

Article

Design and Control of a Bionic Underwater Collector Based on the Mouth Mechanism of Stomiidae

Zexing Mo, Ping Ren *, Lei Zhang , Jisheng Zhou, Yaru Li, Bowei Cui and Luze Wang

Department of Automation, College of Engineering, Ocean University of China, Qingdao 266100, China; mozexing1356@stu.ouc.edu.cn (Z.M.); zjs5059@stu.ouc.edu.cn (J.Z.); liyaru9660@stu.ouc.edu.cn (Y.L.); cbw@stu.ouc.edu.cn (B.C.); wlz1280@stu.ouc.edu.cn (L.W.)

* Correspondence: robotics@ouc.edu.cn (P.R.); zhanglei1107@ouc.edu.cn (L.Z.)

Abstract

Deep-sea mining has gradually emerged as a core domain in global resource exploitation. Underwater autonomous robots, characterized by low cost, high flexibility, and lightweight properties, demonstrate significant advantages in deep-sea mineral development. To address the limitations of traditional deep-sea mining equipment, such as large volume, high energy consumption, and insufficient flexibility, this paper proposes an innovative Underwater Vehicle Collector System (UVCS). Integrating bionic design with autonomous robotic technology, this system features a collection device mimicking the large opening–closing kinematics of the mouth of deep-sea dragonfish (Stomiidae). A dual-rocker mechanism is employed to realize the mouth opening–closing function, and the collection process is driven by the pitching motion of the vehicle without the need for additional motors, thus achieving the advantages of high flexibility, low energy consumption, and light weight. The system is capable of collecting seabed polymetallic nodules with diameters ranging from 1 to 12 cm, thus providing a new solution for sustainable deep-sea mining. Based on the dynamics of UVCS, this paper verifies its attitude stability and collection efficiency in planar motions through single-cycle and multi-cycle simulation analyses. The simulation results indicate that the system operates stably with reliable collection actions. Furthermore, water tank testings demonstrate the opening and closing functions of the UVCS collection device, fully confirming its design feasibility and application potential. In conclusion, the UVCS system, through the integration of bionic design, opens up a new path for practical applications in deep-sea resource exploitation.

Keywords: deep-sea mining; bionics; Underwater Vehicle Collector System; double-rocker mechanism



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1. Introduction

The process of modernization has led to a continuous increase in global demand for mineral raw materials, particularly in high-tech and new energy fields [1]. Such substantial demand for minerals will inevitably result in over-exploitation and depletion of terrestrial resources. Consequently, researchers have gradually turned their attention to the ocean, the Earth's most vast repository of resources. Deep-sea mining has, thus, emerged as a critical domain for resource exploitation, with scholarly research on deep-sea mineral collection becoming a subject of intense interest in contemporary times [2,3]. The practice of deep-sea mining relies on specialized mining equipment and systems [4]. However, these traditional mining apparatuses and systems [5–9] are typically bulky, energy-intensive,

and lack flexibility. They are prone to damaging seabed sediments and posing risks to the benthic ecosystem. Against this backdrop, minimizing operational noise, mitigating plume effects, and thereby reducing harm to marine biodiversity have become inevitable requirements for the development of deep-sea mining.

Unmanned underwater vehicles (UUVs) offer a cost-effective, flexible, and lightweight solution for deep-sea mineral exploration and other complex tasks [10]. In the field of unmanned underwater vehicles, the integration of bionic principles has attracted significant attention due to its distinct advantages [11,12]. Considerable efforts have been devoted to the design and performance optimization of bionic robotic fish, resulting in machines that exhibit efficient underwater locomotion capabilities [13,14]. In particular, inspired by the predatory behavior of octopuses, the “bending wave” motion of their tentacles has been emulated to capture prey, leading to the development of a soft octopus arm whose tip can perceive and grasp objects in a manner similar to an octopus sucker [15]. Likewise, a soft manipulator inspired by octopuses has been designed for underwater autonomous vehicle capture devices, enabling the effective capture of targets of varying sizes [16]. The design and implementation of bionic jellyfish robots employing jet propulsion mechanisms to replicate jellyfish locomotion have also been reported [17,18]. Furthermore, studies on beavers have investigated their swimming behavior, focusing on the paddling motion of their hind limbs and tail usage for balance [19,20]. Reference [21] introduced a compact underwater robot inspired by tadpole locomotion, which exhibits strong environmental adaptability. Similarly, a bionic manta ray robot that mimics the undulating movement of manta ray pectoral fins has been developed to enhance underwater maneuverability and stability [22]. Sea turtle-inspired underwater robots have been designed with emphasis on joint structure, sealing, and control systems, achieving robust maneuverability [23,24]. A fin design modeled after fish pectoral fins was proposed to improve the braking and maneuvering performance of underwater robots [25]. Additionally, a squid-inspired bionic robot featuring water pump propulsion, a flexible rudder, a miniaturized structure, and buoyancy control was presented in ref. [26]. A scallop-inspired underwater robot employing jet propulsion and capable of rapid movements has also been introduced [27].

However, most of these designs primarily emphasize mimicking the locomotion capabilities of marine organisms to enhance underwater mobility. Research on object capture and collection—mainly imitating octopus tentacles for grasping—remains limited by low retrieval efficiency and significant gaps in functionality for specific applications, especially underwater mining. These challenges motivate the design rationale of the present study’s proposed collector, which draws inspiration from the mouth structure of Stomiidae fishes.

Most manipulators equipped on traditional Underwater Vehicle Manipulator Systems (UVMSs) are gripper-type manipulators [28–31], which are commonly used for high-precision underwater tasks. However, such gripping mechanisms show low efficiency in underwater mineral collection. Additionally, the extra motors mounted on the manipulator require additional energy supplied by the underwater vehicle itself, which limits their suitability to restricted collection scenarios. To address these drawbacks of traditional mining equipment and manipulators, this paper proposes a bionic collection device inspired by the mouth of the Stomiidae, integrating bionic principles. When combined with an underwater vehicle, the device forms an Underwater Vehicle Collector System (UVCS). Stomiidae [32,33] possess an exceptionally large gape, supported by long, flexible lower jaws and specialized head joints, as illustrated in Figure 1a. The mouth-opening mechanism of Stomiidae features a flexible hinge located between the skull and the first vertebra—an uncommon “functional head joint” among deep-sea fish living in aphotic environments. This joint, formed by the occipital bone and notochord, allows the head to elevate signifi-

cantly, thereby further increasing the range of mouth opening. Figure 1b displays the head joint of a typical fish; in contrast to bony fish, which lack such a functional head joint, the skull of Stomiidae can be pulled farther upward and backward. Reference [34] conducted a simplified analysis of the Stomiidae structure based on mechanism linkages. Building upon this, the present study simplifies the linkage design further for engineering applications (Figure 1c). A double-rocker mechanism (a type of four-bar linkage) is employed to biomimetically replicate the fish's mouth opening and closing movement. The rotation of the input link transmits motion to the upper jaw of the collector, enabling it to open and close. To ensure sufficient operational strength during collection, the lower jaw of the collector has been fixed. During the design of the collector, the sizes of seabed minerals [35,36] were taken into account, ensuring that the minimum opening size of the upper jaw exceeds 12 cm to meet target collection requirements. Furthermore, this collector is integrated with an unmanned underwater vehicle [37–41], which allows collection operations to be conducted through the vehicle's pitching motion (Figure 2).

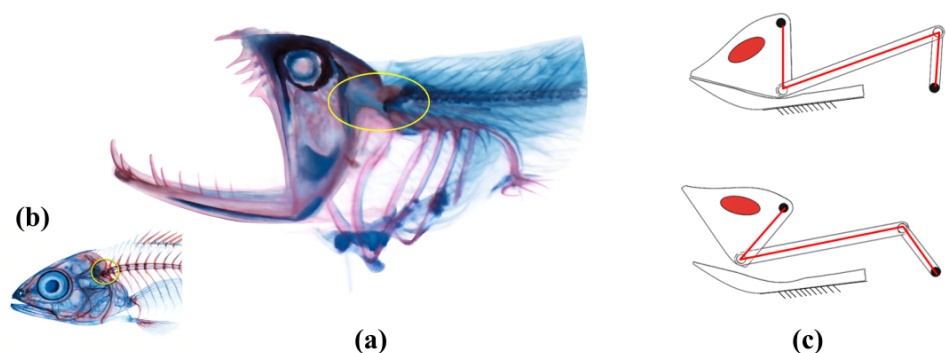


Figure 1. Comparison between the mouth mechanism of the Stomiidae and the simplified bionic linkage mechanism: (a) The skeleton and anatomy of a barbeled dragonfish (a kind of Stomiidae) with a true functional head joint. (b) Head joint of common fish (non-functional, stiff, in the case of a young Mediterranean sea bass). (c) Opening and closing state of the bionic fish mouth linkage structure. Modified from <https://insider.si.edu/2017/02/odd-anatomy-flexible-joint-skull-spine-allow-dragonfish-open-wide/> (accessed on 1 February 2017).

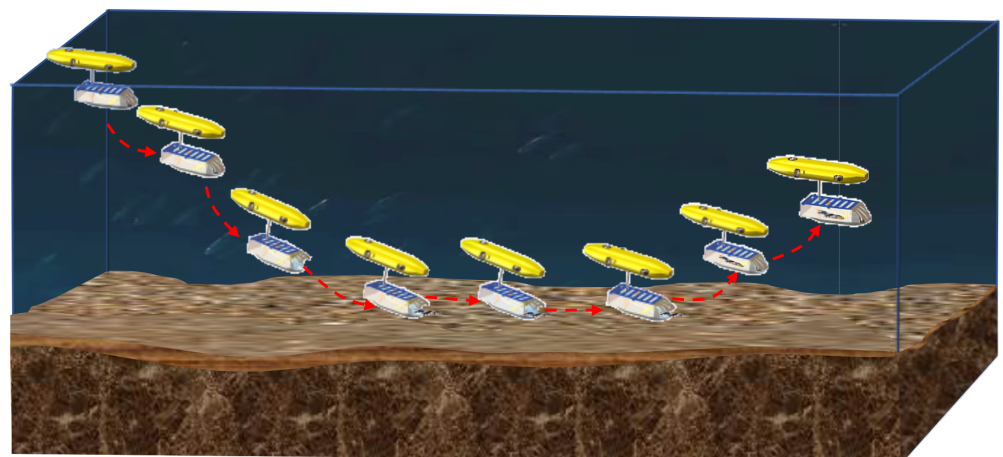


Figure 2. The underwater collecting process of UVCS.

