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Design and Test of an Efficient Automatic Clip Seedling System for Raft Aquaculture Kelp

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Abstract: Kelp, as a kind of climate-friendly food, animal feed, and bioplastics material, has been gradually cultivated worldwide. In the process of kelp culture, clipping seedling operation is essential to guarantee the yield. Traditionally, the clipping seedling operation is conducted by hand with low production efficiency and high labor intensity. In this paper, a novel automatic clipping seedling machine is developed to improve efficiency. The machine consists of an automatic seedling clipping core device, an automatic seedling feeding device, an automatic seedling rope conveyor, and an automatic product storage device. The corresponding structure, mechanism, and control system are introduced and analyzed. The performances of the automatic machine are tested and compared to manual kelp seedling clipping. Compared to manual kelp seedling clipping, the automatic machine can improve efficiency by 35%. Additionally, the quality of kelp seedling clipping is investigated. The attaching force of the kelp seedling clipped by the automatic machine is 2.179 N (224.4 g $\times$ 9.8 N/Kg $\times$ 10^{-3}). The rate of the clipped kelp seedlings falling off the rope is only 1.3%. These performances prove that the automatic machine Is feasible and can be used to improve clipping efficiency and ensure clipping quality at the same time.

Keywords: kelp aquaculture; kelp seedling clipping; vertical seedling clipping; control system; automatic equipment

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1. Introduction

Nowadays, as a promising marine crop, kelp has been gradually cultivated worldwide [1]. Kelp has numerous benefits and uses. Firstly, kelp can be used as human food [2], animal feed [3], and fertilizer [4]. Secondly, kelp can be applied as raw materials for bioplastics [5–7]. Thirdly, kelp can improve water quality [8–10]. Considering the food issue and the environmental issues, all these benefits and uses make kelp culture more and more important and widespread [11].

In 2022, global kelp production reached approximately 14.05 billion tons, marking a slight 0.21% increase from 2021. In North America, the United States and Canada are major contributors to kelp production. Similarly, Norway, Ireland, the United Kingdom, and France play significant roles in kelp production within Europe. Australia and New Zealand are notable kelp producers in Oceania. The kelp industry is highly developed and concentrated in Asia, particularly in China. China is one of the largest countries of kelp culture [12]. The ocean area is 2.997 million square kilometers. In 2020, the yield of kelp culture was 1.569 million tons, increasing 1.9% from 2019. The kelp cultivated in this article is Saccharina japonica, which belongs to Phaeophyta, Phaeophyceae, Laminariales, Laminariaceae, Saccharina, and is composed of rhizoid fixators, stalks, and leaves, which are attached to rocks and cultured rafts through fixators.

The process of kelp culture can be mainly divided into three stages, i.e., hatching, cultivating, and harvesting [13]. In the hatching stage, kelp spores are fertilized and bred to kelp seedlings in the nursery. In the cultivating stage, the kelp seedlings are clipped to ropes (named kelp ropes). Then, the kelp ropes are tied to the artificial floating raft to cultivate the kelp in seawater. Finally, when the kelps grow long enough, they will be harvested. Actually, kelp culture is a complex challenge [14]. In the nursery, circumstances such as temperature, light, and nutrients must be precisely controlled to ensure the kelp spores grow healthily [15]. During cultivation, kelp seedlings should be adhered to the rope tightly to prevent falling off [16]. That is essential to the yield. Additionally, harvesting is labor-intensive work under harsh conditions.

Nowadays, with the continued growth of the kelp farming industry, it requires more and more automatic equipment to improve efficiency and save manual labor [17]. At present, the control equipment and system of the nursery have been employed to control the hatching environment and are sufficient for the corresponding accuracy requirement, considering the relatively static situation of the nursery [18]. Due to the low efficiency and high labor intensity of the harvesting procedure, several machines and equipment also have been developed to save manpower and improve efficiency. For example, the harvesting machine that was developed by Zhang Y et al. to automatically perform the harvesting of kelp culture in a floating raft [19]. Based on this, Jiang T et al. proposed a novel automatic harvesting machine that is able to adapt to more kelp culture situations and achieve higher efficiency [20].

However, several problems such as low efficiency, high labor intensity, and clipping quality that existed in kelp seedling clipping are neglected. More importantly, the kelp seedling clipping procedure also plays a critical role contributing to the yield of kelp culture. Therefore, in this paper, we develop an automatic machine to improve the efficiency of the kelp seedling clipping and ensure the quality of kelp clipping at the same time. Compared to manual kelp seedling operation, the proposed automatic machine achieves a higher efficiency and obtains a satisfactory attachment force of the kelp seedling to the rope (that realizes a low drop rate of kelp seedlings from the rope). However, kelp seedling clipping has so far mainly relied on manpower, leading to associated problems such as harsh environments and high labor intensity [21–23]. Several enterprises, universities, and research institutions have accomplished progress in kelp seedling clipping. However, their designs mainly replicate manual clipping actions, focusing on seedling clipping functionality but facing challenges related to speed and seedling injury rates [24–30].

To address these issues, an automatic kelp seedling clipping machine is developed in this paper to improve the efficiency and ensure the quality of kelp seedling clipping. In contrast to manual methods, the developed automatic machine ensures improved efficiency and better attachment of kelp seedlings to seedling ropes, resulting in a reduced seedling drop rate. This work offers valuable data and technical guidance for future research on automatic kelp seedling clipping equipment.

2. Kelp Seedling Clipping Operation

Kelp seedling clipping is one of the key processes in kelp aquaculture. Considering kelp seedling clipping is conducted in the winter, the work is highly labor-intensive and in a wet and cold environment, as seen in Figure 1. The kelp seedlings are first clipped onto a seedling rope then placed on a raft in the sea for cultivation and aquaculture. Traditionally, kelp seedling clipping is performed manually, as shown in Figure 2. The operations involved cover four steps: rope loosening, rope unwinding, seedling clipping, and rope tightening.

