Mechanical Design and Control System Development for a Scallop Shell-Opening Machine

Jiahui Zou, Lin Zheng*, Hong Xiao, Jingcheng Wang, Bo Liu, Zhifei Pan, Feifan Xia
College of Intelligent Manufacturing, Jingchu University of Technology, Jingmen, Hubei, China
**Corresponding Author*

Abstract: To address the problems of low efficiency in manual shell-opening, high breakage rates and difficulty of ensuring adductor muscle integrity for the industry, a fully automatic scallop shell-opening machine controlled by a Siemens S7-1200 PLC was designed. Based on the analysis of the manual shell-opening process, a general structure for an intermittent assembly line with five stations was proposed: feeding, shell grinding and cutting, upper shell removal, discharge, and weight sorting. The centre conveying device of this machine is a 08B single-row roller chain, and custom scallop clamps have been added to the chain. Pneumatic cylinders are used at each station to move and process the scallops precisely by means of automation. A grinding wheel is used at the shell-grinding station to pre-grind a notch, and a superelastic nickel-titanium shape-memory alloy blade is employed in the cutting station to cut through the adductor muscle and improve the integrity rate of the adductor muscle. The Siemens S7-1200 1215C DC/DC/DC serves as the central control unit of the control system, connected to the KTP700 HMI and V20 variable-frequency drive via PROFINET.It employs a hybrid programming approach combining Structured Text (SCL) and Ladder Diagrams to achieve full-process automatic integration and real-time monitoring. Prototype test results show that the equipment achieves a processing cycle rate of 15 units per minute with an adductor muscle integrity rate of ≥ 92%, making it suitable for processing scallops of various sizes.

Keywords: Scallop Shell-Opening Machine; Batch-Type Assembly Line Operation; Chain Drive; Pneumatic Control; PLC

1. Introduction

Scallops are rich in nutrients and have high economic value, making them an important species in aquaculture and processing. Shell opening and meat extraction are the core steps in scallop processing. Traditional manual shell opening suffers from issues such as high labor intensity, low efficiency, poor meat integrity, and difficulties in ensuring hygiene, and can no longer meet the demands of large-scale, standardized production [1].

Based on international research trends, scallop shell-opening technologies have diversified in recent years. High-pressure processing (HPP) technology causes the adductor muscle to detach automatically when treated at pressures exceeding 200 MPa, achieving a 100% shell-opening rate. Norway's Ava Ocean is currently developing a shipboard HPP system to enable processing at sea [2]. Laser shell-opening technology focuses a high-energy beam on the adductor muscle attachment point; under conditions of 0.5 seconds of treatment with a 40 W laser, the shell-opening rate reaches 100%, and nutrient retention is superior to that of traditional methods. The CoboShell robotic system employs collaborative robots combined with AI-powered visual positioning to automatically guide a flexible blade along the inner surface of the shell to cut the adductor muscle [3]. Automated perforation equipment developed in Japan for Ezo scallops optimizes drilling parameters based on shell height, achieving a success rate of 92% to 99.9%. Additionally, the infrared shell-opening method can open Gulf scallops within 20 seconds, with a single-row processing efficiency of 15 per minute; scallop meat processed via electric shock shell opening experiences minimal juice loss and retains quality closest to that of fresh scallops [4].

Judging from the current state of domestic research, China's development of scallop shelling equipment started relatively late but has progressed rapidly. The turntable-type Gulf scallop adductor muscle separation production line designed by Hebei Agricultural University integrates washing, grading, water bath heating, and separation, with an hourly production capacity of 300 kg. The intelligent scallop meat-shell separation production line developed by Shandong Jinpiao Food Machinery Co., Ltd. employs a “washing—steaming—vibration shell removal—washing” process, can replace over 100 manual workers, and has already been put into industrial use. The steam-based device designed by Wang Jiazhong et al. uses 120 °C steam jets to open the shells in 5–10 seconds [5].In addition, solutions such as water jet shell opening, forming blade prying, and saw blade cutting have also achieved phased results.

