DESIGN AND EXPERIMENT OF A NEW TYPE OF SORTING, EVISCERATION, AND CLEANING EQUIPMENT FOR SEA CUCUMBER

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一种新型海参分拣除脏清洗设备的设计与试验

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ABSTRACT

In sea cucumber production lines, manual sorting, de-sanding, and organ removing operations still predominated, severely limiting production efficiency and posing significant risks to product consistency and hygiene. This paper introduced a novel piece of equipment for sea cucumber sorting, de-sanding, organ removing, and washing. Employing an innovative process combining "automatic sand mouth removal + high-pressure water jet washing + hook-assisted organ removal," the equipment adapted well to sea cucumbers of various sizes and conditions, offering high versatility and facilitating an automated, efficient, and standardized processing workflow. Moreover, due to the high sensitivity to the sea cucumber's external shape and posture and the complexity of the background caused by residues during the de-sanding and organ removing process, which further complicated the recognition of the sea cucumber's sand mouth, this study proposed a sand mouth recognition algorithm for complex backgrounds. Utilizing tiered recognition technology, the algorithm precisely located the sea cucumber's sand mouth following the extraction of its position through artificial intelligence, significantly enhancing the success rate of recognition. Experimental results indicated that the prototype of this equipment increased the speed of de-sanding and organ removing by 107.8% compared to existing integrated sea cucumber washing and cutting equipment. The cleaning effectiveness was excellent, with a high sea cucumber cleaning acceptance rate of 91%, which was an increase of 6.125% over manual sorting, de-sanding, and organ re-moving methods, and the work efficiency increased more than ninefold, achieving the anticipated outcomes.

摘要

在海参生产线上，人工分拣除脏操作仍占据主导地位，这一现状严重制约了生产效率，也给产品的一致性和卫生带来了巨大风险。本文设计了一种新型海参分拣除脏清洗设备。通过"切割沙嘴 + 高压水冲洗 + 钩子辅助除脏"的创新工艺，对不同规格和状态的海参均具有良好的适应性，具备高度通用性，实现了海参的自动化、高效、标准化加工流程。同时，针对海参外形和姿态特征的高敏感度，以及除脏过程中产生的脏污导致背景复杂、海参沙嘴识别困难的问题，提出了一种复杂背景下的海参沙嘴识别算法。该算法利用分级识别技术，在提取海参位置后，通过人工智能精准定位海参沙嘴，显著提高了识别成功率。实验结果表明，该实物样机的除脏速度较现有海参清洗剖切一体化设备提升了 107.8%；清洗效果良好，海参清洗合格率高达 91%，较人工分拣除脏清洗合格率提高 6.125%，工作效率提高 9 倍以上，达到了预期效果。

INTRODUCTION

Sea cucumbers, recognized for their high protein and low fat content, are considered a marine delicacy with an increasingly growing market demand *(Xu et al., 2013)*. However, the processing of sea cucumbers is intricate, particularly in the stages of sorting, de-sanding, organ removal, and washing. These processes are predominantly manual, characterized by low efficiency and high labor intensity *(Liu et al., 2023)*. Impurities such as sand and internal organs within the sea cucumber, if not thoroughly removed, adversely affect the quality and palatability of the product *(Sun et al., 2019)*. Traditional manual methods of sorting, de-sanding, and organ removal not only are inefficient but also prone to damaging the sea cucumbers, leading to inconsistent product quality. Moreover, manual washing fails to ensure uniformity in the size of the cuts on the sea cucumbers, further impacting the standardization of subsequent processing steps (see Fig. 1).

In recent years, as the sea cucumber industry chain has evolved, numerous enterprises have begun to explore the research and application of mechanized and auto-mated processing equipment.

Fig. 1 - A manual labor scene of sea cucumber organ removal

Currently, in the processing of lightly dried sea cucumbers, the sequence involves temporary cultivation, manual de-sanding and organ re-moving (evisceration), flexible bubble automatic washing (*Xu et al., 2016*), multiple washes (including saltwater rinses), boiling (cooked in 85°C boiling water), followed by baking or sun-drying, steam drying, quality-based grading, and packaging (*Li et al., 2016*). Similarly, instant sea cucumbers undergo a process that includes temporary cultivation, evisceration, washing, blanching for shaping, curing, flash freezing, sealing, packaging, and refrigerated storage (*Tang et al., 2012*).

In recent years, as the industry chain has progressively upgraded, many sea cucumber processing enterprises have not only enhanced the construction of aquaculture bases but have also invested heavily in the establishment of automated sea cucumber processing lines (*Wang et al., 2020; Yu et al., 2016; Wu et al., 2023; He et al., 2019*). This has increased production capacity and continuously improved processing techniques, providing consumers with safe, healthy, and convenient sea cucumber products. However, existing devices still exhibit significant shortcomings in terms of cleaning quality, production efficiency, and automation level.

The cleaning equipment designed by Xu Wenqi et al., which employs compressed air bubbles emitted from the bottom of a tank, suffers from uncontrollable foam density and may induce stress responses in sea cucumbers, such as evisceration, thus compromising the quality of the cleaned sea cucumbers (*Xu et al., 2009*). The rotary brush cleaning device developed by Wang Hongyu et al., although capable of washing and slicing sea cucumbers, requires pre-treatment steps before pickling and cannot be applied directly to live sea cucumbers. Additionally, the rotary brush structure is highly likely to damage the ventral foot of the sea cucumbers (*Wang et al., 2018*).

Xu Jing et al. proposed a technique for shedding the skin of fresh or frozen East Sea sea cucumbers, covering steps such as fixation, mechanical abrasion, initial decontamination, enzymatic peeling, further de-contamination, and repeated enzymatic treatment. However, the enzymatic peeling strategy damages the superficial tissue characteristics of the sea cucumbers, affecting their appearance and taste (*Xu et al., 2013*).

Yang Sheng et al. (2024) developed an integrated sea cucumber washing and slicing machine that utilizes high-pressure water mist nozzles and ultrasonic generators to clean both the surface and internal sand of the sea cucumbers. Yet, this equipment requires multiple steps such as flipping, washing, and slicing during operation, leading to low work efficiency and failing to meet operational efficiency requirements. The injection-type equipment used in the Kansai region of Japan, although ensuring the quality of processed sea cucumbers, is cumbersome and unsuitable for assembly line production (*Xue et al., 2022*).