Figure 1. Artificial seedling clipping site.

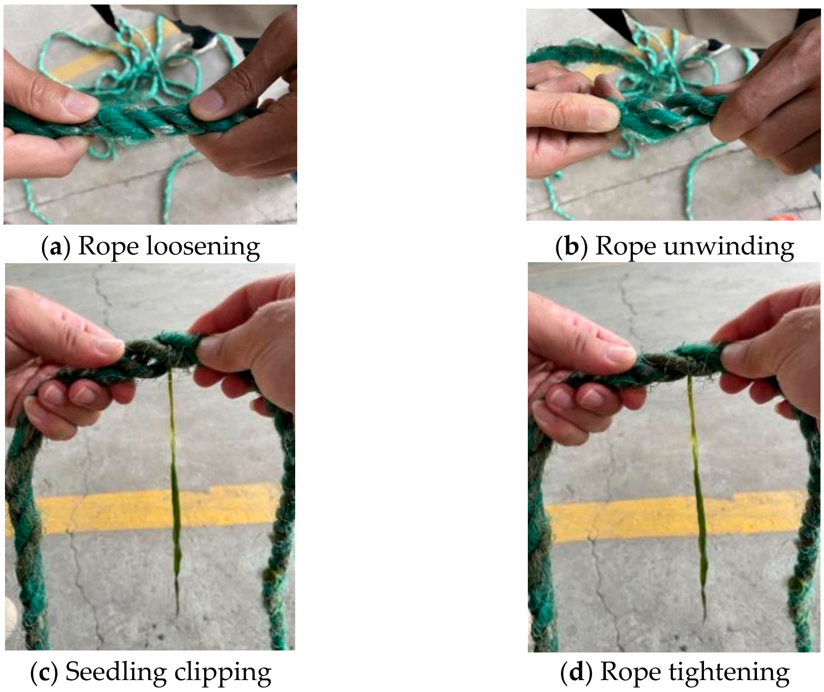

Figure 2. Operating steps for kelp seedling clipping.

As the scene (seen in Figure 1) shows, kelp seedling clipping is highly labor-intensive work in wet and cold environments. That results in relatively low efficiency. It takes an average of 3.597 s to clip one kelp seedling to the rope, taking the Yandunjiao kelp culture area in Rongchen City, Shandong Province of China as an example.

3. Materials and Methods

The automatic machine for kelp seedling clipping developed in this paper is shown in Figure 3. The automatic kelp seedling clipping equipment consists of an automatic kelp seedling clipping core device, an adjustable pneumatic damping winch device, a finished kelp seedling rope storage device, and an automatic kelp seedling feeding device. The core device carries out the function of automatic kelp seedling clipping, the adjustable pneumatic damping winch conveys the seedling ropes, the finished kelp seedling rope storage device collects and recycles the rope, and the automatic feeding device enables 30 seedling clipping stations to simultaneously deliver seedlings for automated clipping. The main technical parameters of the device are shown in Table 1. The system flow chart for kelp seedling clipping is presented in Figure 4.

Figure 3. Automatic kelp seedling clipping machine.

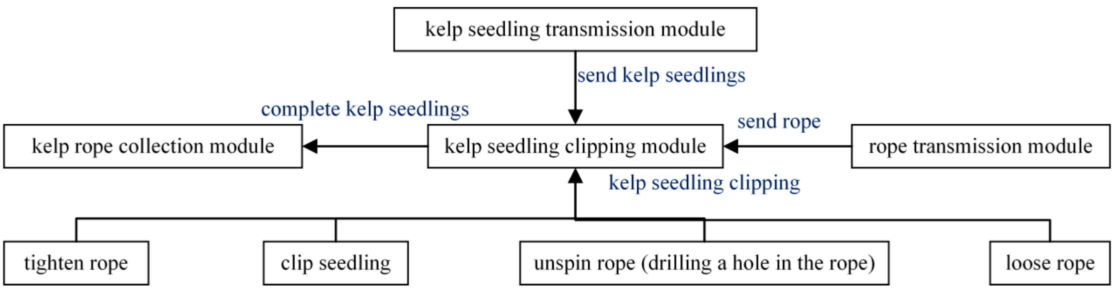

Figure 4. System flow chart for kelp seedling clipping.

Table 1. Main Technical Parameters of the Device.

Device Component	Technical Parameters	Value
Rope transmission module	Size (length × width × height) (m)	1 × 0.45 × 0.58
	Atmospheric pressure (Mpa)	0.4–0.6
	Rope length (m)	200
Kelp seedling transmission module	Size (length × width × height) (m)	1.8 × 0.58 × 0.43
	Atmospheric pressure (Mpa)	0.6–0.8
	Kelp seedlings transmission number	30
Kelp seedling clipping module	Size (length × width × height) (m)	2.8 × 1.1 × 1.7
	Power (kW)	1.2
	Clipping number one time	30
	Rope length (m)	100
	Atmospheric pressure (Mpa)	0.6–0.8
Kelp rope collection module	Size (length × width × height) (m)	1.8 × 0.68 × 2.57
	Power (kW)	0.25
	Speed (m/s)	0.1–0.5

3.1. Rope Transmission Module

An adjustable pneumatic damping winch is designed to continuously and stably transport seedling ropes to the automatic seedling clipping device. By controlling the electrical proportional pressure regulator (model: ITV2050-312), the air pressure can be adjusted to provide pre-tensioning (seedling rope clipping) and relax (seedling rope unwinding) during the clipping process. The specific method is as follows: The PLC controller analog control is set to output 0–10 V through a QW66 analog output to electronic pneumatic pressure regulator analog input. The “NORM_X standardization” and “SCALE_X scaling” commands are used to process simulated values and engineering values, which complete the conversion between analog and engineering values. The electrical proportional control valve can meet the control requirement. Algorithm control is mainly accomplished through PLC programming. At the beginning, the pneumatic is at 0.35 Mpa, when clipping, the rope pressure value is set to 0.8 Mpa, the rope is then loosened to adjust the pneumatic to 0.1 Mpa. This is realized through rope transmission module winch tension adjustment.