The innovative features exhibited by the bionic collector are as follows:

1. **Novel Bionic Mechanical Design:** A pioneering “shovel-type” bionic manipulator acquisition mechanism is designed by referencing the mouth structure of Stomiidae (dragonfish family).

2. **Underactuated Operation Method:** The motor-free collector is integrated with an underwater vehicle to form an Underwater Vehicle Collector System (UVCS), where the acquisition operation is solely driven by the underwater vehicle's pitching motion. This system is modeled as an underactuated Pendubot system, and a control strategy combining LQR (linear quadratic regulator) with a smoothing operator is adopted to achieve motor-free driving control of the UVCS.

The remaining content of this paper is organized as follows: Section 2 describes the design of the collection mechanism and the dynamic modeling of the UVCS. Section 3 introduces the control of UVCS using the LQR method and a smoothing operator. Section 4 describes the water tank experiments. Section 5 provides a summary of the paper and discusses future work.

2. Design and Modeling

2.1. Conceptual Design

The collector is mounted beneath an unmanned underwater vehicle (UUV) and operated by leveraging the UUV's pitching motion. As illustrated in Figure 3a, the collector's shell serves as the frame, with the brown rod functioning as the input link and the fish upper jaw as the output link. A coupling link is positioned between the input and output links. Under the influence of the UUV's downward pitching motion, the input link swings clockwise, driving the upper jaw structure to rotate upward, thereby opening the collector's "mouth." In the open state, an upward pitching motion of the UUV causes the input link to swing counterclockwise, resulting in the closure of the upper jaw. This opening and closing mechanism emulates the natural feeding behavior of Stomiidae, facilitating efficient capture of target objects. The minimum edge dimension of the collector in its open state must be large than 12 cm to accommodate the size requirements of the target minerals, which ensures operational functionality in practical applications.

An exploded view, presented in Figure 3b, provides a detailed depiction of the collector's components and their assembly relationships. The cover plate, located at the top of the collector, is a rectangular flat panel with surface slots designed to reduce weight while maintaining structural integrity, offering protection and support to the underlying components. The lower jaw body, a core component, adopts a streamlined configuration with its front end mimicking the fish's lower jaw for target object collection. Circular holes on its surface effectively minimize water resistance and mitigate the impact of water flow. The upper jaw structure is angular-shaped. It has a rotating joint at the corner that enables opening and closing motions, and its surface is streamlined and incorporates slots to reduce hydrodynamic drag. The input link, situated within the lower jaw body, is designed with a thicker upper section and a thinner lower section, positioning the center of gravity higher to utilize inertia and gravity for motion energy transmission. The coupling link connects the input link to the upper jaw, forming a double-rocker mechanism that transmits radial thrust to the upper jaw. The baffle is designed with an arc-shaped profile and functions similarly to a one-way valve, which permits the entry of target objects while preventing the backflow of collected items. These components are engineered to enhance the collector's hydrodynamic performance, structural stability, and operational reliability in underwater environments, ensuring successful completion of the collection task. The integration of the collector beneath the UUV is depicted in Figure 3c.

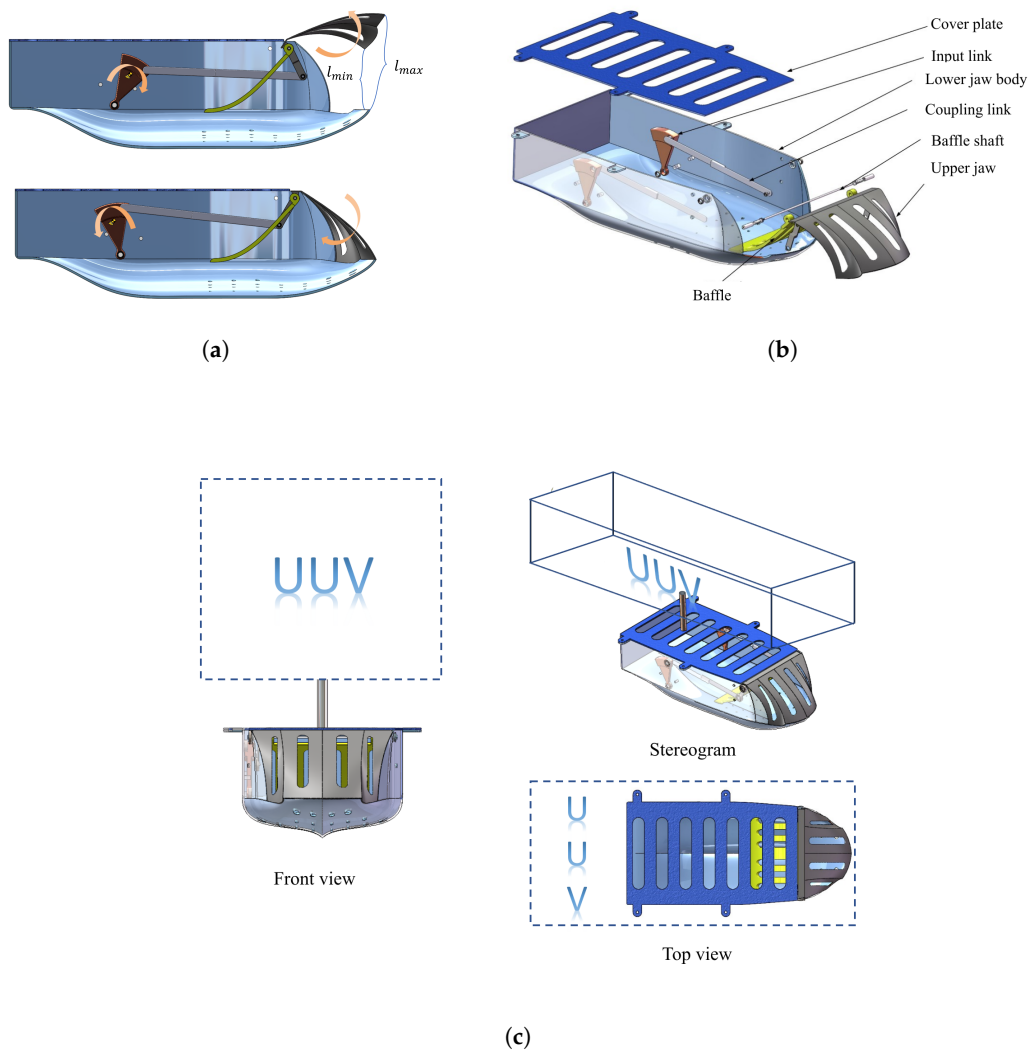


Figure 3. (a) describes the motion of the internal four-bar linkage during the operation of the collector. (b) describes the exploded view of the collector, illustrating its specific composition. (c) describes the three-view drawings of the overall UVCS with the collector mounted on the UUV.

2.2. Kinematic Modeling

The modeling process consists of two parts: 1. Kinematic modeling of the internal double-rocker mechanism of the collector (Figure 4). 2. Dynamic modeling of the overall UVCS.

Equation (1) presents the classical Freudenstein equation [42], which establishes a nonlinear relationship between the input link angle ϕ_1 and the output link angle ϕ_3 :

$$R_1 \cos \phi_1 + R_2 \cos \phi_3 + R_3 = \cos(\phi_1 - \phi_3) \quad (1)$$

where

- $R_1 = \frac{r_0}{r_3}$;
- $R_2 = \frac{r_0}{r_1}$;
- $R_3 = \frac{r_2^2 - r_0^2 - r_1^2 - r_3^2}{2r_1r_3}$;

and

- r_0 : Length of the frame;
- r_1 : Length of the input link;

- r_2 : Length of the coupling link;
- r_3 : Length of the output link;
- ϕ_1 : Input angle;
- ϕ_3 : Output angle.

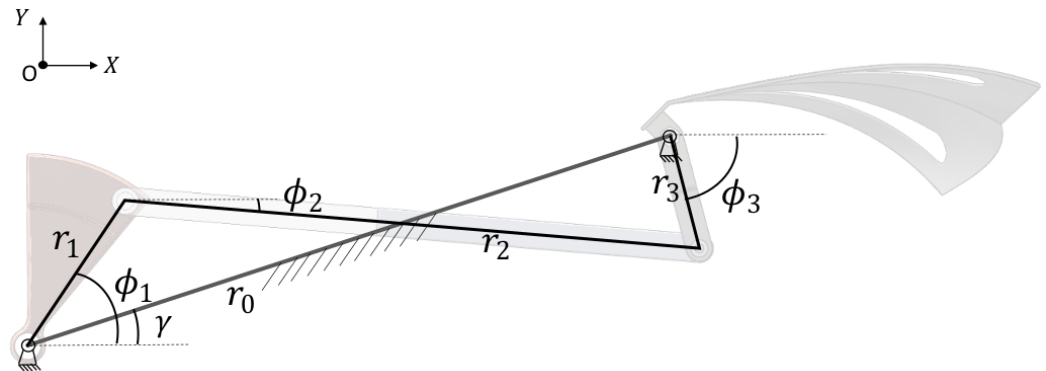


Figure 4. Schematic diagram of double-rocker mechanism in the collector.