Notable advances include Ronel S. Pangan et al.'s processing technology package (preparation tables, boiling devices, etc.), which improves efficiency, quality, and cost-effectiveness (*Ronel et al., 2017*). Akhirman et al.'s new cleaning technology with soft brushes to reduce surface damage (*Akhirman et al., 2021*) and Xu Zhang et al.'s water jet cleaning technology, which removes impurities while preserving surface integrity - optimal results come from parameter optimization (pressure, target distance, etc.) (*Zhang et al., 2021*).

Consequently, the development of an efficient, automated sea cucumber processing equipment that performs sorting, de-sanding, organ removal, and washing is of significant importance for enhancing processing efficiency, reducing labor costs, and ensuring product quality in the sea cucumber industry.

This paper introduces a novel piece of equipment designed for these purposes, which utilizes an innovative process comprising "automatic sand mouth removal via cutting, high-pressure water jet washing, and hook-assisted organ removal." This equipment integrates machine vision technology with intelligent control systems to automate the sorting, de-sanding, organ removal, and washing of sea cucumbers.

Not only does this machine substantially increase production efficiency, but it also maintains the integrity of the sea cucumber's shape and the quality of its cleanliness, thereby providing a new solution for the automation of sea cucumber processing. This also provides feasible technological support for the advancement of agriculture 5.0 *(Taha et al., 2025; Adams et al., 2025)*.

MATERIALS AND METHODS

Structure and Principles of Sea Cucumber Sorting, De-sanding, Organ Removing, and Washing Equipment

In response to the rapid operational demands of the sea cucumber processing line, an innovative automated de-sanding, organ removing, and washing process has been developed. This process transitions from the traditional manual incision and hand removal of viscera to an automated system comprising automatic sand mouth removal, high-pressure water jet washing, and hook-assisted organ removal. The equipment designed for sorting, de-sanding, organ removing, and washing enables automated operations and combines machine vision for image recognition and processing *(Ma et al., 2009)*, intelligent control technologies, and mechanical execution mechanisms to ensure precise and rapid completion of large-scale sea cucumber cleaning tasks. The primary components of this equipment include a sorting feeding mechanism, a pressing conveyor mechanism, a de-sanding, organ removing, and washing mechanism, a washing transfer mechanism, and a frame platform, as illustrated in Fig. 2.

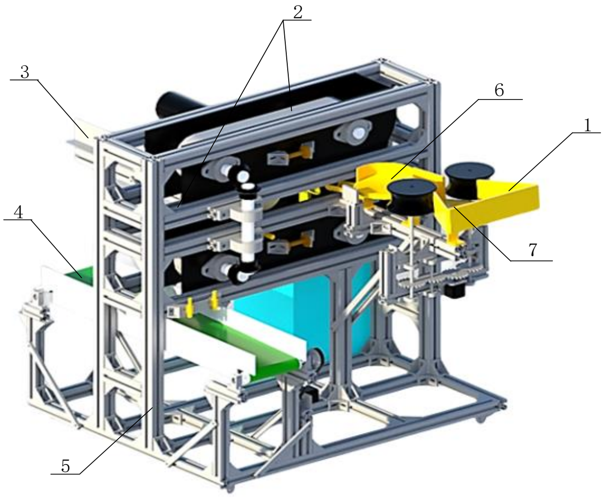


Fig. 2 - Schematic diagram of the sea cucumber sorting, de-sanding, organ removing, and washing equipment

1. Sorting feeding mechanism; 2. Pressing conveyor mechanism; 3. De-sanding, organ removing and washing mechanism; 4. Washing transfer mechanism; 5. Frame platform; 6. Turntable; 7. Chute.

A substantial quantity of sea cucumbers is deposited into the chute of the sorting feeding mechanism, where they are subsequently aligned on a turntable. Vision sensors identify and align the position of the sand mouth, after which they are transferred to the pressing conveyor mechanism. Here, the upper and lower claws of the pressing unit clamp the sea cucumber, positioning it for the cutting component of the de-sanding, organ removing, and washing mechanism to remove the sand mouth. The cleaning component then clears the viscera, and finally, the sea cucumber enters the washing transfer mechanism to complete the cleaning process. The functionality analysis of this equipment is depicted in Fig. 3.

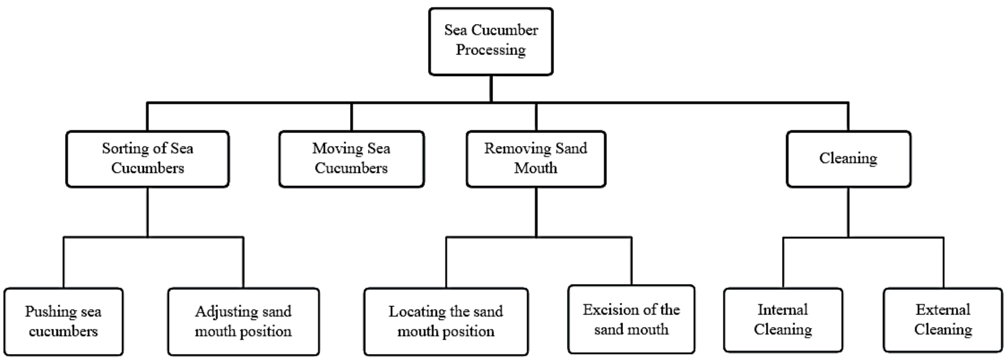


Fig. 3 - Functional analysis diagram of the sea cucumber sorting, de-sanding, organ removing, and washing equipment

Structural Design of Key Components

The key components of the sea cucumber sorting, de-sanding, organ removing, and washing equipment include the sorting feeding mechanism, pressing conveyor mechanism, and de-sanding, organ removing, and washing mechanism. The washing transfer mechanism and frame platform serve as auxiliary components and accessories, which facilitate the external rinsing and conveyance of processed sea cucumbers.

Sorting Feeding Mechanism

The sorting feeding mechanism primarily consists of six components: a vision module (1), a conveyor slide (2), a four-degree-of-freedom turntable (3), rollers (4), a chute (5), and gears (6). It is installed on the right side of the sorting, de-sanding, organ removing, and washing equipment for sea cucumbers. Positioned at the central part of the pressing conveyor mechanism, it aligns precisely with the positioning plate and the clamping claws (see Fig. 4).