3.2. Kelp Seedling Transmission Module

The automatic kelp seedling feeding device automatically lifts the seedlings in the seedling box to the lower end of the clip claw for automatic clipping. The servo motor is used to drive the chain, which drives a lifting device to lift up the kelp seedlings inside the seedling box for seedling clipping.

3.3. Kelp Seedling Clipping Module

The kelp seedling clipping module is the core part of the novel automatic kelp seedling clipping machine. The specifications of the kelp seedling clipping module can be seen in Table 1. The clipping module imitates the manual procedure, which contains four steps (i.e., loosen rope, unspin rope, clip seedling, and tighten rope). The schematic diagram of kelp seedling clipping is presented in Figure 5. The rope law is employed to fix the rope. The extension head is used to drill a hole in the rope (similar to the unspin rope in the manual clipping procedure). The kelp seedling is lifted by the kelp seedling box. The clipping claw is used to clip the kelp seedling to the rope. The equipment used to help hold up the kelp seedling protects the kelp seedling and enhances the attachment performance.

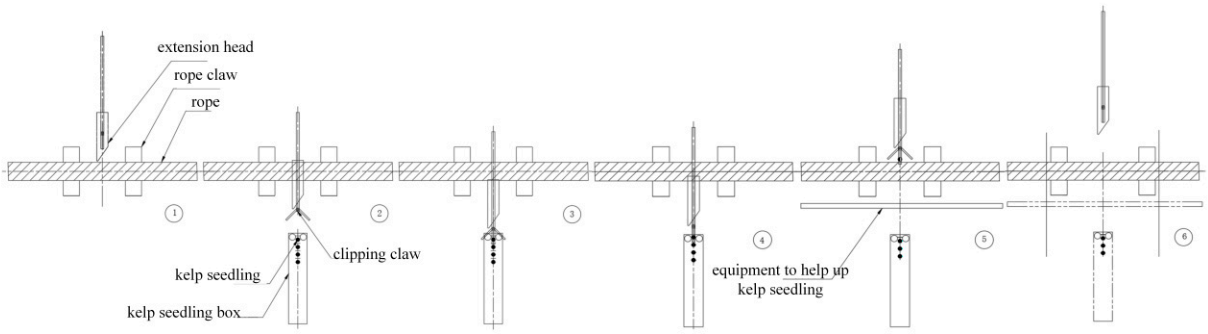

Figure 5. Schematic diagram of kelp seedling clipping.

The automatic clipping procedure is presented as follows.

(1) Use the rope claw to fix the rope.
(2) Employ the extension head to drill a hole in the rope.
(3) Use the clip claw in the extension head to clip the kelp seedling.
(4) Lift the kelp seedling in the kelp seedling box.
(5) Help hold up the kelp seedling to ensure attachment performance.
(6) Tighten the rope.

3.4. Kelp Rope Collection Module

By using a step motor to drive an inverted conical rotating device, the clipped seedling rope is stored and recycled. The conical design ensures that each layer of kelp seedling has a three-dimensional space interval protecting the kelp seedling. The inverted conical rotating device moves up and down in the vertical direction to ensure that the recovery height of the finished kelp seedling rope is always consistent, facilitating the continuous storage of ropes.

The kelp seedling clipping equipment has been made in the core technologies, which includes 30 segments of kelp seedling rope, synchronous unwinding and deflection guidance insertion rope clamping, a precision lifting type seedling box, etc. The development of this kelp seedling clipping machine has integrated the functions of automatic kelp seedling clipping, supplying seedlings, and sending and storing ropes for the first time.

4. The Control System

The control system consists of some pneumatic components and motors to realize servo speed regulation, positioning function, and an automatic clipping procedure.

The specific components contain a PLC (SINAMICS 1215C), touch screen (SINAMICS KTP-700), servo motor (SINAMICS V90), electric proportional regulating value (CNHT ITV2050-312), cylinder (AirTAC MHY2-16D), stepper motor, magnetic switch, and so on.

The novel technologies include automatic speed adjustment and positioning technology (which can realize the overall control of hole drilling of the rope and the control of the lifting of the kelp seedling box), rope unspin technology (which is able to unspin 30 parts of the rope that contributes to clipping 30 kelp seedlings at one time), and the rope transmission length adjustment technology (which is able to clip kelp seedlings in different lengths of rope).

4.1. Automatic Speed Adjustment and Positioning Technology

The accuracy and efficiency of the kelp seedling clipping are essential to kelp cultivation. The longer the kelp seedling is exposed to the air, the more water losses occur. This will result in low activity of the kelp seedling and affect the kelp yield. To improve the accuracy and efficiency of kelp seedling clipping, the servo motor is employed.

Two same-model servo motors are employed. One controls the up-and-down movement of the extension head. The other lifts the kelp seedling in the box. The rated power of the servo motor is 0.75 kW. The rated current is 2.1 A. The rated speed is 3000 rpm.

The design process is shown in Figure 5. During the test, when the upper and lower motors reach the upper part of the seedling rope, the control speed is 20 mm/s. Upon hole expansion, the speed drops to 2 mm/s to ensure stable system operation, as shown in Table 2.

Table 2. Servo Positioning.