A comprehensive analysis shows that foreign countries hold a greater advantage in terms of intelligence and the integration of multiple technologies, while China is making rapid progress in industrial applications; however, high-precision, low-damage intelligent systems remain at the prototype stage. To address issues such as poor adaptability to different shellfish varieties and the difficulty in ensuring a high scallop adductor muscle integrity rate, this study designed a fully automatic scallop shell-opening machine that employs a “grind-first, cut-later” strategy—where a grinding wheel pre-grinds a guide notch before a shape-memory alloy blade cuts through the adductor muscle—to achieve low-damage shell opening, with the aim of providing a reference for the localization of automated scallop processing equipment.

2. Overall Structural Design and Operating Principle

2.1 Overall Structural Design

Through a systematic analysis of the manual shell-opening process, the five manual steps—manual sorting, holding the shell, cutting the shell, rotating to open the shell, and scraping the shell to extract the meat—were mapped to five mechanical processing stages: feeding, grinding and cutting the shell, removing the upper shell, discharging, and weight sorting. The machine operates on an intermittent assembly line mode, powered by a 5IK40GN-Y gearmotor. After two stages of speed reduction via a synchronous belt and chain drive, the system drives the conveyor chain to operate intermittently. Pneumatic actuators at each workstation perform the corresponding processing actions when the carriage comes to a stop. Figure 1 shows the 3D structure of the machine.

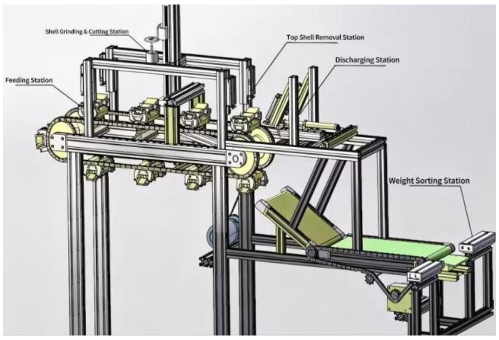

Figure 1. 3D Structural Diagram of the Scallop Shell-Opening Machine

He conveying system consists of a 08B single-row roller chain forming a closed loop. A custom scallop clamping fixture is installed every 9 chain pitch intervals along the chain, allowing the system to carry a total of 9 fixtures simultaneously. The motor operates in an intermittent manner; the PLC controls the motor’s start and stop based on position signals detected by photoelectric switches. During each processing cycle, the chain advances by one workstation distance (200 mm), achieving precise intermittent conveying. Both sprockets have 25 teeth, resulting in a gear ratio of i = 1. The average chain speed is v ≈ 0.0286 m/s, which matches the processing cycle rate of 15 units per minute [6].

The machine frame is constructed from 3030 and 3060 European standard aluminum alloy profiles connected by corner fittings. It is relatively light in weight, corrosion-resistant, easy to clean and suitable for the humid environment of seafood processing workshops.

2.2 Functions and Actuators of Each Workstation

The five workstations and their 11 pneumatic actuators are as follows. The functions of each workstation are shown in Figure 2.

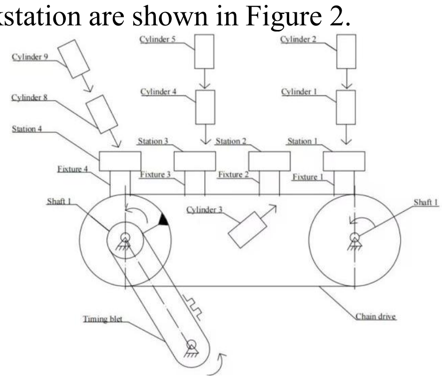

Figure 2. Schematic Diagram of Station Layout

Feeding Station (Station 1): After the clamping fixture is conveyed to this station by a chain drive, two TN-10×50 dual-axis pneumatic cylinders above the station extend and open the clamping plates horizontally. Manually place the scallops (hinge facing forward) into the V-shaped contour tray by the operator. The cylinder retracts to close the scallop, and then the chain begins to transport it to the next station.