The four-degree-of-freedom turntable collaborates with the vision recognition system not only to sort the sea cucumbers but also to adjust the orientation of the sand mouth, ensuring uniformity. During operation, the rotation of the rollers facilitates the rapid alignment of the sea cucumbers into a single row. The Hikvision SC6000 series camera captures the image information of the sea cucumbers and utilizes classification recognition technology to precisely locate the position of the sand mouth. Subsequently, the four-degree-of-freedom turntable rotates to align the sand mouths in a uniform direction, preparing for the subsequent de-sanding, organ removing, and washing processes. This camera is equipped with a 5-megapixel CMOS image sensor with a resolution of 1408×1204, positioned directly above the four-degree-of-freedom turntable, specifically for the recognition and positioning of the sand mouth. Its recognition performance is clear and reliable, efficiently identifying sea cucumbers and detecting the sand mouth from the captured images. Based on pre-set standards, the system grades the sea cucumbers and positions the sand mouth, subsequently sending commands to downstream devices.

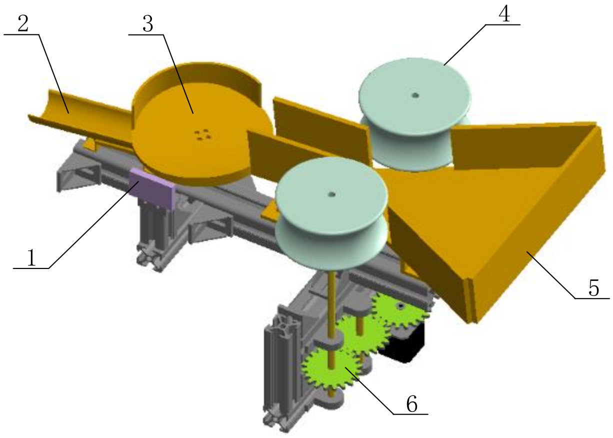


Fig. 4 - Structural schematic of the sorting feeding mechanism

1. Vision sensor; 2. Conveyor slide; 3. Four-degree-of-freedom turntable; 4. Rollers; 5. Chute; 6. Gears.

Pressing Conveyor Mechanism

The pressing conveyor mechanism primarily consists of components such as a sprocket (1), a fixed plate (2), a large pulley (3), a drive motor (4), a small pulley (5), a timing belt (6), bevel gears (7), a conveyor chain (8), an arcuate claw compression plate (9), an upper claw (10), and a lower claw (11). The structure of this mechanism is depicted in Fig. 5(a).

This system utilizes a collaborative transmission between the timing belt and the bevel gears to facilitate synchronous movement of the conveyor chain. The configuration of the four bevel gears ensures that the conveyor chain moves in opposing directions. The pressing assembly, as shown in Fig. 5(b) and 5(c), is chiefly responsible for compressing and clamping the sea cucumbers, thereby ensuring their stability during transportation and minimizing displacement. This assembly comprises an arcuate claw compression plate, an upper claw equipped with an internal spring secured by a pin to prevent dislocation, and a lower claw. The pressing assembly is mounted on the exterior of the conveyor chain with the claws affixed to the chain, while the arcuate claw compression plate is positioned at the front, closely conforming to the curved surfaces of the fixed plates located on either side.

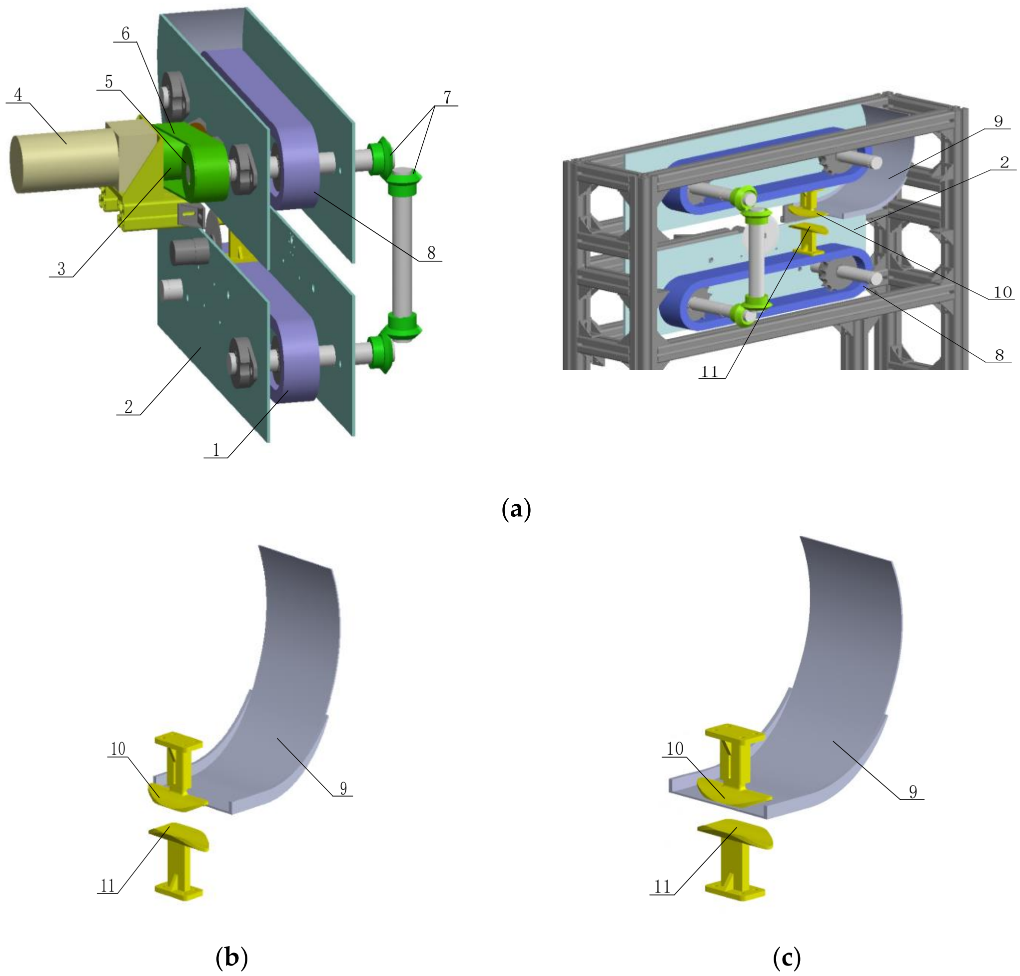


Fig. 5 - Structure and pressing state of the pressing conveyor mechanism.
(a) Schematic of the Pressing Conveyor Mechanism; (b) Compressed State of the Pressing Assembly; (c) Extended State of the Pressing Assembly.
1. Sprocket; 2. Fixed plate; 3. Large pulley; 4. Drive motor; 5. Small pulley; 6. Timing belt; 7. Bevel gear; 8. Conveyor chain; 9. Arcuate claw compression plate; 10. Upper claw; 11. Lower claw.

