: Planning algorithm for altitude maintenance (Removal highlighted in red, addition highlighted in blue):

where $d_{error}(t)$ represents the accumulated altitude error at the given moment ~~t~~ , k_i represents the gain coefficient, k_p represents the integration coefficient.

Reviewer#3

Reviewer#3 Overall comment: This paper proposes an underwater vehicle, which is able to perform complex maneuvers while being close to the seabed. The proposed design and control strategy are promising; however, the manuscript presets several flaws which critically hinder the overall paper quality.

Thank you for your recognition of our work. We have thoroughly read and considered the feedback provided by the reviewer. We understand that the reviewer has identified some flaws or concerns in our manuscript, and we have addressed these concerns and made the necessary changes to enhance the overall quality of our work. We supplemented the field experiments in the **Revised manuscript (Section: Field experiment, L594-649)** and the algorithmic comparison experiments in the **Supplementary Information (Section 6, L166-230)**.

Reviewer#3 Concern #1: The Authors goal seems to be to design a vehicle for near-seabed observation, specifically, (L14-15) “[...] to gather detailed information on species, habitats, and ecological dynamics [...]”. However, it is not clear the direct relationship between the measurements the robot is able to gather (i.e., seabed videos and images) with the actual habitat conservation status. How biologists typically perform seabed status assessments? Which Key Performance Indicators (KPIs) do they use? How does the proposed robot meet the quality requirements for these observations? From the Abstract and Introduction, I was expecting a deeper discussion and analysis on the application of this robot, while, at the moment, the main contribution of this paper seems to be a nice underwater robot, with no straightforward relation with its ecological function.

Thank you for your feedback on the robot's functionality on ecological. As outlined in the Abstract and Introduction, this study demonstrates that positioning the robot closer to the seafloor could reduce light refraction and scattering distances, contributing to producing higher-quality images.

We reviewed multiple studies on seafloor state assessment, many researches revealed that image is commonly employed in observation tasks to gather more precise details. For example, the detection of minerals on the seafloor [57], environmental protection [58], high-precision measurements of coral reef structure [3], and the detection of plant health [1] plays an increasingly important role.

The most important metrics in these observation tasks are image clarity and color accuracy, which directly affect the accuracy of the final results. For example, in the coral reef pigmentation response, the attenuation of red light by the water column makes it challenging to detect PRS lesions, which typically appear bright pink [1]. Furthermore, water turbidity hampers the creation of high-precision topographic images through imagery [3]. The resolution decreases as smaller targets occupy fewer pixel dots due to the large distance from the target [59]. Additionally, the autonomous classification of biota based on underwater imagery results in diminished accuracy as the altitude of the imaging robot increases [60].

Our proposed robotic structure and design concept effectively minimize sediment disturbance during ascent, allowing for closer proximity to the seabed. This design reduces the influence of water on image quality during capture. The research presented in this paper offers a new design approach for robots used in seafloor observation, enabling the development of platforms that can observe the seafloor more closely. This advancement offers marine researchers additional options

for studying seafloor ecology and facilitates other undersea missions reliant on underwater optical information.

We have added the aforementioned applications and challenges related to seabed exploration to the “Discussion” section and have listed potential robotic applications

- [1] J. Burns, W. Grady, A comparison of the diagnostic accuracy of in-situ and digital image-based assessments of coral health and disease. *Frontiers in Marine Science*. **7**, 304. (2020). doi: 10.3389/fmars.2020.00304.
- [3] D.M. Price, K. Robert, A. Callaway, Using 3D photogrammetry from ROV video to quantify cold-water coral reef structural complexity and investigate its influence on biodiversity and community assemblage. *Coral Reefs*. **38**, 1007-1021. (2019). doi: 10.1007/s00338-019-01827-3.
- [57] B. Mbani, T. Schoening, I.Z. Gazis, Implementation of an automated workflow for image-based seafloor classification with examples from manganese-nodule covered seabed areas in the Central Pacific Ocean. *Scientific Reports*. **12.1**. 15338. (2022). doi: 10.1038/s41598-022-19070-2.
- [58] D. V. Politikos, E. Fakiris, A. Davvetas, I.A. Klampanos, G. Papatheodorou, Automatic detection of seafloor marine litter using towed camera images and deep learning. *Marine Pollution Bulletin*. **164**. 111974. (2021). doi: 10.1016/j.marpolbul.2021.111974.
- [59] C. Smart, C. Roman, S. Carey, Detection of diffuse seafloor venting using a structured light laser sensor: 1. Development of a classification based detection method[J]. *Earth and Space Science*, **4(6)**, (2017). doi:10.1002/2017EA000262.
- [60] J. Walker, A. P. Bennett, B. Thornton, Towards observation condition agnostic fauna detection and segmentation in seafloor imagery for biomass estimation. *Oceans 2021: San diego–porto*. pp. 1-8, (2021). doi: 10.23919/OCEANS44145.2021.9705692.

Revised manuscript (L682-708) Section: Discussion (Removal highlighted in ~~red~~, addition highlighted in blue):

With the ongoing advancement of ocean observation, the significance of image information in seabed exploration has grown considerably. The richness of image data offers significant value for a variety of applications, including the detection of hydrothermal vents on the seabed⁵⁶, the detection of minerals on the seabed⁵⁷, environmental protection⁵⁸, high-precision measurements of coral reef structure³, and the detection of plant health¹.