Procedure	Range/mm	Speed/mm/s	Time/s
Drill (whole clipped seedlings descend and expanding rope head descends for hole expansion)	0~−120	10	12
Clip (seedling clipping claw descends for seedling clipping)	−120~−130	5	2
Pull up (seedling clipping claw rises to the upper part of the seedling rope)	−130~−60	5	14
Reset (whole clipped seedling returns to initial position)	−60~0	10	6

The overall upper and lower servo motors are driven by gears and racks, while the seedling feed and jacking servo motors are driven by chains. Calculation of the motor stroke per revolution in the parameter settings of the upper and lower servo motors and the jacking servo motors [31,32] gives the following:

$$L_1 = \frac{\pi d_1}{i_1} \tag{1}$$

$$L_2 = \frac{\pi d_2}{i_2} \tag{2}$$

$$d_2 = \frac{p}{\sin\left(180^\circ / z_1\right)} \tag{3}$$

$$\frac{z_2}{z_1} = \frac{n_1}{n_2} = i \tag{4}$$

$$i_2 = i \times i_3 \tag{5}$$

where L_1 is the stroke of each revolution of the up–down servo motor, L_2 is the stroke of each revolution of the jacking servo motor, d_1 is the diameter of the entire up–down indexing circle, i_1 is the overall up–down deceleration ratio, d_2 is the diameter of the jacking indexing circle, i_2 is the jacking deceleration ratio, p is the chain pitch, z_2 is the number of driven gear teeth, z_1 is the number of driving gear teeth, n_1 is the driving gear speed, n_2 is the driven wheel speed, i is the transmission ratio, and i_3 is the speed ratio of the reducer.

The test results are $d_1 = 110$ mm, $i_1 = 1:40$, $p = 12.7$ mm, $z_1 = 17$, $z_2 = 18$, and $i_3 = 100$, and it is drawn after calculation as $L_1 = 8.635$ mm, and $L_2 = 2.14$ mm.

The position setting is shown in Table 2. These meet the technical requirements of kelp seedling clipping and are suitable for kelp growth.

4.2. Rope Unspin Technology (Drilling the Hole in the Rope)

Eccentric rotation self-guided hole expansion refers to the use of a rotary motor to drive 30 hollow eccentric rope insertion heads to rotate, thereby expanding holes and inserting them from the gaps of the corresponding kelp seedling ropes and protecting the kelp claws inside the rope insertion heads from penetrating the seedling ropes.

Rope expansion tests were conducted on eight rope expansion devices. After extensive testing, the eccentric insertion head was chosen (No. 8) due to its low resistance, fast speed, and success rate of 99% in penetrating the seedling rope with no damage to the rope.

4.3. Rope Transmission Length Adjustment Technology

In response to the demand for long seedling ropes in single rope kelp harvesting, a new model for long seedling rope kelp aquaculture is adopted. During the seedling clipping process, color selection sensors are used to identify the pre-selected segments of the seedling clipping. The length information of the seedling rope is accurately identified by using the coloring standard of the seedling rope, thereby achieving the predetermined seedling rope length. Referring to the traditional seaweed raft aquaculture model, the designed distances of long rope seedling clipping are 2.3 m-2.3 m-1.5 m-2.3 m-2.3 m-1.5 m in repeated and detoured series, with no clipping at 1.5 m [20].

The test result is presented in Table 3. It can be seen that the recognition rate of reflective stickers is the highest in terms of color recognition. This solves the key technical difficulty of seedling rope length recognition in the pre-selected section of long seedling ropes, while also ensuring proper kelp seedling clipping in the selected section length. During the test, the recognition rate of the pre-selected section of seedling rope length was 100%.

Table 3. The test of color sorting sensor identification.

Mark Color	Trails No.	Successful Detection No.	Rate
Black	10	4	40%
Red	10	5	50%
Yellow	10	8	80%
Reflective	10	10	100%

Greatly affected by light, the color selection sensor suffers from recognition bias. When there is reflected light present, the reflective sticker has a high recognition rate and the sensor shows the highest accuracy. At the same time, the good ability to distinguish colors in the sea area means that reflective stickers can identify artificial and mechanical seedlings, compare them, and check the growth of kelp.

4.4. Control Circuit System Design

The automatic control system for kelp seedling clipping is implemented by means of PLC logic programming, integrating the functions of rope feeding, seedling feeding, seedling clipping, and rope retraction. Figure 6 shows the circuit diagram for the kelp seedling clipping control system.