Following the method in [43], the relationship between the input angular velocity $\dot{\phi}_1$ and the output angular velocity $\dot{\phi}_3$ is derived as follows:

$$\dot{\phi}_3 = -\dot{\phi}_1 \frac{r_{2x}r_{1y} - r_{1x}r_{2y}}{r_{2x}r_{3y} - r_{3x}r_{2y}}, \quad (2)$$

where

- r_{1x}, r_{1y} : Projections of the input link along the x and y axes;
- r_{2x}, r_{2y} : Projections of the coupling link along the x and y axes;
- r_{3x}, r_{3y} : Projections of the output link along the x and y axes.

Based on the above kinematic relationships, a mapping from the input link to the output link (upper jaw) of the collector is established.

2.3. Dynamic Modeling

To simplify the dynamic analysis, the following assumptions are put forward:

1. Except for the input link, the structural mass of the remaining parts of the double-rocker linkage is negligible, and only the kinematic relationships are considered.
2. Friction at the rotational joints of the double-rocker linkage is negligible.
3. The transmission angle of the double-rocker mechanism is small within the operating range, ensuring high force transmission efficiency, which is therefore assumed to be ideal.

Since this paper focuses on investigating the operational performance of the collector, emphasis is placed on the planar four-degree-of-freedom (4-DOF) UVCS, including surge (x), heave (z), pitch, and rotation of the input link. The respective coordinates and specific designations of the structural parameters for the planar UVCS are illustrated in Figure 5. Under the assumption that the center of gravity of the UVCS coincides with the rotation center, the following states are selected:

$$\boldsymbol{\eta} = [x, z, \theta_1, \theta_2]^\top, \quad \dot{\boldsymbol{\eta}} = [\dot{x}, \dot{z}, \dot{\theta}_1, \dot{\theta}_2]^\top, \quad \boldsymbol{\nu} = [u, w, q, \dot{\theta}_2]^\top,$$

where

- $\boldsymbol{\eta}$: UVCS state vector in the inertial frame;
- $\boldsymbol{\nu}$: UVCS velocity vector in the body-fixed frame.

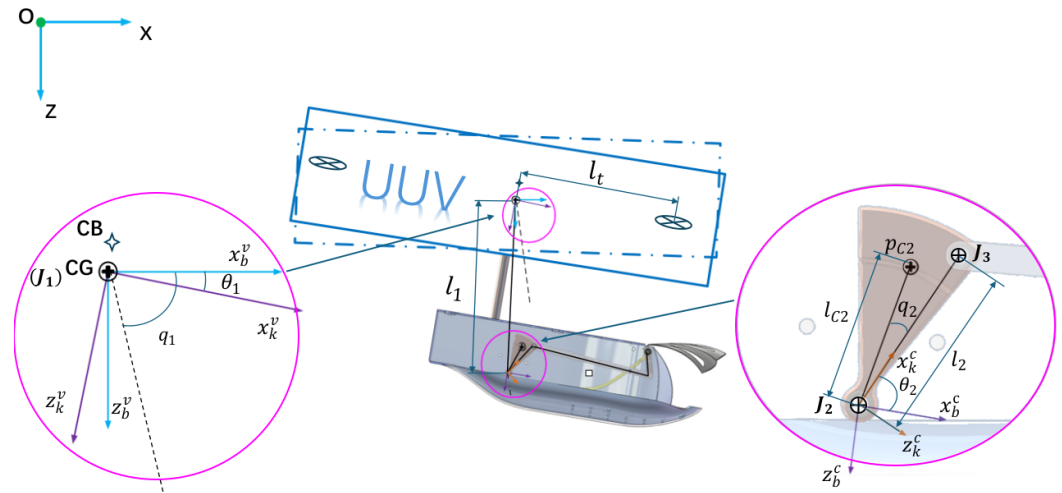


Figure 5. Schematic diagram of parameter and coordinate setting for UVCS.

The transformation between body-fixed and generalized coordinates is given by the following:

$$\dot{\eta} = \mathbf{J}\mathbf{v}, \quad (3)$$

$$\mathbf{J} = \begin{bmatrix} \cos \theta_1 & \sin \theta_1 & 0 & 0 \\ -\sin \theta_1 & \cos \theta_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}. \quad (4)$$

The position of the center of mass of the input link in the body-fixed frame is as follows:

$$p_{c2} = \begin{bmatrix} l_1 \cos q_1 + l_{c2} \cos(\theta_2 + q_2) \\ -l_1 \sin q_1 - l_{c2} \sin(\theta_2 + q_2) \end{bmatrix} \quad (5)$$

where

- l_1 : Distance from the vehicle joint to the input link joint (J_1 to J_2);
- l_{c2} : Distance from the input link joint to its center of mass (J_2 to p_{c2});
- q_1 : Structural angle between l_1 and the x -axis of body coordinate;
- q_2 : Structural angle between l_2 and l_{c2} .

The inertial mass matrices of the vehicle and the collector are presented as follows:

$$\mathbf{M}_{RB}^v = \begin{bmatrix} m_v & 0 & -m_v z_G^v \\ 0 & m_v & m_v x_G^v \\ -m_v z_G^v & m_v x_G^v & I_y^v \end{bmatrix}, \quad \mathbf{M}_{RB}^c = \begin{bmatrix} m_c & 0 & -m_v z_G^c \\ 0 & m_c & m_v x_G^c \\ -m_v z_G^c & m_v x_G^c & I_y^c \end{bmatrix},$$

where

- m_v, m_c : Masses of the vehicle and the input link.
- I_y^v, I_y^c : Moments of inertia about the pitch axis.
- (x_G^v, z_G^v) : The coordinates of vehicle's center of gravity.
- (x_G^c, z_G^c) : The coordinates of input link's center of gravity.

The kinetic energies are as follows:

$$T_v = \frac{1}{2} \mathbf{v}_v^\top \mathbf{M}_{RB}^v \mathbf{v}_v, \quad T_c = \frac{1}{2} \mathbf{v}_c^\top \mathbf{M}_{RB}^c \mathbf{v}_c, \quad (6)$$

where

- $\mathbf{v}_v$: Velocity vector of the vehicle;

- v_c : Velocity vector of the input link.

and the total kinetic energy is as follows:

$$\bar{T} = T_v + T_c, \quad (7)$$

Based on the total kinetic energy of the rigid body, and following the quasi-Lagrange formulation in ref. [44], the rigid-body dynamics is expressed as follows:

$$M_{RB}\dot{v} + C_{RB}(v)v = \tau_{RB}, \quad (8)$$

where

- M_{RB} : Total rigid-body inertial mass matrix.
- $C_{RB}(v)$: Total rigid-body Coriolis and centrifugal force matrix.
- τ_{RB} : The total rigid-body generalized external force matrix.

The added mass matrix of the vehicle is computed via CFD and expressed as follows:

$$M_{add}^v = \text{diag}(m_x, m_z, m_p), \quad (9)$$

Due to the small volume of the input link, its added mass can be neglected; consequently, the kinetic energy equation for the added mass can be derived through the same kinetic energy-based method:

$$M_{add}\dot{v} + C_{add}(v)v = \tau_A, \quad (10)$$

In underwater motion, the system is also subject to hydrodynamic damping effects. The damping matrix can be written as

$$D(v) = \text{diag}(d_1, d_2, d_3, d_4), \quad (11)$$

where

- d_1, d_2, d_3 : Hydrodynamic damping coefficients for the longitudinal, vertical, and pitching motions of the vehicle;
- d_4 : Equivalent damping term of the input link at the joint,

$$d_4 = d_r + d_l(\dot{\phi}_3)$$

where d_r is the hydrodynamic resistance of input link (neglected in this paper), and $d_l(\dot{\phi}_3)$ is the hydrodynamic resistance encountered by the upper jaw rotation, which is coupled with the transmission ratio of the double-rocker mechanism after being obtained through CFD fitting.

In the inertial coordinate system, the restoring force/moment vector is

$$g(\eta) = \begin{bmatrix} (W_v - B_v) \sin \theta_1 \\ -(W_v - B_v) \cos \theta_1 \\ (z_G^v W_v - z_B^v B_v) \sin \theta_1 + (x_G^v W_v - x_B^v B_v) \cos \theta_1 \\ (z_G^c W_c - z_B^c B_c) \sin \theta_1 + (x_G^c W_c - x_B^c B_c) \cos \theta_1 \end{bmatrix}, \quad (12)$$

where

- W_v, B_v : Weight and buoyancy of the vehicle;
- W_c, B_c : Weight and buoyancy of the input link;

- $(x_G^v, z_G^v), (x_B^v, z_B^v)$: Coordinates of the center of gravity and center of buoyancy of the vehicle in the body-fixed coordinate system;
- $(x_G^c, z_G^c), (x_B^c, z_B^c)$: Coordinates of the center of gravity and center of buoyancy of the input link in the body-fixed coordinate system.

Substituting the above terms into the standard Fossen form ref. [45], the complete dynamic equation of the UVCS in the body-fixed coordinate system is obtained as

$$M(\boldsymbol{v})\dot{\boldsymbol{v}} + C(\boldsymbol{v})\boldsymbol{v} + D(\boldsymbol{v})\boldsymbol{v} + \boldsymbol{g}(\boldsymbol{\eta}) = \boldsymbol{\tau}, \quad (13)$$

where

- $M(\boldsymbol{v}) = M_{RB} + M_{add}$;
- $C(\boldsymbol{v}) = C_{RB}(\boldsymbol{v}) + C_{add}(\boldsymbol{v})$;
- $\boldsymbol{\tau}$ is the vector of external control and disturbance inputs.