The use of image information has significantly enhanced our understanding of the undersea world, and with the continuous advancement of technology, it is expected to play an even more central role in underwater observation in the future. However, we cannot overlook the impact of water refraction and scattering on image contrast and color accuracy, particularly for seabed state analysis based on image data. For example, in the coral reef pigmentation response, the attenuation of red light by the water column makes it challenging to detect PRS lesions, which typically appear bright pink¹. Furthermore, water turbidity hampers the creation of high-precision topographic images through imagery³. The resolution decreases as smaller targets occupy fewer pixel dots due to large distance from the target⁵⁹. Additionally, the autonomous classification of biota based on underwater imagery results in diminished accuracy as the altitude of the imaging robot increases⁶⁰. The primary factor influencing the extent of light refraction and scattering in water is distance. As the distance increases, the effects become more pronounced⁶. Therefore, a practical approach to mitigating these challenges is to minimize the robot's distance from the seabed.

Among existing ocean observation robots, wheeled and legged types encounter significant challenges in rough terrains, where obstacles and sloped surfaces can hinder their functionality. In contrast, floating robots can navigate above challenging seabed terrain, but their operations near the seabed, especially during ascent could disturb sediment. This disturbance often results in sediment resuspension, which obscures visibility.

Revised manuscript (L764-780) Section: Discussion (Removal highlighted in red, addition highlighted in blue):

This paper presents a robot specifically designed for near-seabed observation and introduces a levitating robot that minimizes disturbance to seafloor sediments while maintaining the robot's agility. The NS-MUV and its design concepts offer biologists enhanced seafloor exploration capabilities, including low-disturbance designs that facilitate the development of observation robots positioned closer to the seafloor to improve image quality for various image-based seafloor observation missions, aiding biologists in distinguishing textures and colors. Simultaneously, a study shows that incorporating seabed texture information can improve terrain-matching navigation⁶¹, with image-based texture information yielding more detailed features than traditional sonar. The NS-MUV capabilities enhance image clarity, aiding in seabed positioning and advancing the autonomy of seabed observations. Moreover, optical information delivers significantly richer details than sonar, and a study has shown that LiDAR can enhance the classification of underwater ores⁶². NS-MUV's ability to observe the seafloor at close range can help minimize light refraction and scattering underwater, which could facilitate the practical application of such research. This advancement potentially increases the efficiency and sustainability of marine resource exploration and management.

Reviewer#3 Concern #2: It is not clear if the robot is autonomous or not. This point is not discussed in the paper, despite it is crucial.

Currently, the NS-MUV does not have the capability for autonomous environmental recognition; therefore, all our underwater experiments are conducted using either pre-programmed settings or remote control. We apologize for any confusion regarding this point, and we have added details in the presentation of the test results to clarify whether the implementation was conducted remotely or through pre-programmed means.

The primary contribution of this paper is the design of a robot intended for close to the seafloor, significantly reducing disturbances to the bottom environment during ascent. This design enables the robot to navigate closely along the seabed, facilitating the capture of clearer underwater images. The seafloor environment is rich in textural information that surpasses the capabilities of sonar technologies [61], offering more features for localization. We contend that the capabilities of this robot could support the future advancement of autonomous operations on the seabed.

[61] C. Hsinhung, W. Chauchang, S. Dengchau, L. Yuanhe, A Preliminary Study on Positioning of an Underwater Vehicle Based on Feature Matching of Seafloor Images, *2018 OCEANS - MTS/IEEE Kobe Techno-Oceans (OTO)*. pp. 1-6. (2018). doi: 10.1109/OCEANSKOB.2018.8559367.

Reviewer#3 Concern #3: The terrain tracking experiments does not seem precise from Fig. 4C. What is the actual reference?

In the initial manuscript, the directional control shown in Fig. 4C was achieved through remote control. To prevent confusion for the reader, we have included details about the means of experimental realization in the revised manuscript.

Revised manuscript (L371-372) Section: Terrain tracking (Removal highlighted in ~~red~~, addition highlighted in blue):

We conducted an initial test of the capability of the NS-MUV to observe the bottom closely using manual direction control.

Revised manuscript (L612-613) Section: Field experiment (Removal highlighted in ~~red~~, addition highlighted in blue):

The experiments were conducted with the driver utilizing camera feedback from the user interface to adjust the robot's pose (Fig.8 A, B, C and D).

Revised manuscript (L635-637) Section: Field experiment (Removal highlighted in ~~red~~, addition highlighted in blue):

Simultaneously, we executed the scanning task in a real undersea environment by pre-programming the speed (constant forward force) and direction, with the driver providing the desired altitude through camera feedback.

Reviewer#3 Concern #4: How does the robot localize itself?

The NS-MUV does not have the capability to self-localize on the seabed; instead, it provides only a rough estimate of displacement based on accelerometer readings, which tend to drift over time. For improved localization accuracy, external methods such as short or ultra-short baseline localization techniques are needed; however, these techniques are not currently integrated into the existing robotic system.