The automatic kelp seedling clipping device can automatically complete the seedling clipping function in segments of the 100 m seedling rope, with the control system featuring both automatic and manual switching functions. Before automatic seedling clipping, the system needs to be reset, with the gripper, servo motor, etc. running to their initial positions; the 100 m marked seedling rope is then coiled onto the pneumatic damping winch. A section of the long seedling rope passes through the middle of the rope clipping claw and is fastened to the finished kelp seedling rope storage device. At the same time, the seedling box filled with kelp seedlings is installed on the automatic feeding device, after which automatic clipping begins (as shown in the Figure). The action of operation is as follows: the seedling rope storage device rotates forward to pull the seedling rope (Q8.0) → color selection (I1.5) → seedling rope storage device stops → seedling rope cylinder pre-clips (Q1.1) → pre-clip limit (I8.4) reached → seedling rope cylinder pre-tenses (Q1.0) → pre-tension limit (I8.2) reached → 30 seedling rope cylinders clip (Q0.0) → seedling rope clip limit (I0.3) reached → seedling rope cylinder pre-shrink (Q1.0) → pre-shrink limit (I8.3) reached → seedling rope cylinder pre-releases (Q1.1) → pre-release limit (I8.5) reached → 30 seedling clipping rope cylinder retracts (Q0.1) → seedling clipping rope retraction limit (I0.6) reached → rotating hole expansion motor acts (Q0.6) → seedling clipping servo motor descends for hole expansion → once in place, the seedling clipping servo motor stops, and rotating hole expansion motor stops → seedling clipping cylinder descends (Q0.4) → lower limit (I1.2) reached → seedling clipping cylinder opens (Q0.3) → seedling clipping cylinder open limit (I1.0) reached → seedling feeding platform cylinder moves forward (Q0.7) → seedling feeding platform cylinder forward and limit (I8.0) reached → servo motor lifted by 3 mm → upper and lower servo motors descend 3 mm → seedling clipping cylinder closes (Q0.2) → seedling clipping cylinder close limit (I0.7) reached → servo motor lifted by 3 mm → servo motor of the seedling clipping device moves up to the upper part of the seedling rope → seedling supporting cylinder moves up (Q8.4) → feeding platform cylinder moves back (Q0.7) → feeding platform cylinder movement limit (I8.1) reached → clipping cylinder opened (Q0.3) → clipping cylinder open limit (I1.0) reached → servo motor of seedling clipping device moves up and to initial position → seedling rope stretching cylinder (Q0.1) → stretching limit (I0.5) reached → seedling supporting cylinder moves down (Q8.4) → seedling clipping cylinder closed (Q0.2) → seedling clipping cylinder close limit (I0.7) reached → seedling clipping cylinder moves up (Q0.5) → upward limit (I1.1) reached → 30 seedling clipping rope cylinders released (Q0.0) → seedling clipping rope's release limit (I0.4) reached → kelp finished seedling rope storage device rotates forward and pulls the seedling rope (Q8.0). These actions are then repeated.

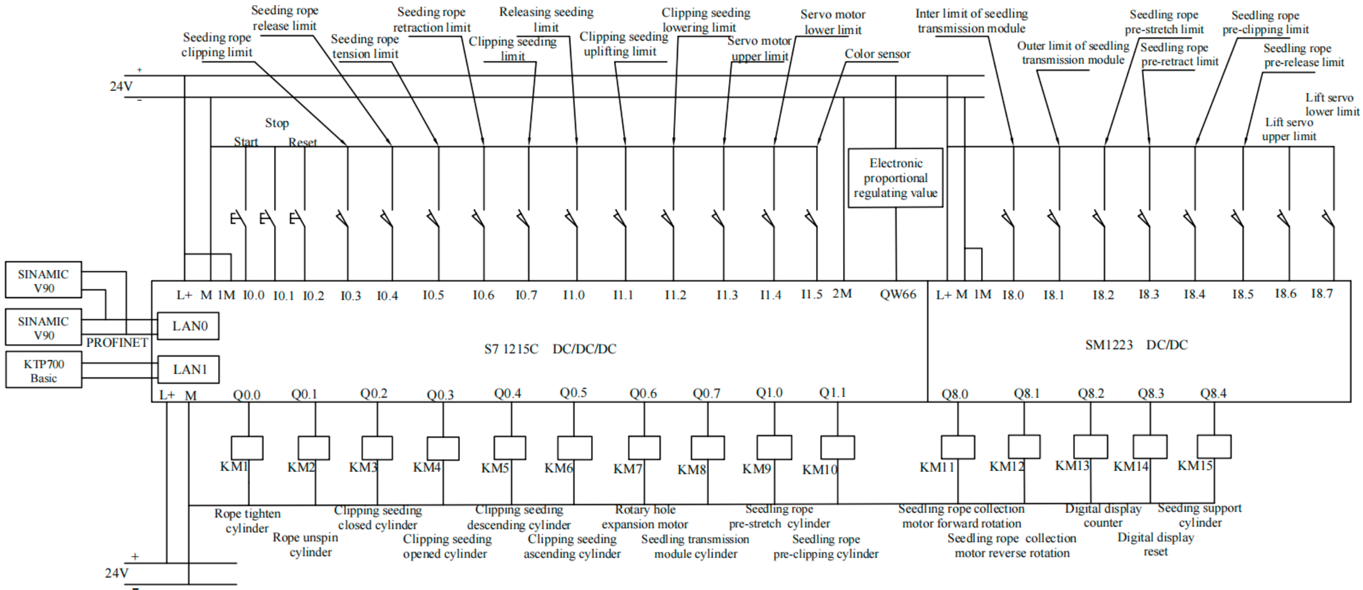

Figure 6. Circuit diagram. Note: L+ and M are 24 VDC power inputs, 1 M and 2 M are common terminals, I0.0~I1.5 and I8.0~I8.7 are input button and limit switch, AI0 is analog input, Q0.0~Q1.1 and Q8.0~Q8.4 are control outputs, SIEMENS V90 is a Siemens V90 inverter, KTP700 Basic is a Siemens KTP series touch screen, LAN0 and LAN1 are Ethernet ports, PROFINET is the communication protocol, and KM1~KM15 are 24 V intermediate relays.

In order to realize the functions of the automatic kelp seedling clipping machine, limit switch signals are added to each actuator to ensure the correct position and accurate control. The main process of seedling clipping can be summarized as follows: seedling rope clipping → untwisting → release of seedling → rope expansion → feeding seedling → clipping seedling → supporting seedling → loosening seedling → stretching → lifting → supporting seedling withdrawal → releasing seedling rope.

The automatic control system of kelp seedling clipping is mainly realized by PLC logic programming, which integrates the functions of rope sending, feeding the seedling, clipping the kelp seedling, and rope retraction. The automatic speed regulating and positioning technology is adopted to realize the speed control of the whole position of the seedling rope reaming and the precise control of the lifting distance of the seedling box. The logic sequence control technology is employed to control the pneumatic and electrical components to realize the clamping action.

5. System Test

The automatic kelp seedling clipping system was tested in the workshop of the Xunshan Group in Rongcheng City, Shandong Province. The performance indices include the running time, the successful clipping rate, and the attaching force of the kelp seedling to the rope.

