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Classification and Technical Characteristics Analysis of Collection Mechanisms for Water Surface Garbage Cleaning Robots

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Abstract

With the aggravation of urban water pollution, the research and application of water surface garbage cleaning robots have gradually emerged. Among them, the garbage collection mechanism, as a key module, directly affects the operational efficiency and environmental adaptability of the system. To address the complexity of garbage distribution in different water bodies, researchers have designed various types of collection mechanisms. This paper systematically reviews the current mainstream water surface garbage collection mechanisms from three perspectives: structural principles, advantages and disadvantages, and applicable scenarios. The mechanisms discussed include tipping-bucket type, conveyor-belt type, baffle type, robotic-arm sorting type, rotary-gathering type, and vortex type, which are further classified into external and embedded configurations according to their integration modes. Through comparative analysis, the technical features and adaptation trends of each mechanism are summarized. Furthermore, future research directions are proposed in terms of intelligent perception integration, multi-structure collaboration, and green energy-driven solutions, aiming to promote the intelligentization and practical development of cleaning robot systems.

Keywords: water surface garbage; cleaning robot; collection mechanism.

Introduction

With the worsening of urban water environment pollution, floating debris on water surfaces has exerted a broad impact on ecosystems, water quality, and landscapes. Traditional manual salvage methods are characterized by low efficiency and high labor intensity, making them inadequate for large-scale and high-frequency cleaning demands. Consequently, water surface garbage cleaning robots have become an important development direction in water environment management.

Within these robotic systems, the garbage collection mechanism serves as the core component linking perception, decision-making, and execution. Its structural design and performance directly determine the cleaning efficiency and environmental adaptability of the system. To address variations in garbage types and distribution under different water conditions, researchers have proposed a variety of representative collection mechanisms focusing on structural configurations, motion mechanisms, and functional extensions.

This paper analyzes the current mainstream water surface garbage collection mechanisms from three perspectives—structural principles, advantages and disadvantages, and applicable scenarios. It systematically classifies these mechanisms into tipping-bucket, conveyor-belt, baffle, robotic-arm sorting, rotary-gathering, and vortex types, establishing a clear comparative framework. Furthermore, the paper discusses future development trends, providing technical references for subsequent system optimization and engineering applications.

1. Structural Classification Description

To systematically analyze the types and application characteristics of current water surface garbage collection mechanisms, this paper summarizes and compares them from three dimensions: structural principles, advantages and disadvantages, and applicable scenarios.

On this basis, according to the integration method of the collection device on the robot, the mechanisms can be divided into two main categories:

External Structures: Examples include tipping-bucket, conveyor-belt, baffle, and robotic-arm sorting types. In these designs, the collection device is mounted outside the hull, offering straightforward structure, easy replacement, and convenient maintenance. They are particularly suitable for open water areas and the centralized collection of medium to large debris.

Embedded Structures: An example is the vortex type, in which the device is tightly integrated with the hull structure. By utilizing water flow control, it achieves debris suction and separation, making it suitable for confined spaces or enclosed water bodies with stable flow conditions.

2. External Collection Structures

2.1 Tipping-Bucket Type

Structural Principle:

The tipping-bucket collection mechanism typically employs a crank-slider system to drive the bucket for garbage scooping and flipping operations. This mechanism consists of a drive arm, slide rod, guide track, linkage system, and a front-end bucket. When the cleaning robot navigates to a garbage-concentrated area, the bucket, driven by the mechanism, first performs an underwater scooping action, then lifts along a predefined trajectory and flips backward to dump the collected debris into the onboard garbage storage compartment. In some designs, the bucket is combined with a sieve-like structure, enabling the device to mimic the operational path of manual netting through bottom-up scooping and backward flipping, thereby achieving the processes of garbage retrieval, transfer, and unloading[2][11].

Advantages and Disadvantages:

The tipping-bucket structure features a clear motion path and a mechanically stable and reliable design, making it particularly suitable for periodic and continuous operations. The crank-slider mechanism offers excellent controllability and trajectory repeatability, facilitating simulation optimization and parameter tuning. The flipping action is precisely controlled, ensuring high unloading efficiency while minimizing adhesion and clogging issues, which makes it ideal for collecting small to medium-sized floating debris[2].