The specific formulas for transforming Equation (13) to the inertial coordinate system via the Jacobian matrix (defined in Equation (4)) are as follows:

$$\begin{cases} M_\eta(\boldsymbol{\eta}) = \boldsymbol{J}^{-\top} M(\boldsymbol{v}) \boldsymbol{J}^{-1} \\ C_\eta(\boldsymbol{v}, \boldsymbol{\eta}) = \boldsymbol{J}^{-\top} \left(C(\boldsymbol{v}) - M(\boldsymbol{v}) \boldsymbol{J}^{-1} \dot{\boldsymbol{J}} \right) \boldsymbol{J}^{-1} \\ D_\eta(\boldsymbol{v}, \boldsymbol{\eta}) = \boldsymbol{J}^{-\top} D(\boldsymbol{v}) \boldsymbol{J}^{-1} \\ \boldsymbol{g}_\eta(\boldsymbol{\eta}) = \boldsymbol{J}^{-\top} \boldsymbol{g}(\boldsymbol{\eta}) \\ \boldsymbol{\tau}_\eta(\boldsymbol{\eta}) = \boldsymbol{J}^{-\top} \boldsymbol{\tau} \end{cases} \quad (14)$$

Consequently, the dynamic equation in the inertial coordinate system is obtained:

$$M_\eta(\boldsymbol{\eta})\ddot{\boldsymbol{\eta}} + C_\eta(\boldsymbol{v}, \boldsymbol{\eta})\dot{\boldsymbol{\eta}} + D_\eta(\boldsymbol{v}, \boldsymbol{\eta})\dot{\boldsymbol{\eta}} + \boldsymbol{g}_\eta(\boldsymbol{\eta}) = \boldsymbol{\tau}_\eta(\boldsymbol{\eta}), \quad (15)$$

Equation (15) is the complete dynamic model of the UVCS used for the subsequent controller design and simulation verification.

3. Control

Due to the absence of a power source in the collector, the input vector $\boldsymbol{\tau}_\eta$ is given as $[f_x, f_z, f_{\theta_1}, 0]$, indicating that only three effective inputs are available to control four degrees of freedom. Consequently, the UVCS can be categorized as an underactuated system. The attitude control of the UVCS could draw insights from the control theory of underactuated two-link manipulators. According to ref. [46], underactuated manipulators are generally classified into two types: the Acrobot and the Pendubot. Specifically, the actuated joint of the Acrobot is located at the “elbow,” whereas that of the Pendubot is situated at the “shoulder.” In the case of the UVCS, its structural configuration is more analogous to the Pendubot model:

- The vehicle is regarded as the first link;
- The input link of the collector is regarded as the second link;
- The rotation center of the vehicle serves as the active joint;
- The rotation center of the input link serves as the passive joint.

The operation of the collector primarily relies on gravity acting on the input link and the coupling forces, which are closely related to the vehicle’s rotational posture. To ensure the stability of the collector, limiters are designed to control its operating angle. Under conditions without limiters, the equilibrium position of the input link is the same as the system’s natural equilibrium state, which corresponds to the energy minimum and can be manifested as a free-hanging configuration. Upon installation of limiters, the

motion range of the input link is constrained, and the system's natural equilibrium state is correspondingly mapped onto the stop positions of the limiters. In other words, the stop positions essentially represent equivalent stable points of the natural equilibrium state under the mechanical constraints imposed by the limiters. For the Pendubot system equipped with limiters, the equilibrium position of the input link is confined to the stop points e_1, e_2 (Figure 6), and these two stop points can be regarded as equivalent stable equilibrium points to the natural equilibrium state.

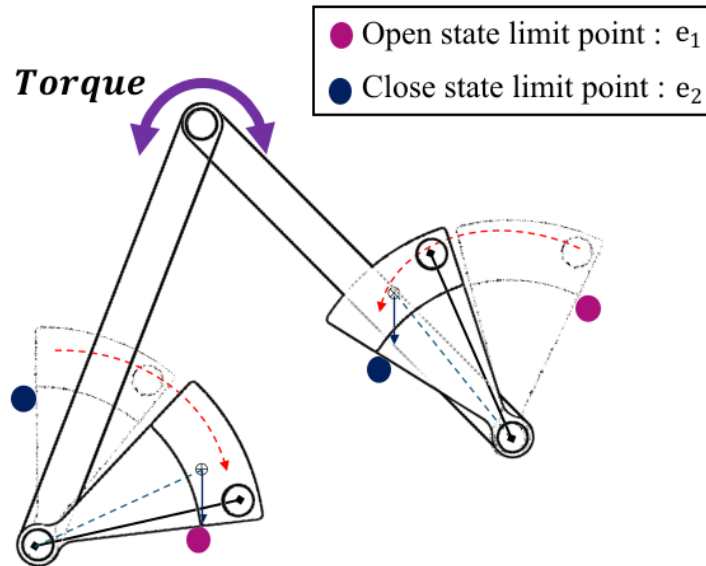


Figure 6. Schematic diagram illustrating the limit point constraint on the input link during its operation.

For control purpose, a linearization is performed around the natural free-hanging configuration. The resulting linearized system is a time-invariant linear system, whose stability can be easily determined. As the state approaches the equilibrium point, the input link is held at the desired angle by the limiter, thereby simplifying the control strategy. Moreover, the equilibrium states for opening and closing the collector are related to θ_1 ; thus, the equilibrium states must also include the torque required to maintain the angle of θ_1 , where the torque setting is achieved through thrust allocation. The magnitude of the required torque is associated with the setting of CG and CB positions of the UVCS. When the UVCS performs pitching motion, the deviation between the CG and CB generates a restoring torque that tends to return the UVCS to a horizontal state. To counteract the effect of this restoring torque, the thrusters must maintain a certain level of thrust to stabilize θ_1 at the desired angle.

Since matrix M is positive definite, according to Equation (15), it can be derived that

$$\ddot{\eta} = M_{\eta}(\eta)^{-1}(\tau_{\eta}(\eta) - C_{\eta}(\nu, \eta)\dot{\eta} - D_{\eta}(\nu, \eta)\dot{\eta} - g_{\eta}(\eta)) \quad (16)$$

The limiter restricts the swing of the input link to a relatively small area so that the control problem of the underactuated system can be transformed into the control of the two-link manipulator in the attraction region. In this paper, the linear quadratic regulator (LQR) method is used for controller design. Meanwhile, a smoothing operator is used on the basis of LQR to smooth the output of LQR and stabilize the output force. Its framework is as Algorithm 1.

Algorithm 1 LQR method for UVCS

Procedure:

- Select state variables(actual-equilibrium deviation):

$$\begin{aligned}\xi &= (x, \dot{x}, z, \dot{z}, \theta_1, \dot{\theta}_1, \theta_2, \dot{\theta}_2) \\ \dot{\xi} &= (\dot{x}, \ddot{x}, \dot{z}, \ddot{z}, \dot{\theta}_1, \ddot{\theta}_1, \dot{\theta}_2, \ddot{\theta}_2) = f(\xi, \tau)\end{aligned}$$

- State equation:

$$\dot{\xi} = \mathbf{A} \cdot \xi + \mathbf{B} \cdot \tau$$

Since the UVCS is an under-actuated system where the power source exists only on the vehicle and not on the collector, τ is therefore $[f_x, f_z, f_{\theta_1}, 0]$

- Linearization at the natural equilibrium:

$$\mathbf{A}_{(8 \times 8)} = \frac{\partial f(\xi, \tau)}{\partial \xi}, \mathbf{B}_{(8 \times 4)} = \frac{\partial f(\xi, \tau)}{\partial \tau}$$

- Select weight matrix:

$$J = \int (\xi^\top \cdot \mathbf{Q} \cdot \xi + \tau^\top \cdot \mathbf{R} \cdot \tau) dt$$

$\mathbf{Q} \in \mathbb{R}^{8 \times 8}, \mathbf{Q} \geq 0$ (state weighting)

$\mathbf{R} \in \mathbb{R}^{4 \times 4}, \mathbf{R} > 0$ (control weighting)

- Solve the algebraic Riccati equation:

$$\mathbf{A}^\top \mathbf{P} + \mathbf{P} \mathbf{A} - \mathbf{P} \mathbf{B} \mathbf{R}^{-1} \mathbf{B}^\top \mathbf{P} + \mathbf{Q} = 0$$

- Compute the optimal feedback gain matrix:

$$\mathbf{K} = \mathbf{R}^{-1} \mathbf{B}^\top \mathbf{P}$$

- Compute optimal control law:

$$\tau = -\mathbf{K} \cdot \xi$$

- Smoothing Operation:

$$\tau^* = \sigma_1 \cdot \tau + \sigma_2 \cdot \int \tau d\tau$$

- Final simulation equation:

$$\dot{\xi} = \mathbf{A} \xi + \mathbf{B} \tau^*$$

- Apply the control law to the system to form a stable closed-loop system.

- The stability of the system is guaranteed by the LQR algorithm [47], which can be rigorously demonstrated through the application of Lyapunov's stability criterion.

In a complete working cycle, the UVCS sequentially undergoes three phases: opening, collecting, and closing. Its motion trajectory is illustrated in Figure 7, and the analysis of simulation results are presented in Figure 8, with the selected parameters listed in Tables 1–3. During the opening phase, the UVCS performs pitch attitude control, where the body pitch angle θ_1 decreases, thereby causing θ_2 to decrease, driving the collector to switch from the closed state to the open state. In the collecting phase, the UVCS maintains stable angles of θ_1 and θ_2 , submerges along the z-axis (depth direction) to reach the predetermined operating depth, and simultaneously performs the collecting task forward along the horizontal x-axis. After arriving at the predetermined operating depth, its position along the z-axis holds steady or moves slightly downward. For the closing phase, opposite to the opening phase, the UVCS adjusts its pitch attitude to increase θ_1 , and θ_2 increases accordingly, driving the collector to switch back from the open state to the closed state. Meanwhile, it ascends along the reverse z-axis direction (toward the water surface) to return to the initial position, preparing for the next working cycle. As shown in Figure 8a,b, the desired trajectory is as follows: in the x-direction, the x-position is held constant during the opening phase, moves forward during the collecting phase, and holds the x-position steady again during the closing phase; in the z-direction, it submerges during the opening phase, maintains a constant depth during the collecting phase, and ascends during the closing phase.

Table 1. Numerical values of key parameters.