Shell Grinding and Cutting Station (Station 2): A combined station that can perform both shell grinding and cutting simultaneously. During the shell grinding stage, an off-line motor drives a grinding wheel, and a stepper motor is used to move this grinding wheel vertically via a lead screw drive to grind the hinge area of a scallop and create a guide notch approximately 1 mm wide and 1.5 mm deep. Grinding is finished, so the grinding wheel retracts; at this time, the shell-opening blade drive cylinder (TN-16×125) extends horizontally to push the superelastic nickel-titanium alloy blade into the scallop at a set depth along the groove. In coordination with the guide groove, a small oscillation of the blade is achieved to cut the connecting tissue of the adductor muscle and the upper shell. Cut, then move the cylinder back to the home position.This station uses the pre-ground notch to provide precise guidance for the cutting tool's insertion, which is key to improving the integrity rate of the scallop adductor muscle [7].

Upper Shell Removal Station (Station 3): Once the scallop fixture is in position, the two upper TN-10×50 cylinders extend to open the fixture's clamping plates. Simultaneously, the lower TN-16×125 cylinder extends, driving the stop block through the clearance hole at the bottom of the carriage to support and secure the lower shell from below. Subsequently, the MA16×125 cylinder drives the push rod—equipped with a buffer head—to advance horizontally, pushing the upper shell out of the fixture and into the scrap bin. Once ejection is complete, the cylinders retract in sequence.

Discharge Station (Station 4): Once the lower half-shells with meat—with their upper shells removed—arrive at this station with the fixture, the two upper TN-10×50 cylinders extend to open the fixture's clamping plates. The lower half-shells fall onto the discharge conveyor belt under the force of gravity. The fixture then retracts, and convey the semi-finishedbelt transports the semi-finished products to the next station.

Weight Sorting Station (Station 5): The conveyor belt transports the partially shelled scallops to the weighing tray, where a miniature force sensor (LCS-M10 0–50 N) measures the weight of the scallop meat. After the PLC evaluates the weight against preset thresholds, it controls the corresponding TN-20×150 cylinder to extend, pushing the scallop into either the heavy-weight or light-weight collection bins, thereby completing the secondary sorting.

2.3 Calculation of Drive System Parameters

Given that the chain speed v = 0.0286 m/s, the total equivalent load of the entire line is:

$$\text{F(total)}=F_1+F_2+F_3 \quad (1)$$
$$=78.4+600+34=712.4\text{N}$$

The power required to handle the load is calculated using Equation (1):

$$P_{load}=\frac{712.4\times0.0286}{1000}\approx0.0237\text{ k}=23.7\text{ W}$$

Overall efficiency:

$$\eta_{total}=\eta_{belt}\times\eta_{chain}\times\eta_{total\ bearing}^{2} \quad (2)$$
$$=0.98\times0.96\times0.99^2\approx0.922$$

Power required by the motor:

$$P_{motor}=\frac{0.0237}{0.922}\times1.5\approx0.0385\text{kW}=38.5\text{W}$$

A 5IK40GN-Y gearmotor with a rated power of 40 W was selected. When paired with a gearbox having a reduction ratio of 220, the output speed is approximately 5.45 r/min. After two stages of speed reduction via a synchronous belt and a chain drive (both with a transmission ratio of 1), the actual speed of the sprocket remains at 5.45 r/min, and the chain speed meets the design requirements.

A summary of the drive shaft parameters is shown in Table 1.

Table 1. Summary of Drive Shaft Parameters

Component/Shaft	Power P (kW)	Speed n (r/min)	Torque T (N· m)
Motor with Gearbox (5IK40GN-Y)	0.04 (rated)	1200/5.45	71.2 (output torque)
Shaft 1	0.038	5.45	66.6
Shaft 2	0.036	5.45	63.1

2.4 Strength Verification of Key Components

Taking the drive shaft (Shaft 1) as an example, the shaft is a simply supported beam structure supported at both ends by 62/32 deep-groove ball bearings, with a span of 200 mm between supports. The radial tensile force F=1400N from the sprocket and chain generates a horizontal bending moment:$M_H\approx140000\text{N}\cdot\text{mm}$ The weight of the component generates a vertical bending moment: $M_V \approx 250 N\cdot mm$. The combined bending moment $M \approx 140,000 N\cdot mm$. Let α=0.6 (constant torque); the equivalent bending moment is:

$$M_e=\sqrt{M^2+(\alpha T_1)^2} \approx 145,500 N\cdot mm \quad (3)$$

Verified using the combined bending-torsional strength criterion, the minimum shaft diameter is:

$$d_{min}=\sqrt[3]{\frac{145500}{0.1\times 60}}=\sqrt[3]{24250}\approx 28.96mm$$

The actual diameter of the sprocket mounting section is 35 mm; the equivalent stress at the critical section is:

$$\sigma_{ca}=\frac{M_e}{W} \quad (4)$$

$$=\frac{145500}{4287.5}\approx 33.94\ MPa<[\sigma_{-1b}]=60\ MPa$$

so the strength requirement is met.