However, this structure has certain limitations. Its fixed bucket path leads to poor adaptability, and when the debris is scattered or consists of large floating objects, the effective collection range is limited. Moreover, the entire mechanism occupies considerable space, involves complex assembly, and imposes high demands on power matching and structural rigidity[11].

Applicable Scenarios:

The tipping-bucket mechanism is well-suited for water bodies such as urban lakes, rivers, and ponds where debris is relatively concentrated and the surface is calm. It is particularly effective in operations requiring fixed-point and periodic cleaning, as it enables a stable and efficient mechanical collection and unloading process. Considering its mature design and ease of maintenance, this mechanism is suitable as a foundational collection module for low- to medium-speed garbage cleaning robot platforms.

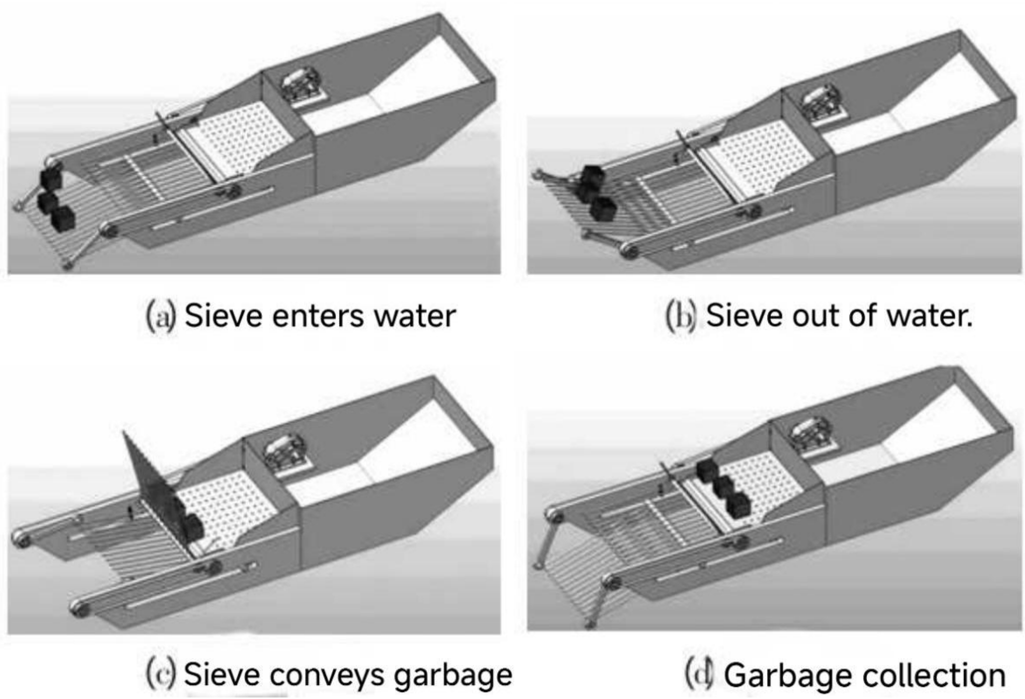

Figure 1 Operating Principle of the Tipping-Bucket Cleaning Vessel[2]

2.2 Conveyor-Belt Type

Structural Principle:

The conveyor-belt collection mechanism primarily consists of a driving and driven roller, a mesh-type conveyor belt, a drive motor, a supporting frame, and anti-slip devices. During operation, the front end of the conveyor belt is submerged in water at a certain angle with the water surface. As the vessel advances, floating debris on the surface is naturally guided to the lower end of the conveyor belt. Driven by the motorized system, the belt circulates to transport the debris into the onboard storage compartment. To prevent lightweight debris from slipping off, some designs feature bucket-shaped anti-slip paddles or V-shaped elastic structures on the belt surface, thereby ensuring efficient transfer and automatic unloading[5][10].

Advantages and Disadvantages:

This structure offers excellent continuity, a high degree of automation, and compatibility with visual recognition and sorting systems, making it a crucial component for achieving intelligent water surface debris collection. Additionally, the conveyor belt's length and inclination can be flexibly adjusted according to the vessel's dimensions, providing strong adaptability. However, system stability is significantly affected by factors such as water flow fluctuations, entangled aquatic plants, and the accumulation of floating algae, which may cause jamming or slipping. Therefore, enhanced anti-corrosion and anti-adhesion design for the conveyor chain materials is necessary[8][10]. Furthermore, when the system relies on water-wheel-driven power, water flow speed must be carefully considered, as both excessive and insufficient flow rates can impair transfer stability.