The primary objective of this study is to present a robot designed to minimize disturbances to seafloor sediments resulting from its proximity to the seafloor. As such, this paper primarily focuses on the robot's design and the resolution of depth control about its configuration. By addressing these issues, we improved the robot's capacity to obtain clearer images by moving closer to the seafloor. This enhancement provides critical technical support for future marine robots to implement localization based on the textural information of seafloor images [61].

[61] C. Hsinhung, W. Chauchang, S. Dengchau, L. Yuanhe, A Preliminary Study on Positioning of an Underwater Vehicle Based on Feature Matching of Seafloor Images, *2018 OCEANS - MTS/IEEE Kobe Techno-Oceans (OTO)*. pp. 1-6. (2018). doi: 10.1109/OCEANSKOB.2018.8559367.

Reviewer#3 Concern #5: The video is nice and informative, but I was expecting to see all the experiments reported in the manuscript, while they are different. This limits the paper clarity. For instance, it would be nice to see the video of the experiments in Fig. 3.

We are pleased to hear that the manuscript's experimental videos have been well received. We have added a video of the experiment included in Fig. 3 to the **Supplementary Video (Bottom Disturbance.mp4)**.

Reviewer#3 Concern #6: In Sec. "Resistant to Strong Disturbances", the proposed algorithm is compared to a PID controller. This comparison is not fair. PID is a very simple controller, whose performance are heavily dependent on the selected gains. The slow response (L391) of the PID could be affected by a poor gain selection. How did you tune the gains?

Thank you for your feedback on the details of the comparison test. The PID algorithm is a very simple controller; however, it is crucial to note that the algorithm presented in this paper also employs a simple PD controller. The only difference with PID is in the strategy for resisting disturbance. During the comparison, we ensured that both the gain and differentiation terms of the controller proposed in this study were identical to those of the PID controller. Additionally, the analysis specifically evaluated the impact of different integral gains within the PID controller on control performance. Detailed results of these comparisons are in our **Supplementary Information** (Section 6, L166-230; Fig. S5, S6). The experimental results confirm that the PID controller exhibits a slower response speed to external disturbances, corroborating the inference in the section "**Anti-disturbance Algorithms**".

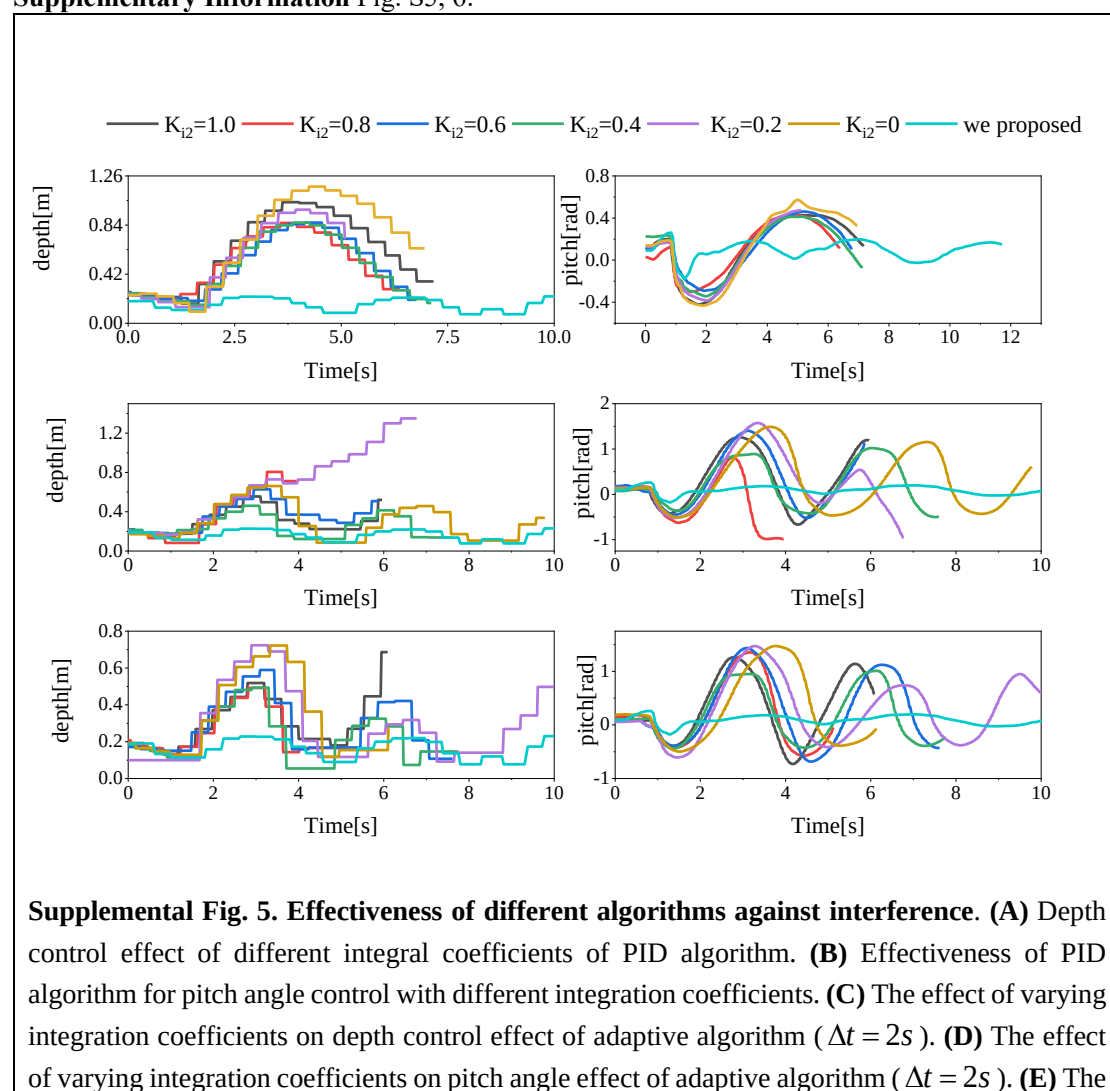
To answer your questions about control responsiveness, we implemented an adaptive algorithm that incorporates both an adaptive term and tanh-sigmoid-surface control laws to augment the controller's anti-disturbance capabilities. In practical experiments, this algorithm demonstrated a significantly quicker response speed compared to the PID algorithm, effectively minimizing depth control errors. Specifically, with the adaptive controller, the time required for the pitch angle to stop decreasing after the disturbance was applied decreased from 1.23 s with the PID controller to 0.55 s (Fig. S6). However, the algorithm exhibits significant overshoot during the weight block stabilization phase while attempting to control the depth, thereby compromising the overall stability of the robot's attitude.