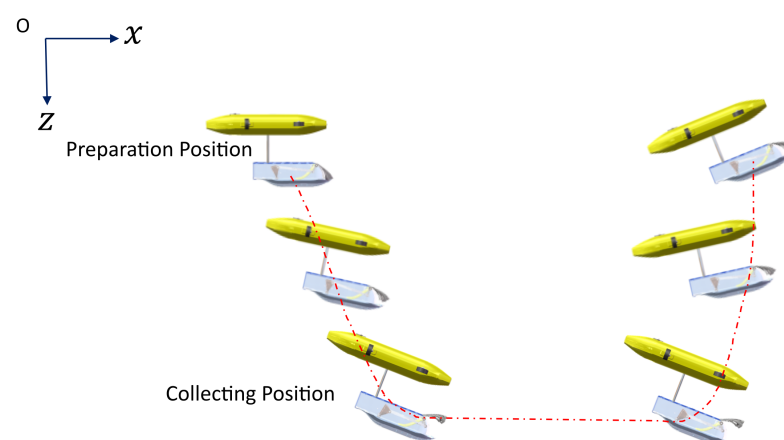
Parameter	Value (Units: kg, m, rad, $\text{kg}\cdot\text{m}^{-3}$, $\text{m}\cdot\text{s}^{-2}$, m^3)
CG	(0, 0)
CB	(0, −0.06 m)
m_v	146 kg
m_c	2.2 kg
l_1	0.6 m
l_2	0.1 m
l_{c2}	0.076 m
l_t	0.35 m
q_1	−1.396 rad
q_2	0.262 rad
ρ	1024 $\text{kg}\cdot\text{m}^{-3}$
g	9.8 $\text{m}\cdot\text{s}^{-2}$
I_y^v	35.2 $\text{kg}\cdot\text{m}^2$
I_y^c	0.059 $\text{kg}\cdot\text{m}^2$
e_1	(−0.349 rad, 0.852 rad)
e_2	(+0.349 rad, 1.497 rad)
m_x	17 kg
m_z	61 kg
m_p	72 kg

Table 2. Formulas for water damping coefficients.

Water Damping Coefficient	Formula
d_1	$180u^2 + 9.5u - 2.07$
d_2	$724w^2 - 47.6w + 10.6$
d_3	$13.65\dot{\theta}_1^2 + 7.61\dot{\theta}_1 - 0.81$
d_4	$0.1\dot{\theta}_2^2 + 0.53\dot{\theta}_2 + 0.027$

Table 3. Numerical values of the weighting matrices, Q and R.

Weighting Matrix	Value
Q	$\text{diag}(4000, 400, 8000, 1000, 8000, 100, 1000, 1000)$
R	$\text{diag}(2, 1, 1)$

**Figure 7.** Core working steps of UVCS: Open–collect–close.

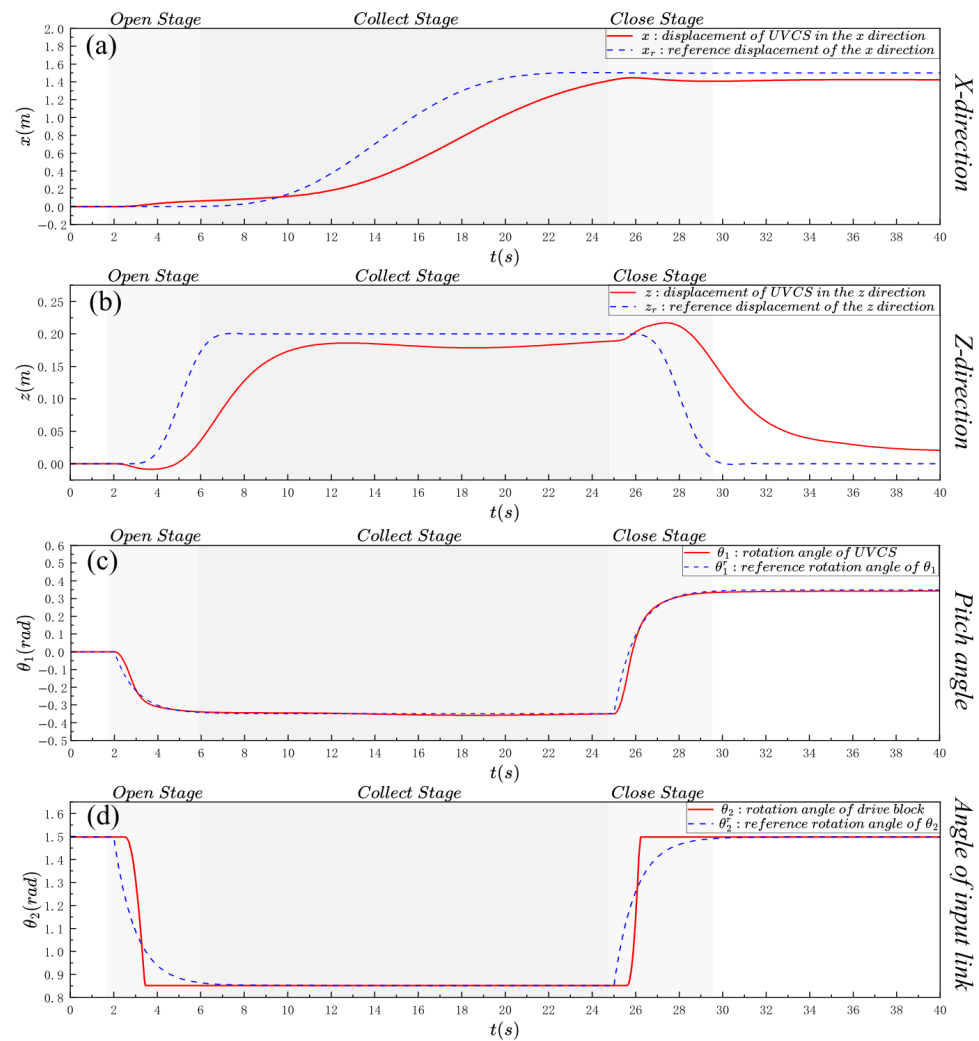


Figure 8. Simulation results for the core working steps of the UVCS: (a) X-direction displacement tracking of UVCS. (b) Z-direction displacement tracking of UVCS. (c) Pitch angle tracking of UVCS. (d) Rotation angle tracking of input link.

However, there are deviations between the actual simulation trajectory and the desired trajectory, with a deviation of approximately ± 0.1 m in the x -direction and ± 0.025 m in the z -direction. Such deviations are mainly caused by the system coupling effect: as an integrated system, there is a coupling effect between the vehicle and the collector. To control the collector to maintain the open state, the vehicle body needs to maintain a specific operating attitude angle, and changes in attitude angles in turn affect the overall motion trajectory. In the UVCS, operational stability is the primary consideration, so the research focus is centered on the control of the collector's opening and closing angles. In controller design, a higher weight is assigned to θ_1 to ensure that θ_1 and θ_2 can better track the desired trajectories, as shown in Figure 8c,d, thus achieving good tracking performance in key states.

When performing long-duration underwater operations, the workflow of the UVCS is no longer confined to a single cycle but sequentially undergoes multiple “opening–collecting–closing” cyclic processes. Within each cycle, the UVCS completes the collecting task along a predetermined trajectory and prepares for the next cycle during the closing phase. As the operation proceeds, the UVCS can repeatedly execute the opening, collecting, and closing actions at different spatial positions or collecting points, enabling efficient collecting over a larger range or for more targets. After all the predetermined collecting

cycles are completed, the UVCS enters the recovery phase, ascends along the water surface direction, and finally returns to the initial position or the designated recovery point, thus completing the entire operation task. The multi-cycle simulation results are presented in Figure 9. In this simulation, the UVCS is set to continuously complete five collecting cycles, and each cycle repeatedly implements the standard process of “opening–collecting–closing.” The operation features a total length of 8 m and a depth of 0.2 m. Figure 9a,b, respectively, illustrate the simulation results of the displacement of the UVCS in the x-direction and z-direction during multi-cycle operations. It can be observed that during multi-cycle operations, the actual displacement curves of the UVCS can track the desired trajectories well; particularly, after reaching the set depth in the z-direction, the UVCS can move stably along the x-direction, indicating that the system can effectively complete continuous collecting tasks. Meanwhile, in the collecting phase, the z-direction position remains essentially constant with only slight diving fluctuations, further verifying the depth control accuracy of the system. Figure 9c,d, respectively, show the variations of the body pitch angle θ_1 and the collector opening–closing angle θ_2 during multi-cycle operations. The results demonstrate that the actual trajectories of θ_1 and θ_2 both track the desired trajectories well, and θ_2 is correlated with the variation angle of θ_1 . The dynamic characteristics shown are consistent with those in the single-cycle simulation. In other words, the opening and closing actions of the collector can accurately respond to the adjustment of the body attitude. After all the collecting cycles are completed, the UVCS assumes the recovery phase, carrying full loads of collected materials to ascend along the z-direction and move toward the shore-based or offshore operation platform. In this simulation, the recovery process is set to ascend 5 m and move forward 1.6 m to simulate the actual post-operation recovery path. From the simulation results, the displacement of the UVCS during the recovery phase can also track the expected values well. However, as can be seen from Figure 9b,d, during the ascent process, there is a small segment of deviation between the θ_2 angle and the expected value. This phenomenon is mainly attributed to the inertial force caused by the upward acceleration of the UVCS, which leads to slight swings of the input link.

When the UVCS reaches the predetermined recovery position, the inertial force disappears, and the input link naturally returns to the closed stop position under the effect of gravity, with the θ_2 angle subsequently restoring to the expected value. Overall, the simulation results verify the motion control accuracy and system stability of the UVCS during multi-cycle continuous operations and the recovery process. In this simulation, a smoothing operator is introduced based on LQR control so that the output forces of the system are integrated and optimized, which results in smoother output force curves. The parameters of the smoothing operator are determined using a trial-and-error method. Figure 10 presents a comparison of the input forces before and after applying the smoothing operator. Herein, P_1 denotes the thrust of the propulsor located at the vehicle’s tail, which provides the X-directional propulsion force. P_2 and P_3 represent the thrusts of the propellers positioned at the rear and front ends of the vehicle, respectively, and these propulsors supply the Z-directional driving force. Figure 10b illustrates the output force waveforms after smoothing processing; compared with the output forces without smoothing (Figure 10a), the curves are significantly smoother.