Applicable Scenarios:

The conveyor-belt collection mechanism is suitable for urban landscape lakes, park waterways, and irrigation channels where floating debris density is moderate and water flow remains relatively stable. When integrated with image recognition and robotic-arm sorting systems, it can achieve preliminary intelligent classification of floating waste, facilitating the transition from simple "salvage" to "recycling." In water bodies with a certain current velocity, the use of water-wheel-driven systems offers good energy-saving performance and environmentally friendly characteristics[5][10].

2.3 Baffle Type

Structural Principle:

The baffle-type collection mechanism typically consists of guiding baffles, an open mesh box, a fixed cabin, and a height-adjustable structure. The basic working principle involves installing one or more pairs of guiding baffles at the front end of the vessel, extending outward from both sides at a specific angle. As the vessel moves forward, the floating debris on the water surface is funneled toward the center of the bow and passively collected by the open mesh box. The baffles are usually designed with a mesh pattern to maintain good flow-guiding performance while minimizing water resistance. In some designs, lifting tracks or sliding rails are incorporated, allowing the mesh box and baffles to adjust their height according to the depth of floating debris, thus adapting to various floating conditions[3].

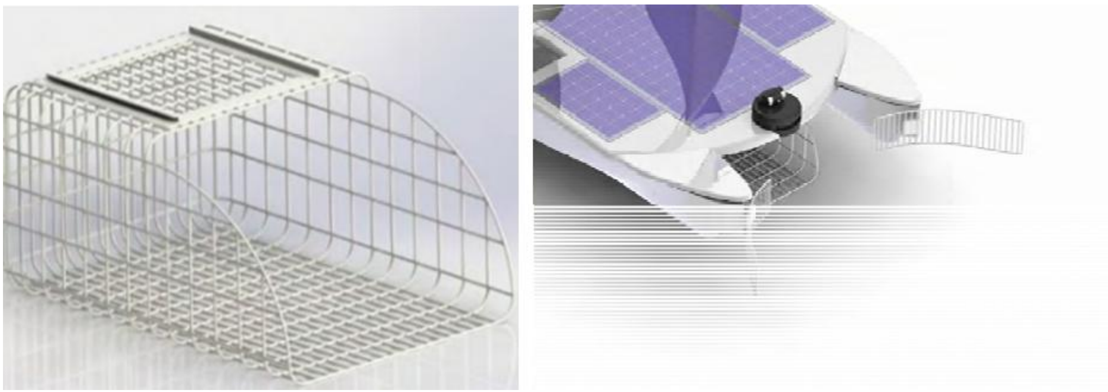

Figure 2 Design of Cleaning Mesh Box and Gathering Mechanism[3]

Advantages and Disadvantages:

The baffle-type structure features significant advantages, including simple design, low energy consumption, and high operational stability, making it particularly suitable for long-duration cleaning operations at low to medium cruising speeds. Since it lacks active mechanical transfer components, mechanical complexity and maintenance costs are greatly reduced, and environmental adaptability is enhanced.

However, this structure has high dependency on vessel speed and debris distribution. When debris is sparsely distributed or poorly aligned with the baffle's guiding direction, collection efficiency is greatly reduced. Furthermore, as a passive collection method, it is less effective in handling high-density, large-sized, or sortable waste. In water bodies with abundant weeds, lotus leaves, or algae, guiding efficiency may decline, and clogging risks may arise[8].

Applicable Scenarios:

The baffle-type structure is suitable for open water surfaces with stable flow and relatively concentrated or predictable debris distribution, such as urban landscape lakes, park artificial rivers, and man-made reservoirs. It is particularly applicable to low-cost platforms lacking image recognition or mechanical grabbing capabilities, or as an "end-stage" gathering device in medium- to low-frequency patrol routes. Additionally, when combined with sliding rails or lifting structures, it can expand its operational range under different water levels while maintaining low energy consumption[3].