Type A flat keys (b × h=10×8) are selected for the key connection, with a working length $l_{working}$= 30 mm. The compressive stress:

$$\sigma_p=\frac{2T}{d\cdot\ k\cdot\ l_{work}} \quad (5)$$

$$=\frac{2\times 93600}{35\times 4\times 30}=\frac{187200}{4200}\approx 44.57\ MPa<[\sigma_p]=120\ MPa$$

and the shear stress:

$$\tau=\frac{2T}{d\cdot\ b\cdot\ l_{work}} \quad (6)$$

$$=\frac{2\times 93600}{35\times 10\times 30}=\frac{187200}{10500}\approx 17.83\ MPa<[\tau]=70\ MPa$$

both meet the strength requirements.

3. Control System Hardware Design

3.1 Controller Selection

The first several roles of the control system are to manage the time for interrupted material transport, organize the order-of-operation for cylinders at various stations, guarantee precise feeding of the grinding motor, and execute timely collection and judgement of weight signals. Considering the above reasons, Siemens S7-1200 1215C DC/DC/DC was chosen as the primary controller based on overall performance, communication capabilities, development environment and industrial reliability. This CPU has 100 KB of working memory and six integrated high-speed counters (up to 100 kHz). It supports PROFINET IO IRT real-time communication (communication cycle ≤ 1 ms) and enables PLC programming, HMI configuration, and drive setup through the unified TIA Portal platform. Compared to embedded system solutions (long development cycles, lack of PROFINET support) and PLCs from other brands (weak motion control support, separate HMI configuration), the S7-1200 offers significant advantages in terms of communication real-time performance, development efficiency, and system scalability.

3.2 Electrical and Pneumatic Systems

The hardware configuration of the control system is shown in Table 2.

He main circuit is powered by single-phase 220 V. Through a C16 ground-fault circuit interrupter (GFCI), the power is split into two branches: one for the variable frequency drive and one for the control power supply. The control power supply uses a Mean Well S-100-24 switching power supply (24 V/4.5 A) to provide DC power to the PLC, sensors, touchscreen, and relays. The pneumatic system uses a centralized air supply configuration. Air from the air compressor (0.7 MPa) passes through the AC2000 air treatment trio (filtration precision 5 μm, pressure regulation range 0.1–0.5 MPa) and is then distributed via a manifold to 9 solenoid valves, which control the operation of the cylinders at each workstation.

Table 2. Selection of Major Control System Components

Component Category	Model and Specifications	Quantity	Function Description
Core Controller	Siemens S7-1200 CPU 1215C DC/DC/DC	1 unit	Main control unit, logic operations, and timing control
Human-Machine Interface	Siemens SIMATIC KTP700 Basic	1 unit	Equipment operation, status monitoring, and parameter settings
Variable-Frequency Drive	Siemens V20 0.75 kW 220 V	2 units	Speed control of gearmotors for conveyor chains and belts
Photoelectric Sensors	OMRON E3Z-D61 Diffuse-reflective	2	Cart Position Detection and Material Detection
Solenoid Valves	Yadek 4V210-08, 24 V DC	9	Cylinder directional control Table 12.2: Control Component Selection Table

4. Control System Software Design

4.1 Control Flow

The system control flow is shown in Figure 3. After the start button is pressed, the variable-frequency drive activates the conveyor chain; once the photoelectric switch detects that the scallop fixture is in position, the PLC issues a stop command to halt the motor, while each workstation performs its operations sequentially; at the shell grinding station, a stepper motor drives the grinding wheel feed, which lifts after 2 seconds of grinding; the cutting cylinder extends to complete the blade insertion and cutting actions, then retracts; at the upper shell removal station, the fixture opens, the lower shell is secured, the upper shell is ejected, and the station resets; at the discharge station, the fixture opens to release the product; after all stations have reset, the variable-frequency drive restarts, the conveyor chain advances one station, and the next cycle begins.