5.1. Dynamic Measurement of Rotating Rope Expanding Torque and Rope Insertion Resistance

Due to the inconsistent thickness of the actual seedling rope and its different tightness at different positions, there is a certain amount of randomness in the rotation and insertion of the head into the seedling rope, which can cause motor blockage, thus affecting the stability of the operation. A dynamic testing platform for rope expansion torque and rope insertion resistance is developed in this study.

A 10-station unwinding and clipping system was used on the detection platform. The torque and resistance sensors were connected with the data acquisition measurement system on a PC through a force value display controller. During the test, the eccentric rope-expanding insertion head was moved to the upper right part of the seedling rope following equidistant unwinding, after which the speed regulating motor was switched on to drive the torque measuring part to descend down to the eccentric rope-expanding insertion head for rope expansion at a constant speed. The measured data are shown in Figure 7.

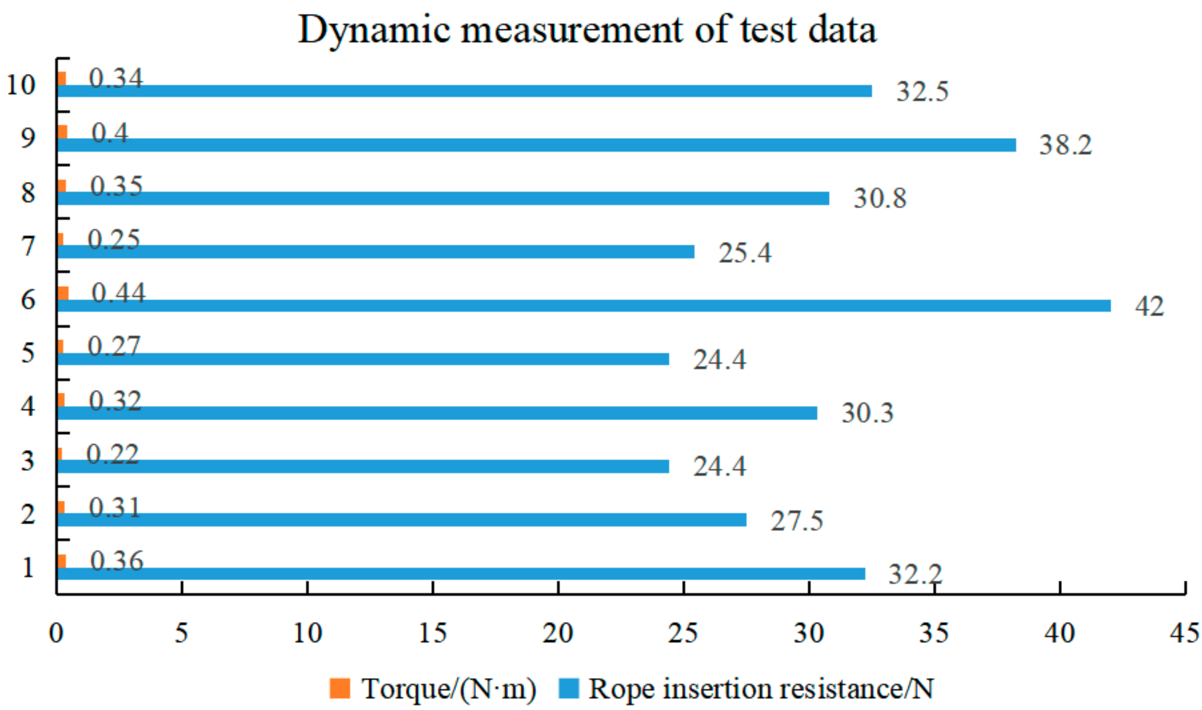

Figure 7. Dynamic measurement of test data.

Eccentric rotation self-guided hole expansion means that 30 eccentric rope insertion heads with hollow inner parts are driven to rotate by a rotary motor, after which they are inserted into the gaps of the seedling ropes corresponding to the kelp, ensuring the clipping claws inside the rope insertion heads penetrated the rope. According to the torque test results, the power calculation for the rotary motor of the rope insertion head device can be calculated as follows:

$$W = max(T_1 : T_{10}) \tag{6}$$

$$T_0 = m \times W \tag{7}$$

$$P = \frac{T_1 \times n}{9550} \tag{8}$$

$$T = F \times r \tag{9}$$

where T_0 is the total rotary insertion head torque, $T_1 : T_{10}$ are the torques of the 10 insertion heads, W is the measurement of the maximum rotary insertion head torque, m is the number of rotary insertion heads, n is the maximum speed of the motor, P is the motor power, F is the highest lower resistance, T is the rated torque, and r is the radius of the indexing circular gear.

The test results are $W = 0.44$ N·m, $T_0 = 13.2$ N·m, $n = 150$ r/min, $m = 30$ pcs, $F = 42$ N, $r = 55$ mm. The rotating motor power is obtained as $P = 0.21$ kW, with the rated voltage motor torque $T = 2.31$ N·m.

The selected rotating motor is an adjustable speed gear reduction box with a power of 0.25 kW; the lower motor is a Siemens V90 servo motor with a brake, which has a rated power of 0.75 kW, a rated speed of 3000 r/min, and a rated torque of 2.39 N·m.