Design and Verification of Clamping Force

The selected material for the springs is SUS304 stainless steel, characterized by a wire diameter (d) of 0.8 mm, a mean diameter (D) of 9 mm, and a total of 10 coils. The initial length (L_0) of the spring is 110 mm, with compressed lengths of 29 mm (L_1) and 9 mm (L_2), resulting in compression displacements of s_1 = 81 mm and s_2 = 101 mm, respectively.

The formula for spring deformation is denoted as:

$$s=\frac{8FnD^3}{Gd^4} \tag{1}$$

From which, the force (F) can be derived:

$$F=\frac{SGd^4}{8nD^3} \tag{2}$$

The shear modulus (G) of SUS304 material is 7000 kgf/mm2 ≈ 68600 MPa. Using this value, the range of clamping force can be calculated by:

$$F_1=\frac{s_1Gd^4}{8nD^3}=\frac{81\times68600\times0.8^4}{8\times10\times9^3}=39.004N \tag{3}$$

$$F_2=\frac{s_2Gd^4}{8nD^3}=\frac{101\times68600\times0.8^4}{8\times10\times9^3}=48.706N \tag{4}$$

Given that each gripper incorporates two springs, the range of clamping force for the gripper assembly is given by:

$$F_{min} = 2F1 = 78.008N \tag{5}$$

$$F_{max} = 2F2 = 97.412N \tag{6}$$

The friction force formula "$f=F\mu$" is utilized, assuming a friction coefficient (μ) of 0.05 between the sea cucumber and the grippers, and a contact area of 6000 mm^2. Consequently, the friction force range between the sea cucumber and the grippers is calculated as:

$$f_{min} = F_{min}\mu=78.008\times0.05=3.9N \tag{7}$$

$$f_{max} = F_{max}\mu=97.412\times0.05=4.87N \tag{8}$$

The claws can provide a maximum friction force of 4.87 N and a minimum of 3.9 N, which satisfies the design requirements.

Selection and Verification of Conveyor Belt Motor

The conveyor belt is designed to handle a maximum load of 50 kg and operates at a speed of 60 m/min, with a roller diameter of 30 mm. The overall efficiency (η) is set at 75%, with a friction coefficient of 0.2 and a safety factor (k) of 1.8. The timing belt pulleys are specified with teeth counts Z_1 = 10 and Z_2 = 30.

The friction force required is calculated by:

$$f=F\mu=mg\mu=50\times10\times0.2=100 \text{ N} \tag{9}$$

The power required for the conveyor belt is given by:

$$P=\frac{fVk}{\mu}=\frac{100\times1\times1.8}{0.75}=0.24 \text{ kW} \tag{10}$$

The rotation speed of the larger shaft is:

$$n=\frac{v}{2\pi r}=\frac{1}{2\times3.14\times0.015}=10.6 \text{ r/s}=636 \text{ r/min} \tag{11}$$

The torque required for the motor is:

$$T=9550P/n=9550\times\frac{0.24}{636}=3.6 \text{ N·m} \tag{12}$$

Based on the relationship defined in:

$$i=\frac{Z2}{Z1}=\frac{30}{10}=3 \tag{13}$$

The actual power required for the motor is determined by:

$$T_0=\frac{T}{i}=\frac{3.6}{3}=1.2 \text{ W} \tag{14}$$

The actual rotation speed of the motor is calculated as:

$$n_0=ni=636\times3=1908 \text{ r/min} \tag{15}$$

De-sanding, Organ Removing, and Washing Mechanism

The de-sanding, organ removing, and washing mechanism comprises a positioning and cutting assembly and an internal cleaning assembly. As depicted in Fig. 6, the positioning and cutting assembly's layout incorporates a conveyor slide (1) precisely aligned with adjustable components and secured on a frame platform. A motor (3) is mounted on the adjustable component, connecting to a circular blade (2) positioned to the right of the adjustable component at a precise distance equivalent to the width of a "sand mouth." Under the cooperative action of the pressing conveyor mechanism, the head and tail of the sea cucumber are compressed, allowing the cutting assembly to precisely execute cutting and expanding operations on the sand mouth. Moreover, the adjustable component facilitates the flexible positioning of the motor, effectively minimizing the removal volume of the sea cucumber, thereby preserving the integrity of its edible portions to the greatest extent.

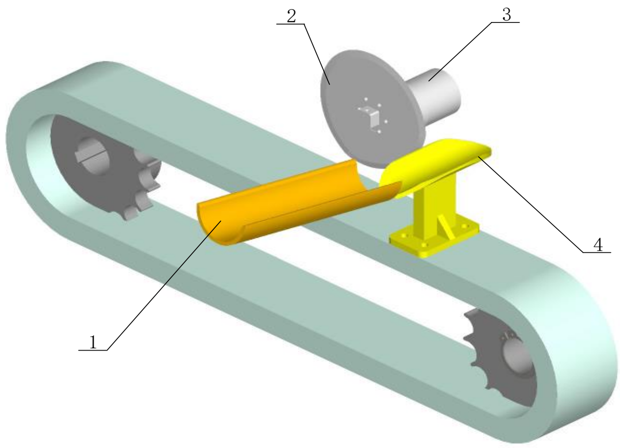


Fig. 6 - Structural schematic of the installation position of the cutting assembly
1. Conveyor slide; 2. Circular blade; 3. Motor; 4. Lower claw.