To quantitatively analyze the smoothness of the output forces before and after smoothing, Fourier transform is employed to perform time–frequency analysis on the output force waveforms, and the results are presented in Figure 11a–c. The analysis results indicate that after smoothing processing, the high-frequency components of P_2 and P_3 are significantly attenuated, and the smoothness of the output forces is greatly improved, whereas the high-frequency components of P_1 change slightly, with a relatively limited smoothing effect.

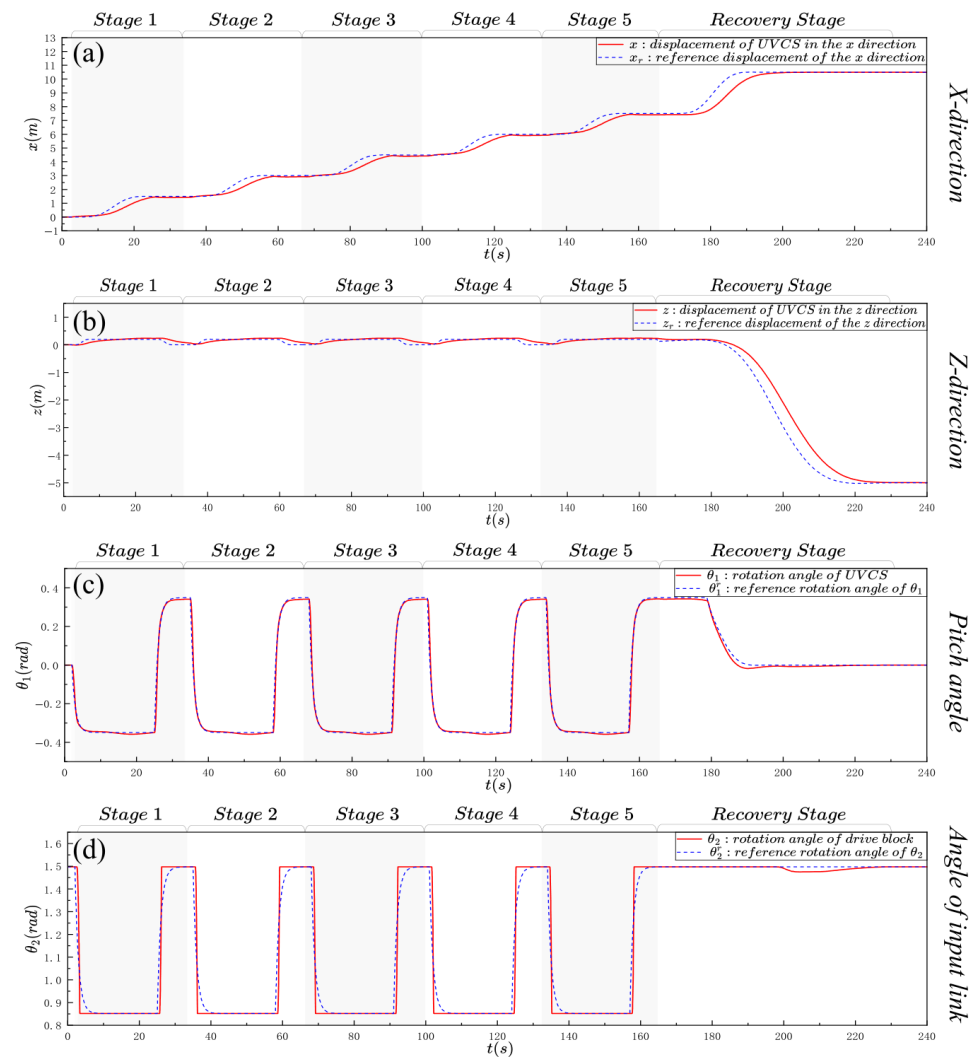


Figure 9. Simulation results of the UVCS core working steps across multiple cycles: (a) X-direction displacement tracking of UVCS over multiple cycles. (b) Z-direction displacement tracking of UVCS over multiple cycles. (c) Pitch angle tracking of UVCS over multiple cycles. (d) Rotation angle tracking of input link over multiple cycles.

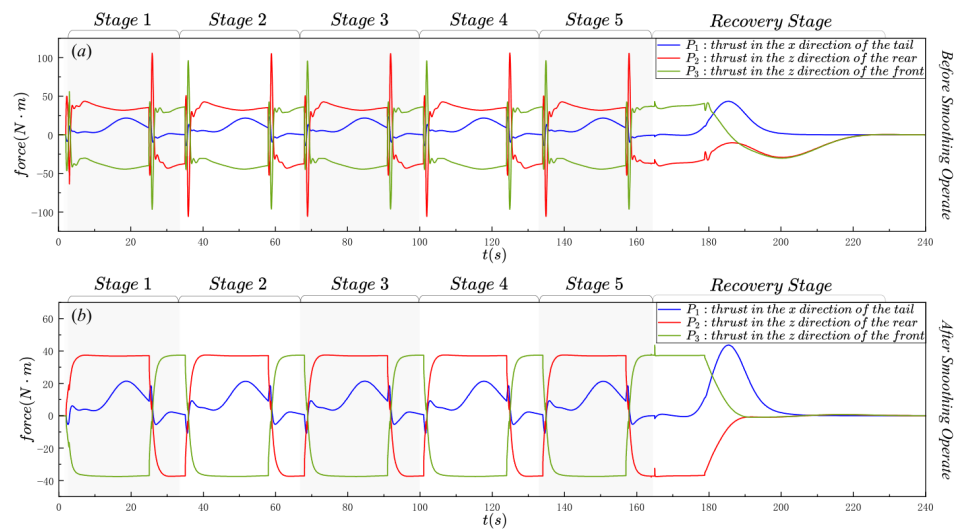


Figure 10. Comparison of simulation results regarding whether a smoothing operator is applied to the input force: (a) before smoothing operator, (b) after smoothing operator.

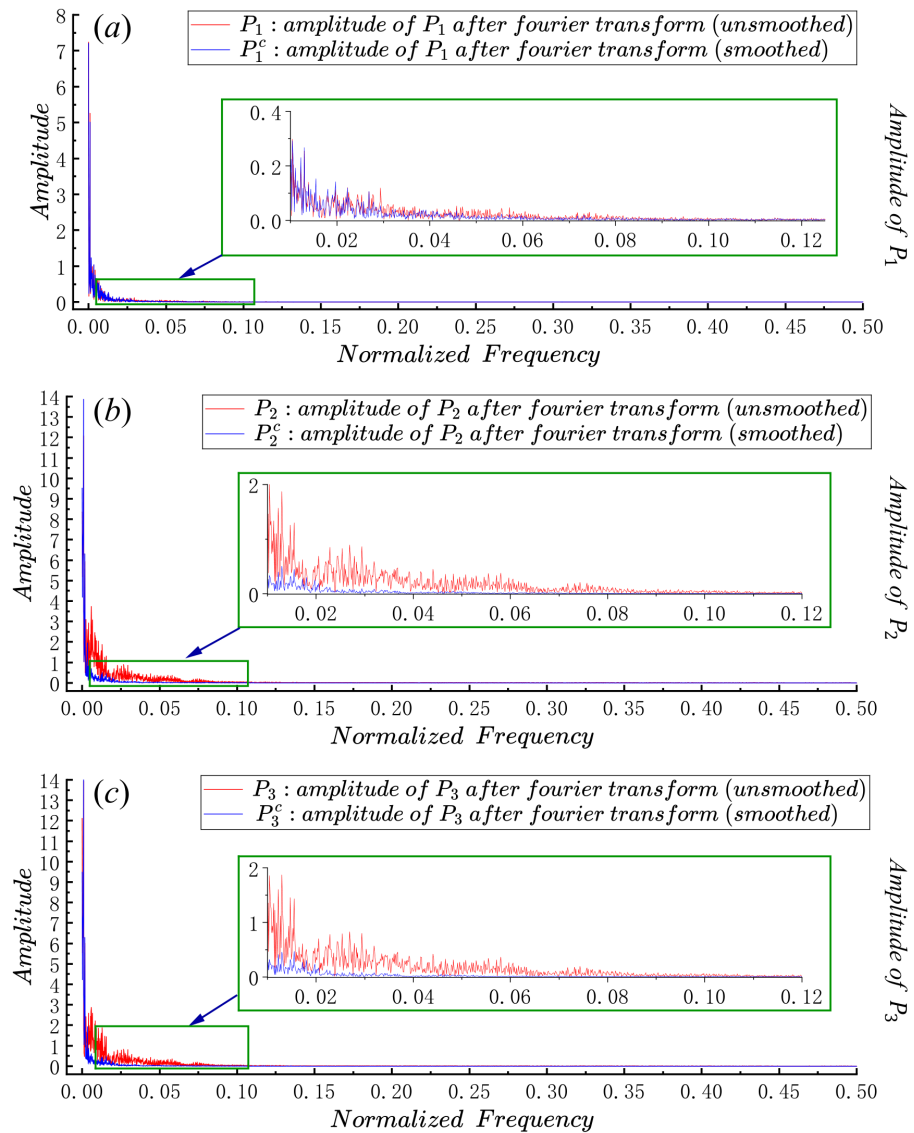


Figure 11. Comparison of Fourier transform spectrum analyses regarding whether a smoothing operator is applied to the input force: (a) comparison of P_1 (Tail-mounted X-direction), (b) comparison of P_2 (Rear Z-direction), (c) comparison of P_3 (Front Z-direction).