5.2. System Operation Analysis

The overall operating time of the seedling clipping system can be divided into the operating time of the finished kelp seedling rope storage device and the kelp seedling clipping time. The designed seedling rope clipping length for each operation is a small 2.3 m string, rather than the large 4.6 m string used in actual aquaculture. Therefore, in the process of clipping the seedlings, the whole running time can be obtained by calculating the clipping times for first clipping 3.8 m, then clipping 2.3 m.

$$T_1 = 2 \times (T_2 + T_3) + T_4 \tag{10}$$

$$T_2 = L_3 / v \tag{11}$$

$$T_4 = L_4 / v \tag{12}$$

$$H = M / T_1 \tag{13}$$

where T_1 is the time required for a single cycle, T_2 is the operating time of the kelp seedling rope storage device, T_3 is the operating time of the kelp seedling clipping process, T_4 is the operating time of the 1.5 m long seedling rope, L_3 is the effective seedling clipping length, L_4 is the invalid seedling clipping length, v is the operating speed of the kelp seedling rope storage device, M is the number of the clipped seedlings, and H is the yield for clipped seedlings.

Through programming and system debugging, it was obtained that $L_3 = 2.3$ m, $L_4 = 1.5$ m, $v = 0.2$ m/s , $T_3 = 65$ s, $T_1 = 160.5$ s, $M = 60$ pcs, and $H = 0.374$ pcs/s. The kelp seedling system test is shown in Figure 8.

5.3. Successful Clipping Rate

In order to verify the number of dropped seedlings after clipping the kelp seedlings, and to calculate the rate of kelp seedling clipping, since kelp seedlings are prone to drop when they penetrate through the holes of the seedling rope and the opening of the clipping claws, a total of 10 tests are conducted. The results show that using automatic seedling support technology can reduce the problem of kelp seedlings dropping from the holes of the seedling rope due to their heavy weight, ensuring efficient kelp seedling clipping. The seedling drop rate is 47.7% when the seedling support device is not used. The measured number is shown in Table 4.

Figure 8. Kelp seedling clipping test.

Table 4. Drop rate of kelp seedlings.

Model	Clipping Times	Number of Dropped Seedlings	Attachment Rate
With seedling support device	10	15, 16, 14, 16, 12, 13, 14, 15, 12, 16	52.3%
Without seedling support device	10	1, 0, 0, 1, 0, 0, 1, 0, 0, 0, 1	98.7%

5.4. Attaching Force

Furthermore, the attaching force of the kelp seedlings to the rope should also be investigated. We use the puller to measure the attaching force. The attaching forces of manual clipping and automatic machine clipping are compared, and their tensile force under the old seedling rope is measured by pulling the roots of the seedlings with a tensile device, which provided a reference for subsequent tension control [33].

Additionally, the morphology of laminaria japonicus is mainly divided into leaves, stalks, and fixators, which are rhizoids. The "root diameter" and the "rhizoid diameter" correspond to the size of the stalk and the fixator, respectively. The morphology details can be seen in Figure 9.

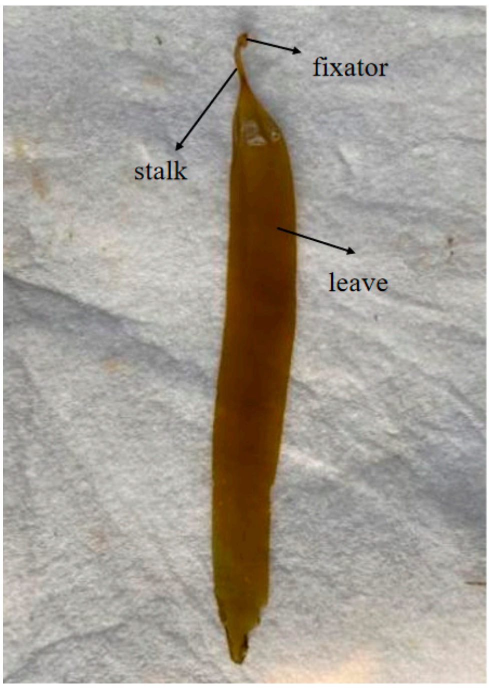

Figure 9. The morphology of laminaria japonicus.

Figure 10 presents the attaching force obtained by automatic clipping and manual clipping, respectively. It can be seen that the root diameter of kelp seedlings ranges from 2.0 (mm) to 4.0 (mm). The rhizoid diameter of the kelp seedlings is in the range of [2.8 (mm) to 10.5 (mm)]. The attaching force clipped manually is in the range of [100 (g), 500 (g)]. The mean attaching force value is 284 (g). For comparison, the attaching force clipped by the automatic machine is in the range of [100 (g), 400 (g)]. The corresponding mean value is 224.4 (g). Despite the attaching force of the seedlings clipped by the automatic clipping machine being a little less than that of the manually clipped seedlings, it still meets the requirement with a rather low drop rate.