2.4 Robotic-Arm Sorting Type

Structural Principle:

The robotic-arm sorting collection mechanism primarily consists of an identification system, a classification module, a robotic arm actuator, and an onboard storage system. Equipped with cameras mounted on the vessel, this system captures water surface images, which are processed by a convolutional neural network (CNN) model to identify and classify debris targets. The robotic arm's end effector then performs grabbing, transferring, and depositing actions according to the classification results. The garbage storage compartments are arranged on both sides of the catamaran, separated into categories such as plastic, metal, glass, paper, organic waste, and hazardous waste, enabling preliminary sorting at the collection stage[4]. Under the coordination of the main control system, the vessel autonomously navigates to the target area, stops when debris is detected, and executes the sorting process.

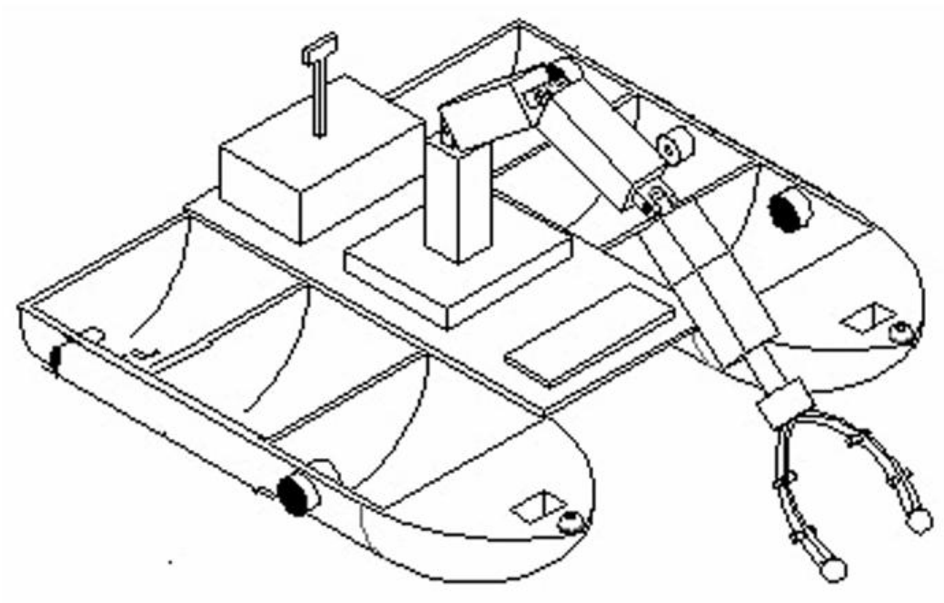

Figure 3 3D Model of the Robotic-Arm Sorting Cleaning Robot[4]

Advantages and Disadvantages:

The primary advantage of this structure lies in its integration of collection, recognition, and sorting into a fully intelligent operation workflow. It prevents mixed waste transportation, significantly reduces the burden of downstream classification, and enhances recycling efficiency and resource utilization. Moreover, its recognition accuracy is relatively high, with some experiments reporting an identification rate exceeding 92%, demonstrating strong classification performance and engineering potential.

However, this structure imposes high requirements on both hardware and software systems. It needs a high-performance computing platform to support CNN-based recognition models, and the control logic is relatively complex. Recognition errors may occur with densely stacked, transparent, reflective, or visually similar debris types. Additionally, dynamic water surfaces or strong lighting and shadow interference can affect system stability. The robotic arm also requires sufficient operational space, making layout planning crucial[4].

Applicable Scenarios:

The robotic-arm sorting mechanism is suitable for small urban rivers, scenic lakes, and other water bodies where both environmental aesthetics and recycling efficiency are highly valued. It is particularly well-suited for intelligent autonomous platforms, enabling not only automatic debris collection but also on-site sorting, aligning with current ecological management and waste classification policies. For medium-sized water areas with relatively calm surfaces, this structure can complete a comprehensive debris processing loop without human intervention.

2.5 Rotary-Gathering Type

Structural Principle:

The rotary-gathering mechanism features a pair of rotating collectors located at the front of the vessel. These collectors are symmetrically arranged on the left and right sides and driven through gear engagement to achieve a counter-rotating "paddling" flow-guiding effect. The operational principle is as follows: when the vessel enters an area with floating debris, the rotating collectors actively gather debris from both sides toward the center, guiding it into a central rotary collector. The rotary collector then transfers the debris into the onboard storage box, completing the entire process from flow guiding to debris collection[9]. The mechanism utilizes motors to drive synchronous belts and gear systems, ensuring coordinated movement.