We extrapolate that the pitch angle oscillations induced by the adaptive algorithm are due to the NS-MUV's indirect depth control approach, which makes it more difficult to resist disturbances. 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. 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.

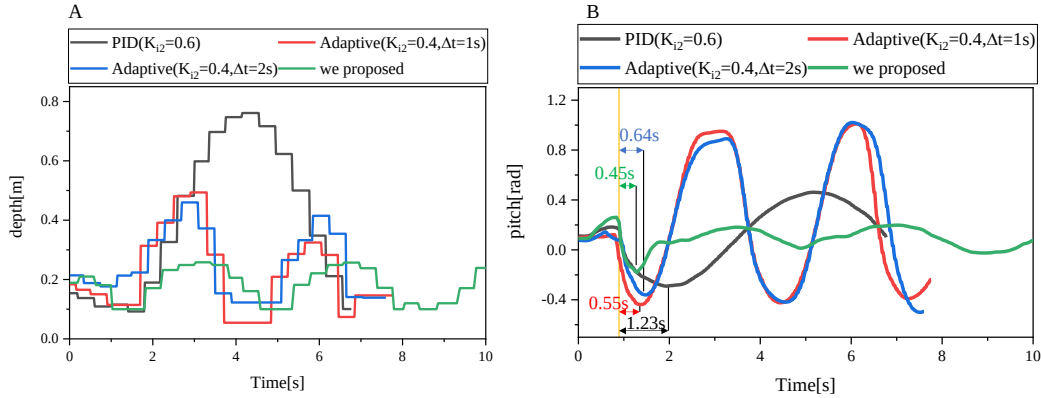
Experimental evidence suggests that simply enhancing the response speed of the control system does not adequately address the depth control issues in this study. The controller implemented herein demonstrates effective suppression of disturbances, which is attributed not to the rapid response of the base controller but to swift observation and compensation of external disturbances. Consequently, although this study employs a basic PD controller on the base controller, the robot effectively withstands external strong transient disturbances.

It is undeniable that the PID controllers and adaptive controls used for comparison in this study, if further fine-tuned, can perform better in the specific case of a 3 kg impact. However, it is difficult to guarantee excellent performances to other types of disturbance. The algorithms presented in this study have been validated through practical experiments, which demonstrate their adaptability to the robot depth control methods discussed herein. The algorithms effectively operate under various conditions, including different block masses, application methods (static or transient impacts), varying falling speeds due to block densities and shape (lead vs. iron), and single or multiple impact scenarios. The algorithm's ability to handle multiple disturbances validates their real-time performance in observing and compensating for these disturbances.

Supplementary Information Fig. S5, 6:



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 ($\Delta t = 1s$).



Supplemental Fig. 6. Anti-jamming ability of the three algorithms. (A)The depth control effects. **(B)**The pitch angle control effects.

Reviewer#3 Concern #7: The Results section contains paragraphs which are more suited for a Discussion section (e.g., L486-495). Conversely, the Discussion section is poor, and it contains paragraphs which are more an introduction than a discussion (e.g., L513-541).

Thank you for your valuable feedback concerning the Results and Discussion. We have revised the conclusion and discussion sections of the paper to more clearly delineate the contributions of this study. We have revised L486-495 to incorporate the relevant information into the discussion section and rewritten L513-541 for improved clarity and coherence.