The internal cleaning assembly, as illustrated in Fig. 7, consists of a slide rail (1), slide rail support (2), water spray pipe (3), three-way block (4), and push rod (5). This assembly facilitates the "automatic sand mouth removal + high-pressure water jet washing + hook-assisted organ removal" cleaning operations for the sea cucumber. The push rod, in conjunction with the nozzle structure, enters the sea cucumber through the cut made post-sand mouth removal to perform internal cleaning, thereby maximally preserving the structural integrity of the sea cucumber. During the cleaning process, the upper and lower claws clamp the sea cucumber and move it toward the front of the cleaning assembly. A high-pressure diaphragm pump draws water, which is then directed through the three-way block to the water spray pipe. Water is ejected from lateral orifices in the water spray pipe. A hook mounted at the front of the water spray pipe aids in the removal of internal organs. Through its reciprocating linear motion, the hook enables repeated high-pressure rinses within the sea cucumber, effectively eliminating internal contents and achieving a thorough cleaning.

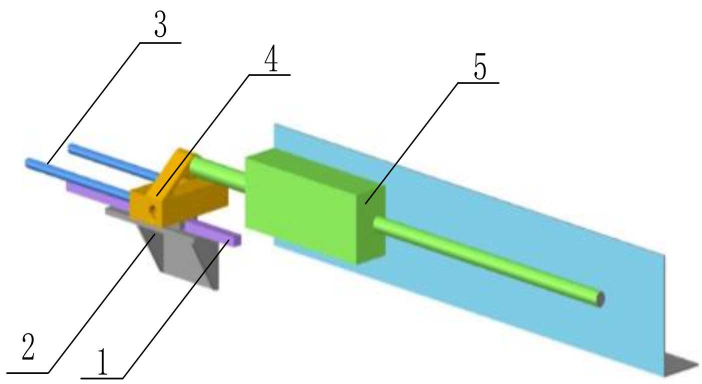


Fig. 7 - Structural schematic of the installation position of the cleaning assembly
1. Slide rail; 2. Slide rail support; 3. Water spray pipe; 4. Three-way block; 5. Push rod.

Design of Control Systems

The comprehensive design of the electrical control system is illustrated in Fig. 8(a). This system is centered around the Siemens S7-1200 PLC as the core controller, which coordinates the operation of various electrical components such as DC motors, stepper motors, servos, high-pressure diaphragm pumps, and solenoid valves. The system operates in a semi-automatic control mode, requiring manual intervention only to activate/deactivate start/stop buttons and emergency stop functions, while other functionalities (including vision recognition and photoelectric switch controls) are executed automatically through pre-set logic, as shown in the control flow diagram in Fig. 8(b).

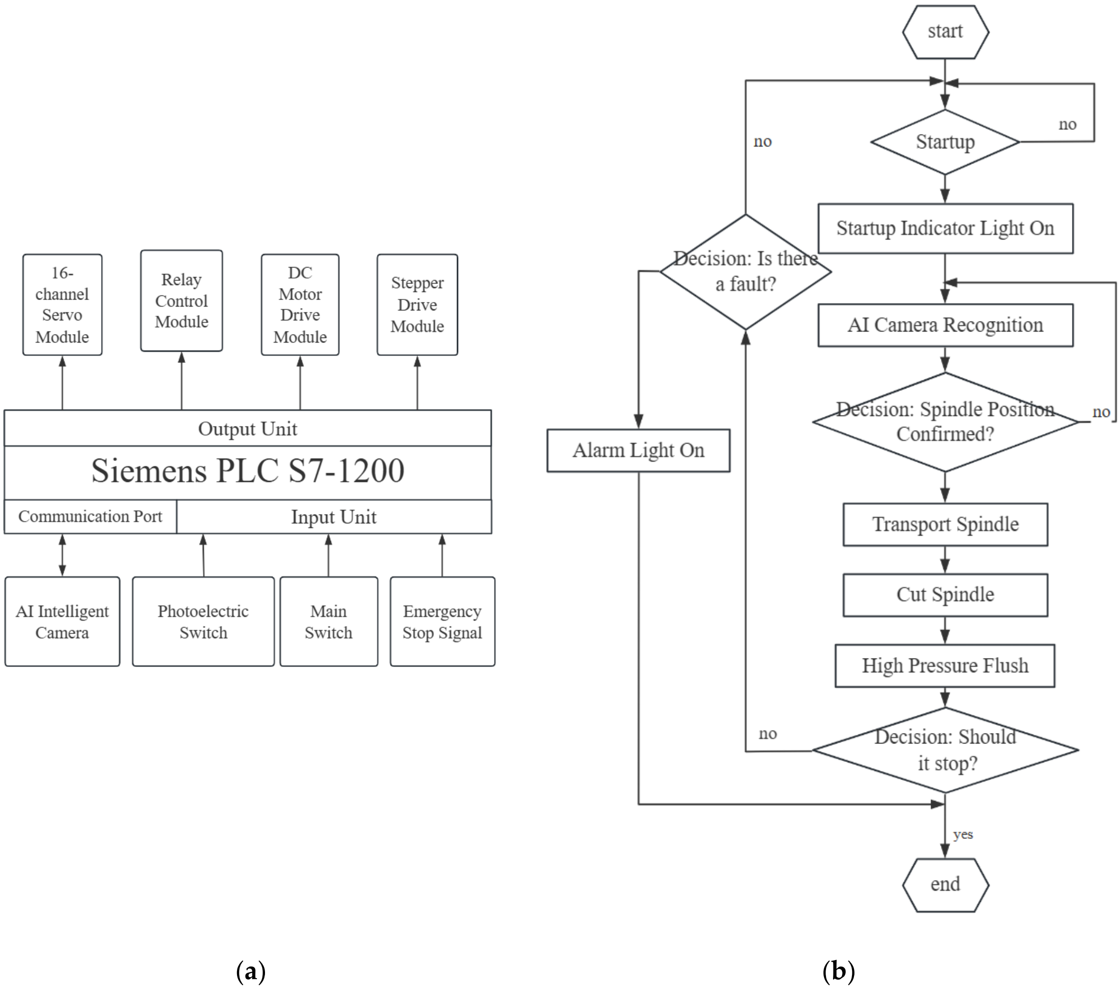


Fig. 8 - Schematic of the electrical control system design and control flow diagram.
(a) Schematic of the electrical control system design; (b) Control flow diagram

The vision recognition control module is primarily utilized for sorting operations, identifying the position and orientation of the sea cucumber's sand mouth, thereby enabling precise sorting without the need for human intervention. Conversely, the photoelectric switch control module is employed in cleaning operations, where photo-electric sensors detect the presence of sea cucumbers at designated cleaning stations, subsequently triggering the cleaning process. The PLC, serving as the system's central control unit, is responsible for programming and executing the overall work logic.