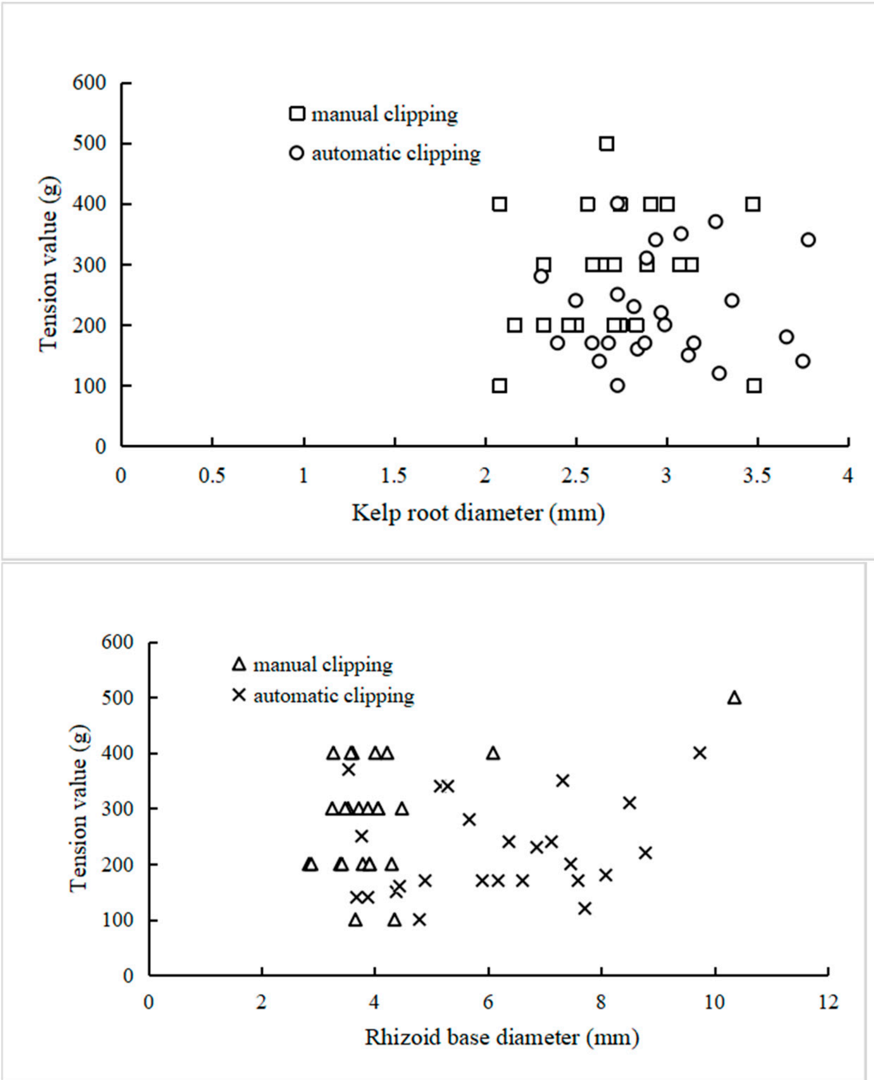

Figure 10. The attaching force of kelp seedlings to rope.

Finally, we comprehensively compare the manual kelp seedling clipping method to the automatic kelp seedling clipping method. Figure 11 shows the performances of the manual kelp seedling clipping and the automatic kelp seedling clipping.

(**a**) the performance of automatic kelp seedling clipping

(**b**) the performance of manual kelp seedling clipping

Figure 11. The performances of the manual seedling clipping and the automatic seedling clipping.

Tables 5 and 6 present the damage rate for kelp seedlings, labor demand (degree of automation), and efficiency. It can be seen that the developed automatic kelp seedling clipping machine outperforms the manual clipping method with low labor demand and high efficiency. Due to the manual clipping being random and the clipping being affected by human factors, the clipping efficiency of different operators is not consistent. At the same time, the machine is not affected by external conditions and the clipping is implemented in sequential steps, so there is no inconsistency problem. However, the probability of losing seedlings exists in both manual clipping and automatic clipping. The average efficiency of manual clipping is 1000 per/h, while the average efficiency of automatic clipping is 1350 per/h.

Table 5. Comparison of manual and automatic clipping.

Model	Clipping Cycles	Number of Seedlings (Per/Hour)	Average Efficiency (Per/Hour)
Manual clipping	10	997, 998, 996, 1002, 1004, 1003, 1001, 999, 1003, 1001, 1001, 999	1000
Automatic clipping	10	1349, 1348, 1348, 1350, 1350, 1350, 1349, 1348, 1350, 1350, 1348, 1350	1350

Table 6. The comparison of manual and automatic clipping methods.

Method	Seedling Clipping Mode	Damage Degree of Seedling Clipping	Labor Demand	Efficiency
manual clipping	clip one by one	low	high	1000 per hour
automatic clipping	clip 30 at one time	low	none	1350 per hour

Compared to manual clipping, the automatic clipping can increase efficiency by 35%. Considering the kelp seedling clipping time can last about 35 days during winter every year, the automatic clipping is able to save a lot of money and improve the clipping worker's working condition. Nowadays, the cost of manual clipping is about 600 CNY/day. Therefore, the whole cost is CNY 21,000. The electricity cost of the automatic clipping machine is 30 CNY/day, and the whole cost is $30 \times 35 = 1050$. The saving can reach up to CNY 20,000 in one year.

6. Limitations

This study also has some limitations. First, the attaching performance of the kelp seedling clipping can be further improved to ensure the subsequent kelp planting yield. Secondly, considering the solar and wind energy by the sea, the electricity cost can be further declined by utilizing photovoltaic and wind power generation. This will also contribute to the ECO development.

7. Future Perspective

The next study will consider the extension of the automatic kelp clipping machine to make it adapt to other kelp seeds and will even use this technology in the red species for which cultivation can also be based on seedling ropes. Additionally, we plan to employ the high precision servo motor to improve the attaching performance of the kelp seedling to the rope. Furthermore, we also plan to utilize photovoltaic and wind power generation to drive the equipment, in order to save electricity costs and be environmentally friendly.

8. Conclusions

Kelp seedling clipping is critical to kelp yield. However, clipping is highly labor-intensive work in a harsh environment. This results in low efficiency and an unfavorable work experience. To deal with the above challenges, we developed a novel automatic machine for clipping kelp seedlings. The automatic machine contains four modules, i.e., the rope transmission module, the kelp seedling transmission module, the kelp seedling clipping module, and the kelp rope collection module. The core module is the kelp seedling clipping module, which can attach 30 kelp seedlings to the rope at one time. And the attaching quality is relatively well-performed, compared to the manual clipping method, with a 98.7% success rate, 224.4 (g) attaching force, and 1350 clipped kelp seedlings in one hour. By contrast, the manual clipping method can only attach 1000 kelp seedlings to the rope in one hour. In a nutshell, the developed automatic kelp clipping machine outperforms the manual clipping method and lays the groundwork for automating algae farming.

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