Revised manuscript (L583-592) Section: Resistant to Strong Disturbances (Removal highlighted in red, addition highlighted in blue):

The experimental findings affirm the substantial robustness of the NS-MUV in controlling the distance between the body and the bottom. The proposed disturbance resistance algorithm markedly enhances the control robustness, preventing the external disturbance torque from affecting the forward direction of the NS-MUV and causing it to hit the bottom. ~~The passive stability of the NS-MUV, which can withstand impacts perpendicular to the bottom to some extent, compensates for inherent delays in the distance control method outlined in this study, resulting in overall robustness in distance control. We successfully addressed the challenge posed by environmental disturbances in controlling the distance between the NS-MUV and the seabed, which enhances its practical applicability in real-world environments.~~

Revised manuscript (L653-725) Section: Discussion (Removal highlighted in red, addition highlighted in blue):

~~Underwater vehicles, which are widely employed in ocean exploration, exhibit exceptional performance owing to their proficiency in traversing the water column for marine life~~

observations, sonar-based seabed topography, and prolonged investigations into deep-ocean chlorophyll and microbes. Extensive research has focused on underwater vehicles for large-scale observations; however, little attention has been directed towards near-seabed observations. Proximity to the seabed facilitates high-definition visual data acquisition, capturing the seafloor color and texture. This capability enables the identification of diverse biota. We contend that endeavors in this realm complement traditional large-scale observations.

Seabed observations are frequently conducted using benthic robots, specifically wheeled and legged robots. While these robots excel in prolonged inspections, their adaptability for a broad spectrum of continuous tasks is limited, specifically in navigating substantial obstacles and slopes. This becomes evident in scenarios requiring close observation of the seabed, where the need to traverse steep terrains necessitates moving away from the seabed. In the case of a legged robot equipped with jumping capabilities, the robot leverages water buoyancy to generate a diminished underwater footprint while propelling itself away from the seabed. This action mitigates the disturbance caused by seabed sediments during the departure of the robot from the seabed. However, this approach entails seabed contact during jumps, resulting in a footprint proportional to both the jump height and the underwater robot weight. While reducing the underwater weight is an option to minimize the footprint impact, it introduces challenges owing to the lack of active control during the jump process and the existing potential influences from the external flow field on the jump trajectory. When floating robots navigate in the upper layers of the seabed, the constraints imposed by the rugged terrain of the seabed can be avoided; however, when floating robots move away from the seabed, which usually relies on the reaction force of the water, this practice generates a wake directed towards the seabed, increasing the potential for re-suspension of seafloor sediments and, consequently, impacting the observation field of view.

With the ongoing advancement of ocean observation, the significance of image information in seabed exploration has grown considerably. The richness of image data offers significant value for a variety of applications, including the detection of hydrothermal vents on the seabed⁵⁶, the detection of minerals on the seabed⁵⁷, environmental protection⁵⁸, high-precision measurements of coral reef structure³, and the detection of plant health¹.

The use of image information has significantly enhanced our understanding of the undersea world, and with the continuous advancement of technology, it is expected to play an even more central role in underwater observation in the future. However, we cannot overlook the impact of water refraction and scattering on image contrast and color accuracy, particularly for seabed state analysis based on image data. For example, in the coral reef pigmentation response, the attenuation of red light by the water column makes it challenging to detect PRS lesions, which typically appear bright pink¹. Furthermore, water turbidity hampers the creation of high-precision topographic images through imagery³. The resolution decreases as smaller targets occupy fewer pixel dots due to large distance from the target⁵⁹. Additionally, the autonomous classification of biota based on underwater imagery results in diminished accuracy as the altitude of the imaging robot increases⁶⁰. The primary factor influencing the extent of light refraction and scattering in water is distance. As the distance increases, the effects become more pronounced⁶. Therefore, a practical approach to mitigating these challenges is to minimize the robot's distance from the seabed.

Among existing ocean observation robots, wheeled and legged types encounter significant challenges in rough terrains, where obstacles and sloped surfaces can hinder their functionality.

In contrast, floating robots can navigate above challenging seabed terrain, but their operations near the seabed, especially during ascent could disturb sediment. This disturbance often results in sediment resuspension, which obscures visibility.

This study introduced a maneuverable underwater robot configuration tailored for near-seabed observations, effectively addressing the aforementioned limitations. Our robot was meticulously designed to navigate a specified terrain swimming style, enabling the NS-MUV to closely examine the seabed and significantly minimize the impact of the propeller wake on sedimentation. As illustrated in Fig. 3, our robot could avoid propeller wake impacts on the seabed compared to a typical underwater machine. Leveraging the passive stability of the NS-MUV enhances its ability to withstand environmental disturbances without active power input, ensuring disturbance resistance without generating a wake perpendicular to the seafloor. Additionally, the passive stability compensates for inherent delays in the altitude control method outlined in this study, resulting in overall robustness in distance control. Active control of the distance between the NS-MUV and seabed is achieved by adjusting the angle between the fuselage and seabed planes. This control strategy not only allows for distance control but also avoids the impact of the wake on the seabed, ensuring optimal observation conditions. We successfully addressed the challenge posed by environmental disturbances in controlling the distance between the NS-MUV and the seabed, which enhances its practical applicability in real-world environments.

Reviewer#3 Concern #8: The Methods section is not particularly solid. Vectors are sometimes defined as columns and sometimes as rows, is it intentional or a typo?

Thank you for your careful review of the equation. We have revised the article according to your doubts and changed the vector representations in the article to columns to ensure the consistency of the formulas in the article.