During the sorting process of sea cucumbers, the PLC first controls the stepper motor to transport the sea cucumbers to the servo-operated area; subsequently, the AI smart camera module recognizes the sea cucumbers and their sand mouth positions. This data is transmitted in real-time to the PLC via the Profinet communication protocol. Based on the received data, the PLC controls a 16-channel servo module to carry out precise sorting and ordering operations, ensuring the sea cucumbers proceed in a pre-determined sequence to the next stage. For the position-specific cutting of sea cu-cumbers, the PLC controls AC motor drives through relay modules and L298N DC motor driver modules, managing the upper and lower conveyor chains. Concurrently, the PLC activates the blade's DC motor to rotate at a set speed. Through the collaborative operation of these components, the system efficiently completes the precise cutting of the sea cucumber's sand mouth.

In the subsequent internal cleaning process, when a sea cucumber is conveyed to a specified cleaning position, the photoelectric switch is activated and sends a signal to the PLC. Upon receiving this signal, the PLC immediately controls the relay module to cease the operation of the AC motors while initiating the diaphragm pump for spray cleaning. Furthermore, the PLC also controls the crank slider mechanism of the motor intermittently, ensuring a thorough internal cleaning of the sea cucumbers.

RESULTS

Experimental Design

To validate the efficacy of each module of the sea cucumber sorting, de-sanding, organ removing, and washing equipment, as well as the operational stability, reliability, and processing outcomes, this study was based on the structural and operational principles of the sea cucumber processing equipment. The construction involved machining and assembling critical modules including the sorting feeding mechanism, pressing conveyor mechanism, and the de-sanding, organ removing, and washing mechanism, along with the washing transfer mechanism. These modules were integrated with an electrical control system and subsequently calibrated, as illustrated in Fig. 9.

The experimental study was divided into four parts.

(1) Sea Cucumber Identification and Sand Mouth Detection Algorithm Efficacy Experiment: This phase aimed to validate the applicability and reliability of the intelligent recognition algorithm and to verify its superiority in operation within the equipment through the accuracy of identification.

(2) Processing Effectiveness Experiment for Various Factors: This part focused on validating the overall system's applicability and reliability, as well as each module's effectiveness. Independent factor experiments were conducted to determine the optimal operational parameters for the equipment.

(3) Comparative Experiment with Other Equipment: Building on the optimal process parameters established in the first part, this experiment compared those parameters with those of existing equipment to affirm the superiority of the proposed design.

(4) Comparison Experiment with Manual Processing: This experiment involved actual production measurements to further validate the stability of the system and the quality of the processing results.

Fig. 9 - Exterior view of the prototype of the sea cucumber sorting, de-sanding, organ removing, and washing equipment

Experimental Evaluation of Sea Cucumber Identification and Sand Mouth Detection Algorithms

As depicted in Fig. 10(a), the sea cucumber identification algorithm proposed in this study demonstrates significant efficacy when applied on a turntable. When sea cucumbers are situated against a clean background, this facilitates the more precise extraction of deep features during the feature extraction process, thereby rendering the features of the sea cucumbers more complete and significantly enhancing the confidence of identification, with confidence levels exceeding 90%. Conversely, for sea cucumbers against a dirty background, the complexity of the image background complicates the distinction between the sea cucumbers and the background. Although the algorithm still successfully detects the sea cucumbers, the confidence levels are typically below 80%, but still surpass 60%, as shown in Fig. 10(b). This performance is sufficient to meet the basic requirements for sea cucumber identification. Furthermore, as shown in Fig. 10(c), through a tiered recognition approach, high-confidence sea cucumbers can be precisely identified for their sand mouth location using artificial intelligence technology, and this identification also exhibits high confidence.

Simultaneously, for sea cucumbers on dirty turntables, the post-tiered processing results for sand mouth location detection are favorable, with confidence levels also reaching above 65%, as illustrated in Fig. 10(d). Therefore, the sea cucumber sand mouth detection algorithm developed in this study demonstrates good applicability and reliability for use in sea cucumber sorting, dirt removal, and cleaning equipment.

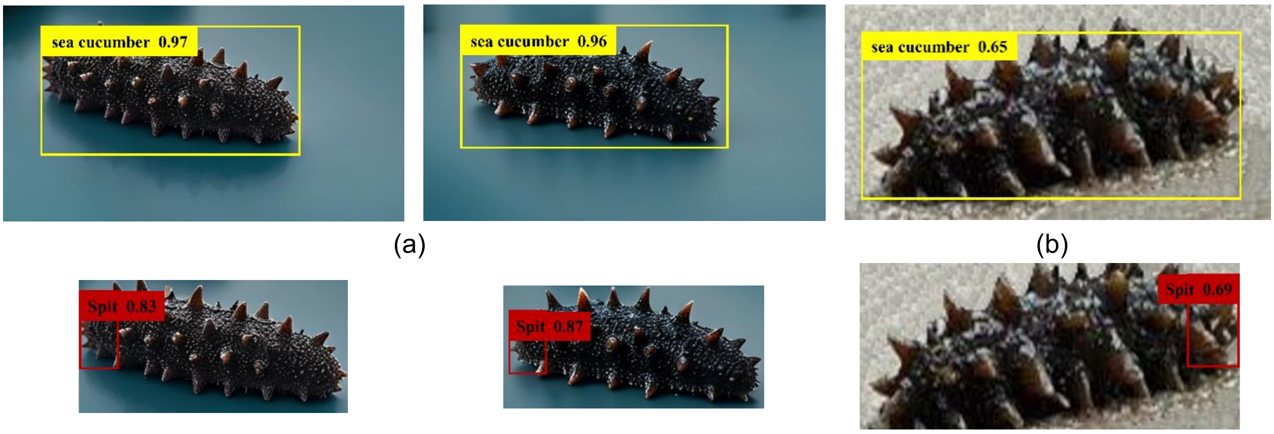


Fig. 10 - Effects of sea cucumber identification and sand mouth detection.