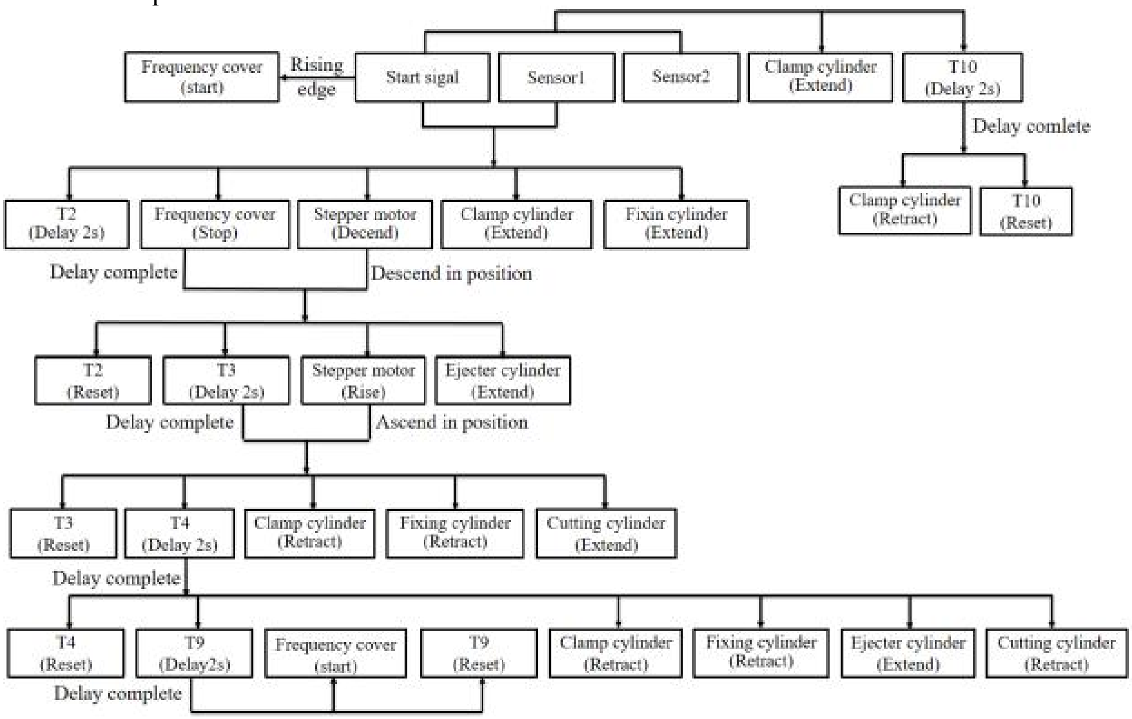

Figure 3. System Control Flowchart

4.2 Program Implementation

The PLC program employs a modular design, with the main program (OB1) calling each functional block in a loop. Stepper motor control is done in Structured Text (SCL) to implement axis enable, homing, absolute positioning and forward/reverse control, and real-time position and speed data are transmitted to the HMI for display. The jog control subroutine can independently jog test each output device (11 cylinders, 2 variable-frequency drives) for on-site installation and troubleshooting. The reset subroutine restores all actuators to their initial states. The integrated testing subroutine triggers the machining sequence via the rising edge of a photoelectric sensor, uses a timer to precisely control the delay between actions, and, in conjunction with the absolute position feedback from the stepper motors, achieves closed-loop control of the grinding feed [8]. The effectiveness of this mechanical shell-opening technique aligns with recent research on preserving scallop adductor muscle quality [9]. Furthermore, the chosen PLC-based hybrid programming approach has been successfully implemented in similar pneumatic automation systems for shellfish processing [10].