- 1) $\boldsymbol{\eta} = [\phi, \theta, \psi]$ amended to $\boldsymbol{\eta} = [\phi, \theta, \psi]^T$
- 2) $\boldsymbol{\varsigma}_1 = [p, q, r]$ amended to $\boldsymbol{\varsigma}_1 = [p, q, r]^T$
- 3) $\boldsymbol{\varsigma}_2 = [a_z, q, a_y]$ amended to $\boldsymbol{\varsigma}_2 = [a_z, q, a_y]^T$
- 4) $\boldsymbol{\varsigma}_3 = [p, a_z, r]$ amended to $\boldsymbol{\varsigma}_3 = [p, a_z, r]^T$
- 5) $\dot{\boldsymbol{\omega}}_1 = [\dot{p}, \dot{q}, \dot{r}]$ amended to $\dot{\boldsymbol{\omega}}_1 = [\dot{p}, \dot{q}, \dot{r}]^T$
- 6) $\dot{\boldsymbol{\omega}}_2 = [a_z / \lambda, \dot{q}, a_y / \lambda]$ amended to $\dot{\boldsymbol{\omega}}_2 = [a_z / \lambda, \dot{q}, a_y / \lambda]^T$
- 7) $\dot{\boldsymbol{\omega}}_3 = [\dot{p}, a_z / \lambda, \dot{r}]$ amended to $\dot{\boldsymbol{\omega}}_3 = [\dot{p}, a_z / \lambda, \dot{r}]^T$
- 8) $\dot{\boldsymbol{\omega}}^T = \mathbf{p}_1 \dot{\boldsymbol{\omega}}_1^T + \mathbf{p}_2 \dot{\boldsymbol{\omega}}_2^T + \mathbf{p}_3 \dot{\boldsymbol{\omega}}_3^T$ amended to $\dot{\boldsymbol{\omega}} = \mathbf{p}_1 \dot{\boldsymbol{\omega}}_1 + \mathbf{p}_2 \dot{\boldsymbol{\omega}}_2 + \mathbf{p}_3 \dot{\boldsymbol{\omega}}_3$

Reviewer#3 Concern #9: The whole “offline learning part” is vague, and it misses important explanation.

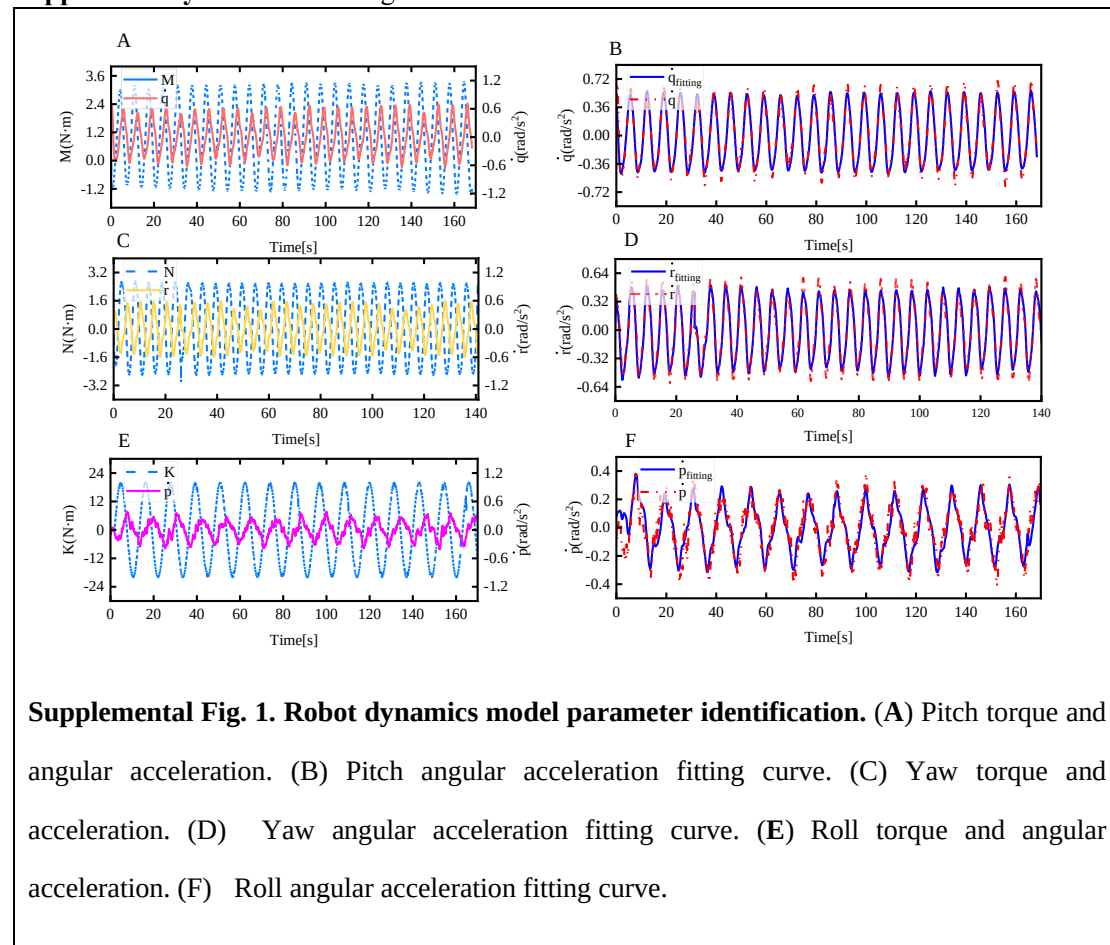
Thank you for your careful review of the manuscript. Detailed explanations of the logic and technical approaches employed in the offline learning section are provided in the **Revised**

manuscript.