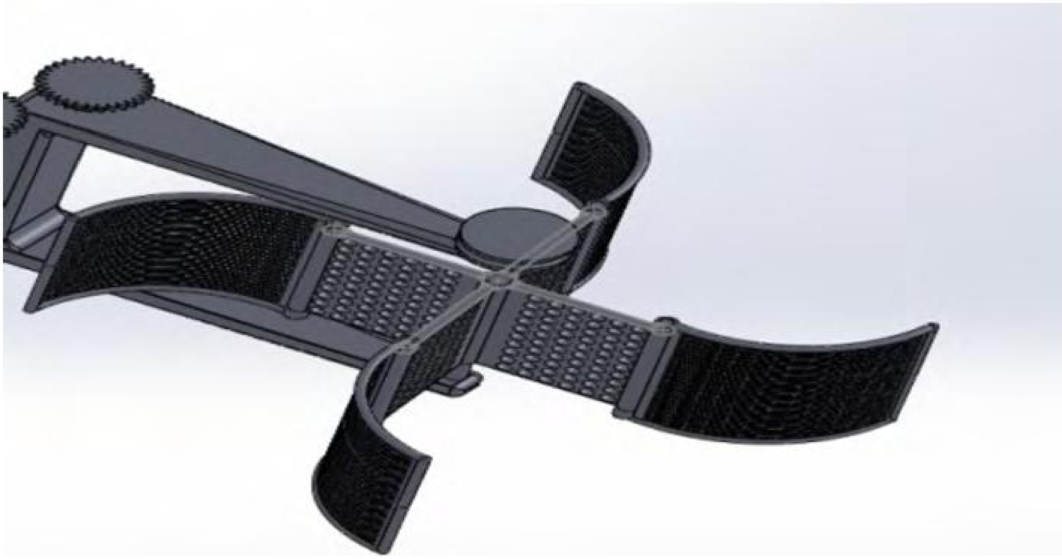

Figure 4 Rotary Gathering Device[9]

Advantages and Disadvantages:

The rotary-gathering structure enables proactive, continuous, and efficient debris aggregation at the vessel's front end, without relying on external flow-guiding conditions, thereby exhibiting strong autonomy and real-time responsiveness. Compared to traditional static baffles or trawl nets, this mechanism is more suitable for real-time cleaning of multidirectional floating debris. Its compact design and high collection efficiency make it ideal for integration into small- to medium-sized platforms.

However, the structure imposes stringent requirements on the precision of the synchronous drive system; any speed mismatch between the two collectors may destabilize the flow-guiding path. Additionally, when dealing with adhesive or large debris, the rotary paddling effect may be less effective than conveyor-belt or grab-based mechanisms. The system is also sensitive to easily entangled objects such as aquatic weeds or soft algae, posing a risk of clogging[9].

Applicable Scenarios:

The rotary-gathering mechanism is suitable for urban landscape waters, ponds, and reservoirs where floating debris is scattered but requires continuous and efficient cleaning. It is particularly advantageous in environments where debris drifts randomly and cleaning paths are not fixed. Owing to its strong structural adaptability, this mechanism can be integrated with remote-controlled platforms and solar-powered systems, offering potential for intelligent upgrades and practical engineering applications.

2.6 Trawl-Net Type

Structural Principle:

The trawl-net collection mechanism typically consists of a flexible net bag or mesh frame attached to the rear of the vessel. Utilizing the water flow generated during navigation, floating debris is passively guided into the net, achieving debris collection without active mechanical components. The collection device is semi-fixed to the vessel, allowing it to swing naturally with the current, and can be easily retrieved and cleaned through simple operations.

Figure 5 Single Trawl-Net Cleaner "Jellyfishbot"

Advantages and Disadvantages:

The trawl-net structure offers the advantages of simple construction, low energy consumption, and ease of deployment, making it well-suited for integration into lightweight unmanned vessel platforms. Its operation is straightforward, and maintenance costs are minimal, making it ideal for high-frequency, low-intensity routine cleaning tasks.

However, its collection efficiency heavily depends on the vessel's continuous forward motion and water flow conditions. It cannot actively collect debris when stationary and performs less effectively against semi-submerged or widely scattered waste. Additionally, in waters with waves, aquatic vegetation, or numerous obstacles, the flexible net bag is prone to drifting or entanglement, which may compromise cleaning stability and operational safety.