Table 4 compares the proportion of high-frequency energy in the output forces of each thruster before and after smoothing. Specifically, the high-frequency energy proportion of P_1 decreases from 0.0008 to 0.0003, with an optimization rate of 62.5%; that of P_2 drops from 0.0061 to 0.0001, achieving an optimization rate of 98.4%; and that of P_3 declines from 0.0047 to 0.0001, with an optimization rate of 97.9%.

Table 4. Comparison of high-frequency energy proportions for frequency bands P_1 , P_2 , and P_3 before and after applying smoothing to the output waveform data. Values are rounded to three decimal places; the reduction percentage is calculated as $\text{Reduction Percentage} = \frac{\text{Before} - \text{After}}{\text{Before}} \times 100\%$.

Condition	P_1	P_2	P_3
Before smoothing	0.0008	0.0061	0.0047
After smoothing	0.0003	0.0001	0.0001
Reduction (%)	62.5	98.3	97.9

This paper focuses on the design and application of the bionic collector, and all the displacement and angle simulation results presented in the paper are based on the output forces after smoothing processing. Comparative analysis shows that the input forces under the smoothing condition can slightly alleviate the instability of the response curves of the output state variables, but the improvement is limited. Given that the main purpose of smoothing processing is to facilitate the controller in realizing force signals, this paper does not present the results related to the output of state variables without smoothing processing.

All the simulations were performed in the MATLAB R2024b environment, with system dynamics modeled in Simulink. The LQR controller gain matrix K was computed by calling the built-in *lqr* function, which solves the algebraic Riccati equation to determine the optimal feedback gain based on the specified weighting matrices Q and R .

4. Experiment

Based on the conceptual design of the collector, the physical prototype fabricated using 3D printing technology is shown in Figure 12. To verify the opening and closing performance of the collector, a corresponding experimental testbed was constructed in this study. The specific experimental setup is depicted in Figure 13: the collector body is fixed on the motor shaft through a control bracket, while the motor is suspended under a crane via a motor bracket. The entire assembly of the motor and collector can be deployed into the water tank by the crane. This motor effectively simulates the pitching motion of the underwater vehicle, and its rotation can actuate the attitude change of the collector, thereby realizing the opening and closing actions of the collector. Meanwhile, an encoder is connected to the rotating joint of the upper jaw of the collector to monitor the opening–closing angle of the upper jaw in real-time, with data collected and processed by the host computer. The motion trajectory of the collector in the experiment is shown in Figure 14a, with the initial state at the horizontal position (Figure 14b), the open state (Figure 14c), and the closed state (Figure 14d). It can be observed that the collector is capable of realizing opening and closing movements in the water tank.

To verify the opening and closing performance of the collector, a systematic post-processing analysis of the experimental data was conducted (Figure 15). First, since the encoder records the rotation angle of the collector's upper jaw, it is necessary to determine the mapping between ϕ_1 and ϕ_3 (Figure 15a). Consequently, the single-cycle simulation curve of ϕ_3 was further derived (Figure 15b).

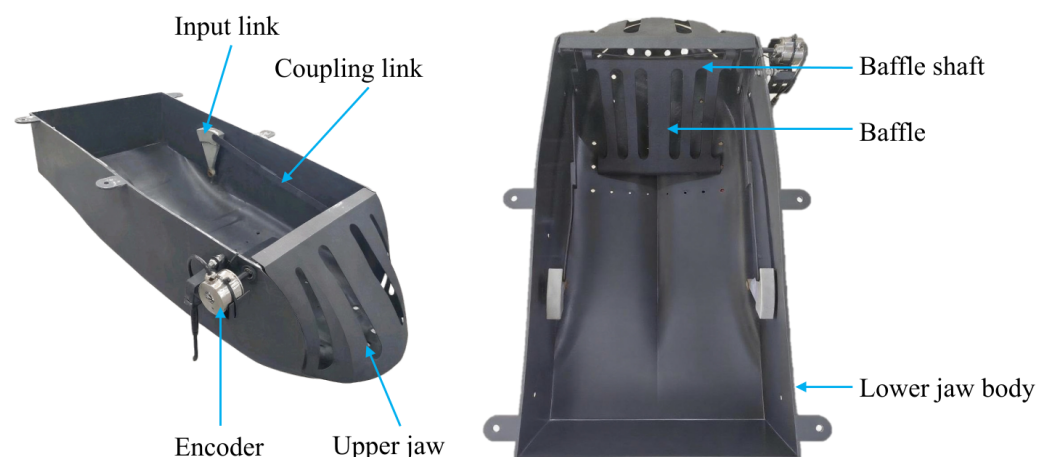


Figure 12. Photographic representation of 3D-printed collector prototype.

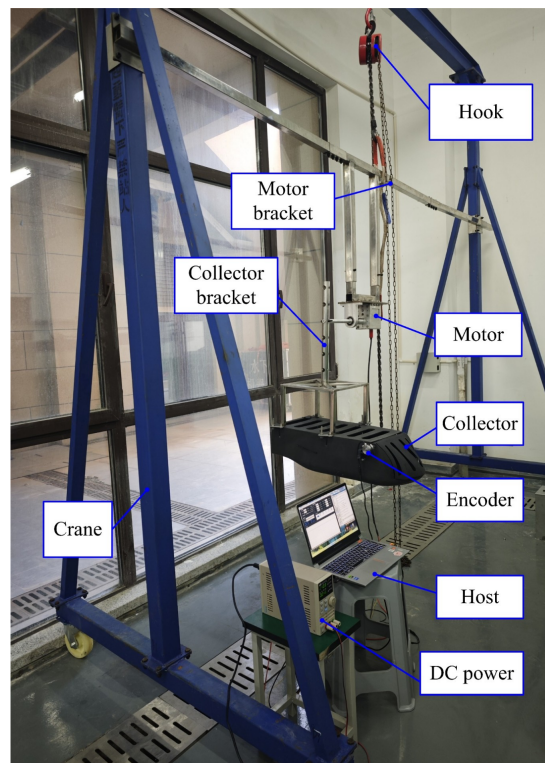


Figure 13. Schematic diagram of hardware configuration for water tank experiment of the collector.

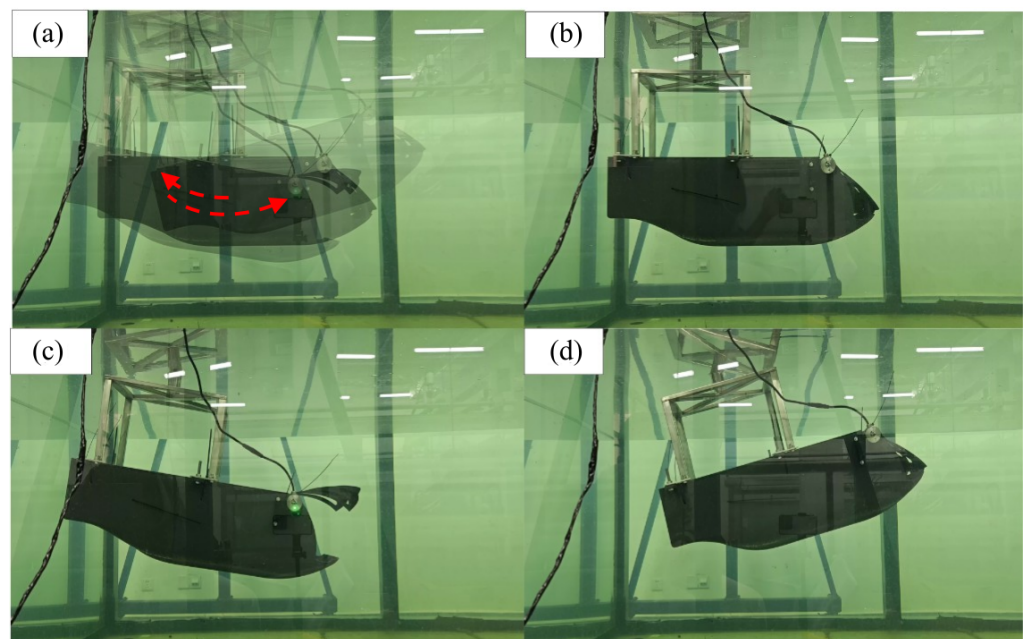


Figure 14. Schematic diagram of the core working postures of the collector in the water tank: (a) Illustrates the overall movement trajectory of the collector: it first starts from a horizontal posture with a counterclockwise activation, followed by a clockwise shutdown. (b) Shows the initial horizontal posture of the collector. (c) Displays the activated posture of the collector, where the upper jaw structure is open. (d) Presents the closed posture of the collector, where the upper jaw structure is closed.

Second, a comparative verification between the simulation and experimental data was performed. The theoretical simulation curve and the encoder-measured data (Figure 15c) show high consistency in the overall trend, confirming the effectiveness of the collector's opening and closing actions. However, there is a systematic deviation of approximately

0.06 rad between the simulation and experimental curves. Additionally, an overshoot of about 0.03 rad appears in the experimental curve during the closing process. The systematic deviation is mainly attributed to inherent sensor errors and machining inaccuracies, with the latter being the dominant factor. Machining position deviations cause fitting dimension errors, and cumulative tolerance stacking leads to actual opening angles deviating from the design values. The overshoot occurs because closing the collector requires upward movement, during which water flow exerts a squeezing force on the upper jaw. Moreover, the upper jaw is made of nylon material, which exhibits high flexibility and is prone to deformation, resulting in angular deviations. Despite these deviations, the values remain within acceptable ranges.