Revised manuscript (L848-855) Section: Static Water Environment Data Collection (Removal highlighted in red, addition highlighted in blue):

The specific methods are as follows, we collect data on the three rotational degrees of freedom concerning PWM input values, attitude angles, angular velocities, and angular accelerations in a static water environment. A classical underwater dynamics model is then used to determine the relationship between each dynamic parameter and the robot's state⁶³ (identification results are provided in the supplementary information). Subsequently, the robot's dynamic parameters obtained through least-squares fitting serve as the foundation for observing external disturbances.

Supplementary Information Fig. S1:



Supplemental 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.

Reviewer#3 Concern #10: Variables are used multiple times with different meanings. For instance, H in (5) is a model, in (6) it becomes a transformation matrix. k is a gain, then it becomes a time instant.

Thank you for your careful review of the equation. The variable ' H ' in equation (6) has been revised; it differs in meaning from that in equation (5). We have corrected equation (7).

Revised manuscript (L866-869) Section: Planning algorithm for altitude maintenance (Removal highlighted in red, addition highlighted in blue):

The transformation relationship between the coordinate systems is given by $\mathbf{V}_c = \mathbf{H}\mathbf{n}$
 $\mathbf{V}_c = \mathbf{J}\mathbf{n}$, where $\mathbf{H}$ $\mathbf{J}$ represents a transformation matrix.

$$\mathbf{H} = \begin{bmatrix} c\psi c\theta & -s\psi c\phi + c\psi s\theta s\phi & s\psi s\phi + c\psi c\phi s\theta \\ s\psi c\theta & c\psi c\phi + s\phi s\theta s\psi & c\psi s\phi + s\theta s\psi c\phi \\ -s\theta & c\theta s\phi & c\theta c\phi \end{bmatrix} \quad (6)$$

$$\mathbf{J} = \begin{bmatrix} c\psi c\theta & -s\psi c\phi + c\psi s\theta s\phi & s\psi s\phi + c\psi c\phi s\theta \\ s\psi c\theta & c\psi c\phi + s\phi s\theta s\psi & -c\psi s\phi + s\theta s\psi c\phi \\ -s\theta & c\theta s\phi & c\theta c\phi \end{bmatrix} \quad (6)$$

Revised manuscript (L888-889) Section: Planning algorithm for altitude maintenance (Removal highlighted in red, addition highlighted in blue):

$$\Delta v = k_p \times d_{error}(k) + k_i \times \sum_{j=1}^k d_{error}(j) \quad (7)$$

$$\Delta v = k_p d_{error}(t) + \sum_{j=1}^t k_i d_{error}(j) \quad (7)$$

Reviewer#3 Concern #11: Several variables are not defined. In (7) there is a X symbol never used before.

Thank you for your careful review of the equation. The 'X' symbol in equation (7), intended to denote multiplication, has been corrected to maintain the arithmetic consistency throughout the article.

$$\Delta v = k_p \times d_{error}(t) + k_i \times \sum_{j=1}^t d_{error}(j) \quad \text{amended to} \quad \Delta v = k_p d_{error}(t) + \sum_{j=1}^t k_i d_{error}(j)$$

Reviewer#3 Concern #12: The supplementary material does not contain deeper information on the methods. The parameters tables are not discussed, and the control gains are not reported.

Thank you for your feedback on the missing deeper information on the methods. We have included a table of control parameters and a description detailing the impact of these parameters on control performance in the **Supplementary Information (Section 10, L264-290; Table 3)**.

Supplementary Information (L264-290) Section 10:

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; this assumes the disturbance observer's prior observations of the perturbations are relatively precise, thus eliminating the need for further updates. This minor error can be mitigated by continuously adjusting the robot's speed, which minimizes moment fluctuations and lessens unnecessary disturbance reject, thereby improving the stability of the robot's pitch angle.

Supplementary Information Table 3:

k	1.5	k_i	0.5
k_p	0.1	$\dot{\omega}_{\min}$	$0.08rad / s^2$
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

Supplemental Table 3. Control parameters

Reviewer#3 Concern #13: Figures are not cited in the correct order.

Thanks for the feedback on the image cite error. We have rechecked and confirmed the order of all image references to ensure the accuracy of the manuscript.

Reviewer#3 Concern #14: The paper is not always clear. There are a few typos (e.g. L88, L373), and unclear sentences (L79-80, L108-110, L543-546).

Thank you for your careful review of the manuscript. We have thoroughly reviewed the entire manuscript and corrected grammatical errors. We sincerely appreciate your assistance in enhancing the clarity and readability of our work. The manuscript has been updated by checking and correcting entire sentences to ensure better readability.