(a) Identification of sea cucumbers against a clean background; (b) Identification of sea cucumbers against a dirty background; (c) Detection of sand mouth against a clean background; (d) Detection of sand mouth against a dirty background.

Experimental Analysis of Factorial Processing Effects

The operational speeds of the sorting feeding mechanism, pressing conveyor mechanism, and washing transfer mechanism are critical determinants affecting the efficiency of sea cucumber cleaning processes, with notable interactions existing among these factors. This study employed a single-factor experimental approach to independently investigate the impact of each mechanism on the cleaning speed of sea cucumbers. Initially, the research focused on the sorting feeding mechanism. The study isolated the feeding rate during the sorting process as the sole variable. Each trial involved the use of 200 sea cucumbers of varying sizes. Evaluation metrics such as the stack count, parallel alignment, miscellaneous issues (including incidents of sea cucumbers falling off or jams preventing operation), sorting completion rate, and time consumption were considered. The outcomes of these experiments are illustrated in Fig. 11. Subsequently, attention was directed towards the pressing conveyor mechanism. Building on the optimal feeding rate established earlier, the pressing force was varied to assess its influence on the efficacy of pressing sea cucumbers. The metrics for evaluation included the rate of damage and the completion rate of pressing, with results depicted in Fig. 12. Finally, the study examined the washing transfer mechanism. Different transfer speeds during the washing phase were analyzed for their effect on the cleaning outcomes of sea cucumbers. Metrics such as the cleaning qualification rate and time consumption were used as evaluative criteria, and the findings are presented in Fig. 13.

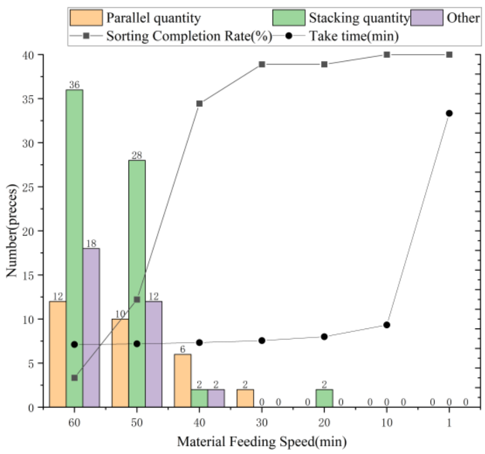


Fig. 11 - Experiment on feeding speed

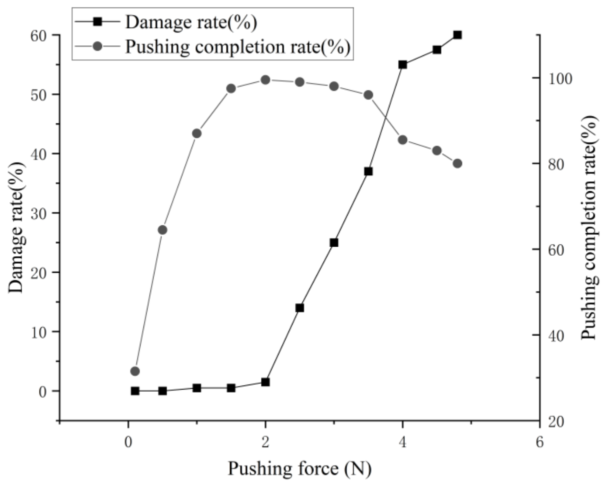


Fig. 12 - Experiment on pushing speed

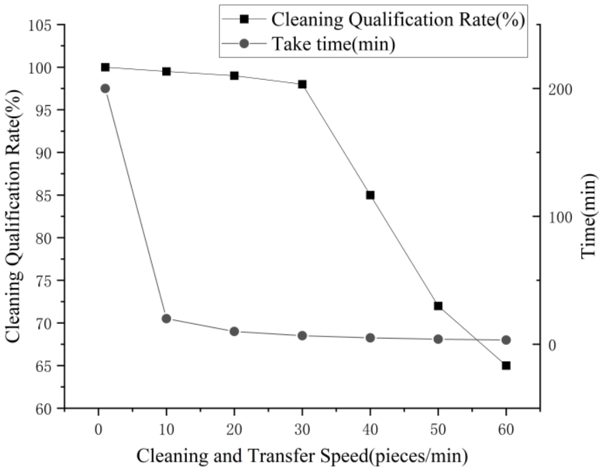
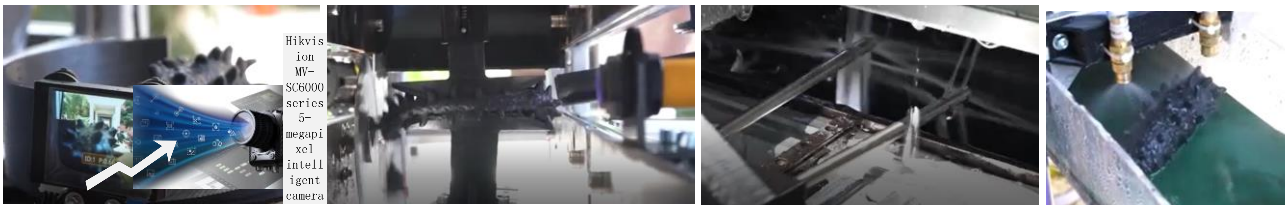