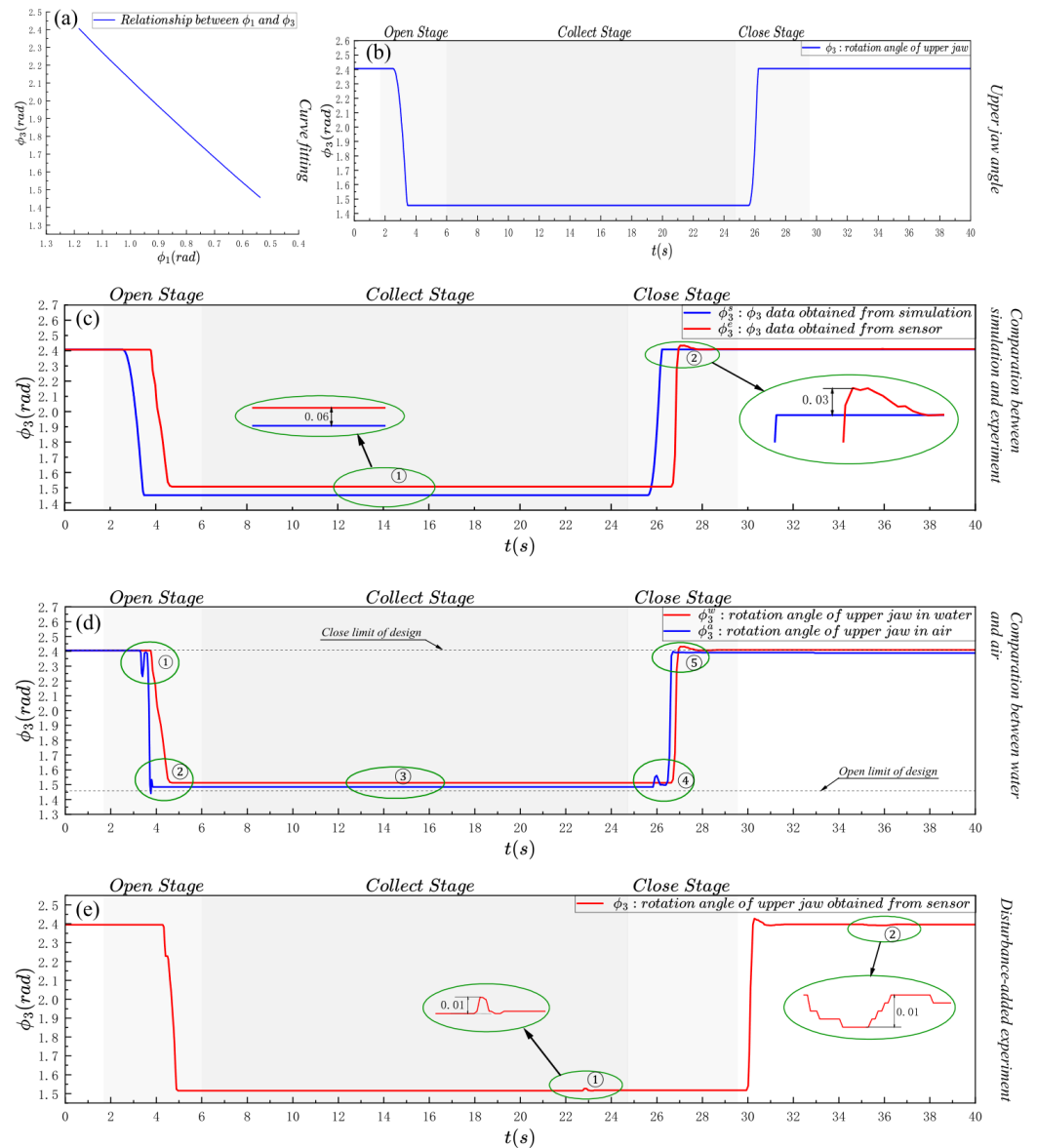


Figure 15. Analysis and comparison of the water tank experiment results for the collector: (a) Mapping relationship between the input link angle and output link (upper jaw) angle. (b) Simulation results of the upper jaw structure, derived from input link simulation under the collector's core working steps. (c) Comparison between the water tank experiment results and simulation outcomes. (d) Comparative analysis of the results in air versus water tank environments. (e) Experimental results under the applied disturbances.

Third, the influence of the medium environment on the opening and closing performance was evaluated. Comparison between the experimental curves of the collector's movements in air and water (Figure 15d) reveals a stroke deviation of about 0.02 rad due to differences in medium resistance. This deviation is minor and acceptable. Notably, the opening and closing curves in air show significant chattering phenomena, whereas the movements in water are relatively smooth. This can be explained physically: the low air resistance allows inertial and centrifugal forces to strongly affect the motor-driven opening and closing, causing larger chattering. In contrast, higher water resistance effectively suppresses these forces, resulting in smoother motions.

Finally, the system's robustness was validated by applying disturbances (Figure 15e). During the opening state (20–24 s), ± 0.35 rad rotation commands were applied to the motor to simulate the disturbances experienced by the UVCS. The resulting chattering in the collector's upper jaw rotation was only around 0.01 rad, indicating good robustness. Similarly, during the closing state (35–37 s), the same disturbance test showed chattering of approximately 0.01 rad, confirming excellent robustness in that state.

These experimental results demonstrate that the designed collector can achieve the intended opening and closing functions, maintain systematic deviations within reasonable ranges, and exhibit strong robustness across different media.

5. Conclusions

This paper addresses the key technical bottlenecks of traditional deep-sea mining equipment, such as large volume, high energy consumption, and severe environmental damage. To overcome these challenges, a novel bionic underwater collector design inspired by the mouth structure of Stomiidae is proposed. Structurally, a bionic opening–closing mechanism is constructed, integrating a streamlined upper jaw, lower jaw body, an input link with a relatively high center of gravity, and a four-bar linkage transmission. This design enables the collection of seabed minerals sized 1–12 cm solely through the vehicle's pitching motion without additional motor drives, overcoming high energy cost in traditional manipulator systems.

A comprehensive 4-DOF dynamic model of the UVCS is established. Leveraging the underactuated Pendubot framework, an LQR controller combined with a smoothing operator is designed to optimize control performance. The simulation results demonstrate displacement tracking errors within ± 0.1 m (surge) and ± 0.025 m (heave). Moreover, multi-cycle simulations confirm stable operation over five consecutive collection cycles, with a 62.5–98.4% reduction in high-frequency thruster output components, enhancing control smoothness and practicality.

Experimentally, a water tank platform verifies the collector's opening and closing performance. Encoder measurements show strong agreement with simulations, exhibiting a minimal systematic deviation of 0.06 rad and a closing overshoot of 0.03 rad, both within acceptable engineering tolerances. Comparative tests in air and water reveal only a 0.02 rad difference in stroke attributable to medium resistance, and disturbance tests under ± 0.35 rad inputs yield upper jaw angle chatter as low as 0.01 rad, demonstrating excellent robustness and environmental adaptability.

The design of UVCS offers a novel technical pathway to address the conflict between deep-sea resource development and marine ecological protection. Looking ahead, this technology can be further extended to frontier areas such as multi-collector collaborative operation, intelligent target recognition and selective collection, and adaptation optimization for extreme deep-sea environments. This will provide theoretical foundations and practical references for sustainable marine resource utilization and marine ecosystem conservation.

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Abbreviations

The following abbreviations are used in this manuscript:

UVCS	Underwater vehicle collector system
$r_{0,1,2,3}$	Rods of the four-bar linkage mechanism
$\phi_{0,1,2,3}$	Angles of the four-bar linkage mechanism
γ	Ground link angle
CG	Center of gravity of UVCS
CB	Center of buoyancy of UVCS
ρ	Density of water
g	Gravitational acceleration
η	State variable of the planar UVCS
$v_{v,c}$	Velocity vector of the vehicle and input link, respectively
J	Jacobian matrices from volume coordinates to generalized coordinates
p_{c2}	Position of center of gravity of the input link
l_{c2}	Distance from P_{c2} to joint J_2
l_t	Distance from the center of the thruster to CG
$J_{1,2,3}$	Rotation joints of UVCS
$\theta_{1,2}$	Pitch angle of UVCS and rotation angle of the input link, respectively
$l_{1,2}$	Distances between each joint
$q_{1,2}$	Angle between l_1 and the X-axis in volume coordinates, and angle between l_2 and l_{c2} , respectively
$m_{v,c}$	Mass of UVCS and mass of the input link, respectively
$m_{x,z,p}$	Added mass of UVCS in the x-direction, z-direction, and pitch angle direction, respectively
$I_y^{v,c}$	Moment of inertia of UVCS in the pitch angle direction and moment of inertia of the input link around the Y-axis, respectively
$d_{1,2,3}$	Water damping coefficients when the vehicle translates in the x-direction, z-direction, and undergoes pitch motion, respectively
d_4	Water damping coefficient coupled to the input link via four-link movement
$T_{(v,c)}$	Kinetic energy of UVCS and collector, respectively
$\bar{T}$	Total rigid-body kinetic energy of UVCS and collector
$W_{v,c}$	Gravity of UVCS and gravity of the input link, respectively
$B_{v,c}$	Buoyancy of UVCS and buoyancy of the input link, respectively
$M_{RB}^{v,c}$	Rigid-body inertial mass matrices of UVCS and the input link, respectively
M_{RB}	Combined rigid-body inertial mass matrix of UVCS and the input link
$C_{RB}(\nu)$	Coriolis and centrifugal force matrix of the rigid body
τ_{RB}	External force matrix of the rigid body
τ	External force matrix

$M(\nu)$	Inertial mass matrix of UVCS and the input link
$C(\nu)$	Coriolis and centrifugal force matrix of UVCS and the input link
$D(\nu)$	Water damping matrix
$g(\eta)$	Restoring forces and moments
M_{add}^v	Added mass matrix of UVCS
M_{add}	Added mass matrix of UVCS and the input link
$C_{add}(\nu)$	Coriolis and centrifugal force matrix for added mass of UVCS and the input link
τ_{add}	External force matrix of added mass
$M_\eta(\eta)$	Inertial mass matrix of UVCS and the input link in generalized coordinates
$C_\eta(\nu, \eta)$	Coriolis and centrifugal force matrix of UVCS and the input link in generalized coordinates
$D_\eta(\nu, \eta)$	Water damping matrix in generalized coordinates
$g_\eta(\eta)$	Restoring forces and moments in generalized coordinates
$e_{1,2}$	Equilibrium point of the open state and closed state, respectively

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