Revised manuscript (Removal highlighted in **red**, addition highlighted in **blue**):

- | |
|--|
| <ol style="list-style-type: none">1) the small area occupied by the rudder makes it challenging to ~~resistant~~ resist the forces and moments on the entire body.2) Typically, ~~bionic robots must employ devices, such as propellers, to enhance their performance.~~ many research efforts have utilized propellers to improve the performance of bionic robots.3) however, this method requires extra energy consumption to resist positive buoyancy to maintain depth. ~~and achieving a faster response necessitates increased positive buoyancy.~~ At the same time when ascending using positive buoyancy, greater positive buoyancy needs to be provided when increasing the rate of ascent, resulting in higher energy consumption to maintain depth. |
|--|

Point-to-Point Response to the Reviewers

Manuscript ID: NCOMMS-24-15186A

“A Maneuverable Underwater Vehicle for Near-seabed Observation.”

by Kaixin Liu, Mingxuan Ding, Biye Pan, Peiye Yu, Dake Lu, Siwen Chen,
Shuo Zhang, Gang Wang

We sincerely appreciate the editor and reviewers' valuable and insightful comments. We have revised and improved our manuscript as suggested. In the following, we provide a point-to-point response to each question raised, and substantial revisions to address the issues presented by the reviewers. Please refer to the revised manuscript (Revised manuscript clean.docx, Revised manuscript.pdf).

We are grateful to the reviewers for recognizing our work, and we are pleased that we were able to address the reviewers' concerns about the content of the manuscript in the previous round of responses. In this response we have addressed each of reviewer 3's comments and suggestions and revised them accordingly.

The authors sincerely thank all the reviewers for their valuable suggestions. We hope the revised manuscript can meet the publication criteria of Nature Communications. We appreciate your time and look forward to your response again.

Reviewer #1

Reviewer#1 overall comment: Thank you for your revisions and the detailed explanations provided. I appreciate the effort you've put into addressing all the comments and suggestions from the previous round.

We are glad that we have addressed the reviewer's concern. We appreciate the valuable feedback you have provided. Your comments have significantly contributed to enhancing the rigor and quality of our manuscript.

Reviewer #2

Reviewer#2 overall comment: I thank the authors for their detailed responses to the previous review comments and the revisions made. After careful review, I believe the authors have adequately addressed the concerns I raised, and the quality of the current version has improved significantly compared to the previous one. The paper's content is clearer, the logic is more rigorous, and the overall depth and breadth of the research have been enhanced.

Therefore, I have no further comments on the current version and recommend that the paper proceed to the next stage.

We are glad that we have addressed the reviewer's concern. We appreciate the reviewer's constructive comments and suggestions that significantly improved our manuscript's quality.

Reviewer #3

Reviewer#3 overall comment: The Authors improved the manuscript's quality. A few issues still remain.

Thank you for your feedback. We have implemented changes in response to each of your comments to improve manuscript quality.

Reviewer#3 Concern #1: β is still not defined.

Thank you for your feedback. In the previous revision, we added a description of β to the Supplementary Information; however, we inadvertently omitted this explanation from the manuscript itself. In this revision, we have included a detailed explanation of β in the manuscript. Additionally, we have conducted a thorough review to ensure that all related issues are comprehensively addressed.

Revised manuscript (L831-832) Section: Planning algorithm for altitude maintenance (Removal highlighted in red, addition highlighted in blue):

$\dot{\omega}_{\min}$ and β denote the thresholds for angular acceleration error and depth error, respectively,

serving as decision conditions for anti-disturbance algorithm.

Reviewer#3 Concern #2: A few limitations mentioned in the rebuttal file (autonomy and localization ability) are not mentioned in the manuscript (Reviewer#3 Concern #2; Reviewer#3 Concern #4)

Thank you for your feedback. We added the current status and limitations of autonomous and localization capabilities of underwater robots in "Discussion". In our last rebuttal file, we mentioned the limitations of robots in terms of localization, however, this is actually a common problem in the field of underwater robotics that requires a concerted effort from the entire industry to solve. In the discussion section, we also explore the potential contributions of the robotics presented in this paper to future underwater robot localization and autonomy implementations.

Revised manuscript (L692-703) Section: DISCUSSION. (Removal highlighted in **red**, addition highlighted in **blue**):

Simultaneously, a study shows that incorporating seabed texture information can improve terrain-matching navigation⁶¹, with image-based texture information yielding more detailed features than traditional sonar. **Since global navigation satellite system (GNSS) signals are unavailable underwater and the inertial navigation approach is prone to accumulate errors underwater⁶². Underwater localization base stations, such as short baseline (SBL) or ultrashort baseline (USBL) , can provide specific positional information for robots; however, these devices are costly. One solution, simultaneous localization and map building (SLAM), improves the robot's localization capabilities in GNSS-denied environments and is widely adopted. ORB-SLAM, which has been tested with mobile robots in various scenarios, has achieved promising results⁶³. Nonetheless, integrating image data in SLAM to enhance accuracy remains challenging due to the effects of illumination and turbidity on underwater images⁶⁴. The NS-MUV capabilities enhance image clarity, aiding in seabed positioning and advancing the autonomy of seabed observations.**

Reviewer#3 Concern #3: The novel videos are nice, but it would be better to have some commentary/explanation like in the first video.

Thank you for your suggestion. We have added detailed explanations in all of our videos.