Fig. 13 - Experiment on transfer speed

The experimental results depicted in Fig. 11 indicate that under conditions of high feeding rates (60, 50, and 40 units/min), the sorting feeding mechanism is prone to issues of sea cucumber stacking, alongside prominent problems of sea cucumbers falling and jamming. Despite achieving a high sorting efficiency, the overall sorting performance is suboptimal. When the feeding rate is reduced to 10 units/min or less, the completion rate of sorting can reach 100%, but the efficiency significantly decreases. At feeding rates of 30 units/min and 20 units/min, the completion rates are both 99%, with reduced time consumption, thereby identifying 30 units/min as the optimal speed for the feeding mechanism. The experimental results presented in Fig. 12 show that under the influence of substantial pressing forces (≥2.5N) during the pressing process, sea cucumbers are highly susceptible to damage due to irreversible deformation caused by excessive pressure. Additionally, slight disturbances or inaccuracies in the pressing location can easily result in the sea cucumbers slipping out. When the pressing force is reduced to 2.0N or below, the damage rate decreases to 1.5% or lower. However, when the pressing force is less than 1.5N, there is a sharp decline in the completion rate of pressing, primarily due to the sea cucumbers detaching during the pressing and conveying process. Thus, the optimal pressing force for the pressing mechanism is determined to be 2.0N or less. Fig. 13 illustrates that during high-speed cleaning and transfer processes, the sea cucumbers are not thoroughly cleaned if the cleaning time is insufficient, leaving mud, sand, and stains on their surfaces. By reducing the speed of cleaning and transfer to 30 units/min or less, the rate of adequate cleaning reaches 98% or higher. Therefore, the optimal speed for the washing transfer mechanism is set at 30 units/min, with a cleaning duration of 2 seconds per sea cucumber. Fig.14 displays the functional verification results of the prototype. These results demonstrate that key components such as the sorting feeding mechanism, pressing conveyor mechanism, and the de-sanding, organ removing, and washing mechanism, as well as the washing transfer mechanism, exhibit satisfactory performance, effectively supporting the automated workflow. Based on the comprehensive experimental results, the optimal process parameters for the equipment are set with both feeding and cleaning transfer speeds at 30 units/min and the pressing force at 2.0N.



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

Fig. 14 - A schematic representation of the functional verification of the prototype model.
(a) Sorting feeding mechanism, (b) Pressing conveyor mechanism,
(c) De-sanding, organ removing, and washing mechanism, (d)washing transfer mechanism

Comparative Experiment with Other Devices

In the comparative experiments with other devices, the newly developed sea cucumber sorting, de-sanding, organ removing, and washing equipment was evaluated against the integrated sea cucumber washing and cutting equipment. Each trial utilized 200 live sea cucumbers of varying sizes. Both machines operated under optimal conditions, with the following process parameters for the integrated equipment: a conveyor belt speed of 0.03 m/s and a vertical gap of 30 mm between the upper and lower rollers of the cutting device. The cleaning efficacy of both devices was compared, as detailed in Table 1. The criteria for damage were defined as physical harm to the sea cucumber's body, and the criteria for inadequate cleaning were defined as incomplete removal of sand from the sea cucumber's mouth.

Table 1

Comparative experiment of sea cucumber cleaning equipment.

Equipment	Total Number	Damaged	Inadequately Cleaned	Time (min)
New sea cucumber sorting, de-sanding, organ removing, and washing equipment	200	4	1	32
Integrated sea cucumber washing and cutting equipment	200	6	0	66.5

The results indicated that the sea cucumber cleaning equipment designed in this study achieved a 1% reduction in damage rate compared to the integrated washing and cutting equipment. However, there was an increase of one in the count of inadequately cleaned sea cucumbers. Moreover, the time taken to complete the same cleaning tasks was reduced by more than 50%. The sorting feeding mechanism and pressing mechanism organized irregularly positioned sea cucumbers neatly, significantly enhancing the cleaning efficiency. The experiments demonstrated that the new sea cucumber sorting, de-sanding, organ removing, and washing equipment significantly improved the automation efficiency of sea cucumber processing, with a reduced damage rate and almost no increase in the number of inadequately cleaned sea cucumbers.

Comparative Experiment with Manual Labor

In the comparative experiments with manual labor, the new sea cucumber sorting, de-sanding, organ removing, and washing equipment was tested against the manual processing of 200 live sea cucumbers of varying sizes by four workers on a production line. The equipment operated under optimal conditions, and the results are summarized in Table 2. The standards for cleaning rate, damage rate, and acceptance rate were de-fined as the number of sea cucumbers cleaned/total sea cucumbers processed, the number of sea cucumbers damaged/total sea cucumbers processed, and the number of sea cucumbers properly cleaned without damage/total sea cucumbers processed, respectively.

Table 2

Comparison of new sea cucumber sorting, de-sanding, organ removing, and washing equipment with manual cleaning

Experiment ID	Cleaning Rate (%)	Damage Rate (%)	Acceptance Rate (%)	Efficiency (units/h)
New Equipment	96	2	91	375
Worker 1	95	9	86.5	33
Worker 2	93	13	80.0	28
Worker 3	96	12	84.5	32
Worker 4	98	10	88.5	30

The experimental results demonstrate that the sea cucumber cleaning equipment designed in this study shows a slight reduction in cleaning rate by 0.5% compared to manual cleaning. However, it significantly reduces the damage rate by 9% and increases the acceptance rate by 6.125%, with an overall efficiency improvement of more than ninefold. The new sea cucumber sorting, de-sanding, organ removing, and washing equipment substantially enhances the efficiency of automated sea cucumber processing. Concurrently, compared to manual methods, it improves the integrity of the sea cu-cumber's form and cleanliness after washing and mitigates the issues commonly associated with manual processing, such as inconsistency in the sea cucumber's form and cleaning quality, as well as safety incidents.

CONCLUSIONS

The application of the sea cucumber sorting, de-sanding, organ removing, and washing equipment represents a significant advancement over the traditional manual sorting and cleaning processes, playing a crucial role in transforming the production paradigm of traditional sea cucumber processing towards standardization and large-scale production. This equipment reduces labor demands, alleviates worker stress, and eliminates reliance on manual experience for quality control, offering a cost-effective solution with a favorable cost-performance ratio. It can serve as a model for the development of similar equipment within the sea cucumber processing line.

(1) The equipment innovates a "automatic sand mouth removal + high-pressure water jet washing + hook-assisted organ removal" method for sea cucumber cleaning, which is considered advanced and effectively speeds up the process of gut cleaning while preserving the integrity of the sea cucumber.

(2) Utilizing machine vision and image recognition technology, a four-degree-of-freedom turntable adjusts the position of the sand mouth, facilitating precise, subsequent cutting operations.

(3) The clever and stable mechanical design features a movable conveyor chain and upper and lower clamps, enabling synchronous transportation of sea cucumbers.

Future research will focus on enhancing the application of image recognition technology to improve the speed and accuracy of cutting and aligning the sand mouth, thereby further increasing the efficiency of sorting and cleaning processes.

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