Applicable Scenarios:

The trawl-net structure is best suited for open and calm water surfaces, such as urban lakes, port docks, and artificial ornamental ponds. It excels in patrol-style, coverage-based daily cleaning operations, particularly in scenarios with low debris density but frequent cleaning requirements. This structure is also commonly used on small unmanned vessels as a cost-effective and flexible debris collection solution.

3. Embedded Collection Structures

3.1 Vortex Type

Structural Principle:

The vortex-type garbage collection mechanism utilizes fluid dynamics principles, generating negative pressure through a pump or propeller to create a vortex that attracts surrounding floating debris into the collection chamber. This structure typically consists of an inlet, a vortex-generating device (such as a submersible pump or high-speed rotating propeller), a debris filter, and a drainage system. During operation, the device floats on the water surface, forming a liquid level difference between the inside of the collection chamber and the external water body by controlling the relationship between drainage flow rate and immersion depth. This level difference, combined with vortex suction, draws debris into the chamber, where it is separated from the water via the filter[1][6][7].

Advantages and Disadvantages:

The vortex-type structure offers a compact design, clear operating principles, low energy consumption, and strong adaptability. Experimental studies have shown that within certain ranges of flow velocity and inflow angle (e.g., 0–2.5 m/s, $-10°$ to $10°$), its drainage efficiency surpasses that of conventional pump-pressure systems, demonstrating good integration potential and engineering applicability [1]. Additionally, this type of device is often integrated with floating platforms, automatic water level adjustment, solar power supply, and remote control modules, enabling round-the-clock, intelligent debris collection[6][7].

However, the structure is highly sensitive to vortex formation conditions. Excessive flow velocity or a large deviation in inflow angle ($\pm 15°$) may destabilize the vortex and significantly reduce suction efficiency. Furthermore, clogging of the filter or drainage path by debris can disrupt suction continuity. Since the suction primarily relies on liquid level differences, the device is less effective against fast-moving or submerged debris, presenting certain limitations in cleaning targets[1].

Applicable Scenarios:

The vortex-type structure is suitable for small or enclosed water bodies with slow flow and stable surfaces, such as ornamental lakes, urban ponds, reservoirs, and irrigation channels. It is particularly effective in areas with moderate debris density and relatively uniform distribution. Featuring miniaturization, automation, and remote-control capabilities, this structure is well-suited for deployment in intelligent water environment management systems and holds significant engineering application potential.

4. Conclusion

As a core component of water surface garbage cleaning robots, the performance of the collection mechanism directly determines the overall operational efficiency, adaptability, and level of intelligence of the system. In recent years, driven by the growing demand for urban water environment management, various collection structures have undergone continuous development and extensive exploration in terms of design principles, mechanical implementation, material selection, and functional expansion. This paper reviews six representative types of collection mechanisms, ranging from traditional tipping-bucket, conveyor-belt, and baffle structures to more advanced mechanisms featuring intelligent recognition and control capabilities, such as robotic-arm sorting, rotary-gathering, and vortex types.

At present, each type exhibits distinct development characteristics. Low-cost, simple passive structures remain widely applicable in small lakes and park water bodies, while intelligent structures integrated with image recognition and autonomous control demonstrate superior precision and scalability. Meanwhile, the introduction of novel concepts such as vortex suction, floating adjustment, and modular assembly has further enriched the implementation approaches, driving collection mechanisms toward lightweight, intelligent, and system-oriented development.

Future research on water surface garbage collection mechanisms can focus on several key areas:

(1) deep integration of structure and perception systems to achieve an integrated "recognition–localization–sorting" workflow;

(2) enhancement of stability under complex water conditions, particularly ensuring performance in fluctuating surfaces, large debris, and mixed pollutants;

(3) development of collaborative mechanisms that coordinate multiple collection methods to address dynamic scenarios and diversified tasks in practical operations. Furthermore, combining artificial intelligence algorithms, IoT platforms, and green energy supply to build a water surface cleaning system with a closed-loop capability of "perception–decision–execution–evaluation" will become an important direction for future advancement.

In summary, as the core functional unit of water surface garbage cleaning robots, the collection mechanism not only carries the engineering mission of environmental remediation but also embodies the potential for cross-innovation in intelligent manufacturing and green technologies, offering broad prospects for research and application.

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