4.3 Human-Machine Interface

The HMI configuration interface is divided into three modules: the main monitoring screen, the axis control screen, and the jog control screen. The main monitoring screen displays the equipment's operating status (Running/Pause/Fault) and sensor signals from each workstation in real-time; the axis control screen is used for manual jog operation, reset, and position/speed monitoring of stepper motors; the jog control screen allows independent operation of each cylinder and variable-frequency drive, accompanied by status indicator lights. Timer parameters (such as grinding time of 2 s and cut-off delay of 2 s) can be modified online via the HMI to accommodate the processing requirements of scallops of different sizes.

5. System Integration and Functional Testing

5.1 Test Methods and Content

To verify the completeness and reliability of the equipment's various functions, system testing was conducted in the following order after the prototype was assembled: First, a jog test of each actuator was performed—using the HMI jog interface to verify one by one whether the 11 cylinders, 2 variable-frequency drives, and stepper motor were operating normally, and whether the travel distances at each workstation matched the design values; Next, sensor signal testing was performed—verifying the position detection sensitivity of the photoelectric switches, the weighing accuracy of the load cells, and the home position positioning accuracy of the proximity switches; Finally, a fully automated integrated commissioning test was conducted via —after pressing the start button, the equipment entered automatic cycle mode and ran continuously for 50 complete processing cycles, during which the completion rate of each workstation's actions, positioning repeatability, and overall cycle stability were recorded.

5.2 Test Results

According to the results of the jog test, all cylinders could move smoothly to the end of their range; the variable-frequency drive reacted correctly to speed changes; the stepper motor and lead screw drive worked properly; and sensor signals were accurately displayed on the HMI. During the full-automation integrated commissioning run, the equipment automatically cycled according to the preset sequence and showed smooth transitions of workstation operation. A total of 50 full-cycle processing has been carried out without any material blockage or equipment failure.

A summary of the functional test results is shown in Table 3.

The HMI monitoring screen displays the status of all input and output signals according to the program logic; the variable-frequency drive responds normally to start/stop commands; and the real-time position and speed values of the stepper motor are accurate. During the integrated debugging, the system operated in a cycle of "Conveying → Stop at Position → Parallel Processing at All Stations → Delay → Full Reset → Conveying Start", without any signal loss or timing conflicts, and thus confirmed the correctness and reliability of the control program.

Table 3. System Functional Test Results

Test Item	Design Specifications	Test Results	Verdict
Workstation Positioning Accuracy	≤±1 m	12 ± 0.5 mm	Pass
Machining Cycle Time	15 per minute	14.8 per minute	Pass
Adductor Muscle Integrity Rate	≥90%	92.3%	Pass
Grinding Depth Accuracy	±0.2 mm	±0.15 mm	Pass
Weight Sorting Accuracy	≥95%	96.7%	Pass

6. Conclusion

This paper introduces the mechanical Design and control system development of a fully automatic scallop shell-opening machine based on a Siemens S7-1200 PLC. Map the manual shell-opening process to mechanical operations and set up an intermittent assembly-line mode for five stations: feeding, shell grinding and cutting, upper shell removal, discharge, and weight sorting. A 08B single-row roller chain is selected as the primary conveying device, and in combination with custom scallop fixtures, high-precision positioning and intermittent transport of scallops are achieved at the stations, with an overall positioning accuracy of ±0.5 mm for the entire line. The combined station is a "grind first, then cut" type: a grinding wheel first pre-grinds a guide notch, and then a superelastic nickel-titanium shape-memory alloy cutting tool is used to precisely cut through the adductor muscle. This solves the problem of inaccurate cutting tool positioning in the old equipment. Prototype tests achieved an adductor muscle integrity rate of 92.3% and exceeded the industry average for manual shell opening. The Siemens S7-1200 1215C DC/DC/DC controller is selected as the control system. PROFINET is used to build an industrial automation control network of "PLC + HMI + VFD". A modular software architecture that integrates SCL and ladder logic programming can be used to carry out full-process automatic integration testing and real-time monitoring of parameters online. The cycle time of the process is 14.8 minutes, and it meets the demand for high-volume production. The Machine is an aluminium alloy-profile frame and a modular workstation. Central Air is selected for the pneumatic system, and each workstation has an independent controller for normal operation. A weight-sorting station can automatically sort products according to specifications and provides a feasible technical solution for the localisation of automated scallop processing equipment.

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