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Autonomous Mobile Water Sample Collection Device for Ecological Floating Islands

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Abstract: In order to solve the problems of low efficiency and poor safety of manual sampling in the water quality monitoring of ecological floating islands, an autonomous mobile water sample collection device was designed. The device integrates Beidou/GPS dual-mode navigation, and has functions such as water sample collection, depth adjustment, and sampling tube sealing position movement. The sampling depth is accurately controlled by the lead screw mechanism, the control deviation is less than 10mm, and the capping torque of the capping machine can be maintained in the optimal sealing area of 2.5N-4N, which can provide a technical reference for the treatment of ecological floating islands.

Keywords: Ecological Floating Islands; Water sample; Autonomous mobility; Automatic capping; Aquatic samples.

1. Introduction

In recent decades, industrial development has led to the intensification of global water pollution, and ecological floating island technology has become the mainstream treatment method due to its advantages of high efficiency, low cost and no secondary pollution. With the popularization of ecological floating islands, the number of detection of various elements in the waters near floating islands is also increasing, and the traditional artificial water sampling method mainly has a high accident rate of manual boat sampling. It takes a long time for a single sampling, which is difficult to meet the needs of high-frequency monitoring. Human factors lead to problems such as the low pass rate of sampling points [1-2]. Therefore, the water sample collection of ecological floating islands is gradually transitioning to high efficiency and automation [3].

Zhang [4] achieved millimeter-level spatial resolution in the field of liquid sampling technology with a microdialysis sampling device, which was able to capture the instantaneous changes in solute concentration at the oxidation-anoxic interface. The device uses a reusable titanium alloy probe array, and the single sampling volume is controlled within 20 μL, which solves the defect of insufficient spatial resolution of traditional passive sampling devices. However, the complexity of the equipment and the operational expertise limit its large-scale application. Zhang [5] optimized the mechanical structure of the graphite-coated polyurethane sponge device to solve the problem of oil pollution treatment on the water surface, and used the PDMS modification process to improve the weather resistance of the material, achieving 34 times the self-weight adsorption efficiency, and its tubular design made the continuous oil-water separation flux reach 12 L/min, but still faced the risk of coating peeling in high-salinity waters. In order to investigate a simple sample collection and transportation method suitable for use outside the laboratory, Meikopoulos [6] optimized a dried urine spot device through a cellulose substrate, whose mechanical pressing structure ensured uniform sample distribution, increased amino acid recovery to 92-105%, and extended transport stability to 30 days, but there was still subjective bias in visual interpretation. In order to instantaneously sample the transition zone above the seafloor, Sauter [7] developed a multi-level bottom water sampler with a depth of 6000 m and is suitable for all types of water bodies, however, the high material cost limits its application in other fields.

To sum up, the current water sample collection device is mainly faced with the problems of insufficient adaptability to complex environments, difficult production of equipment and difficult balance of cost and benefit. Therefore, the development of an autonomous mobile water sample collection device for ecological floating islands with simple structure and low production cost is of great significance for the research of outdoor water environment such as oceans and lakes.

2. Design Methodology

2.1. Sampling Requirements

(1) Sampling Points

① Spatial distribution: According to the water morphology and the layout of the ecological floating island, sampling points are set at key locations such as the periphery of the floating island, the central area, and the water inlet and outlet to cover different pollution gradients. If there is algal accumulation in the water column (e.g., cyanobacteria floating), additional sampling sites should be added to the surface of the floating island and the area near it10.

② Stratified sampling: water depth ≤ 3 meters, only surface water samples (0.5 meters below the water surface) are collected; Water depths range from 3 to 10 m, and water samples are taken from both the surface (0.5 m) and bottom (0.5 m) layers.

(2) Containers & Pretreatment

Container selection: Use a glass water collector or a plexiglass water collector (still water) and a horizontal sampler (running water). Separate sampling for different test items, e.g. dissolved oxygen (DO) and five-day biochemical oxygen demand (BOD_5) should be filled with containers and water-sealed to avoid air residue 110. Cryopreserved samples need to allow room for expansion to prevent vessel breakage.

(3) Container Cleaning

Wash the container 2-3 times with the water sample to be tested before sampling (except for bacterial and organic matter testing items).

(4) Timing & Frequency

① Time selection: Priority should be given to sampling at 8-10 a.m. to avoid the impact of light and temperature changes on the distribution of plankton.

② Frequency setting: adjusted according to the purpose of monitoring, routine monitoring is 1-4 times per month or 1 time per quarter; The seasonal study was conducted once in spring and one in summer, focusing on algal outbreaks. Emergency monitoring, encrypted sampling for pollution events or evaluation of the purification effect of floating islands.

(5) Environmental Parameters

The following environmental parameters should be recorded synchronously when collecting water samples so that the data can be correlated and analyzed. Physical parameters: water depth, flow velocity, transparency, light intensity; Chemical parameters: dissolved oxygen (DO), pH, salinity, temperature, total nitrogen (TN), total phosphorus (TP), COD, etc.; Biological parameters: plant species, coverage, microbial activity of floating islands.

(6) Special Notes

① Sampling depth adjustment: In the dense area of floating islands, the influence of plant roots on water flow and pollutant distribution should be considered, and the sampling depth should be adjusted appropriately.

② Sample identification: The label shall contain the sampling point number, date, time, testing items and samplers, and fill in the "Groundwater Sampling Record Form" simultaneously.

③ Quality control: When stratified sampling, it is necessary to mix the water samples of each layer and take the same amount to ensure representativeness. Seal the container immediately after sampling to avoid contamination or volatilization. The collection of water samples from ecological floating islands should be combined with the characteristics of the water body, the functions of the floating islands and the monitoring objectives, and the sampling points should be scientifically set up and the operation procedures should be standardized. In the future, it can be combined with Internet of Things technology to realize real-time monitoring of water quality parameters and reduce manual sampling errors.

2.2. Implement functionality

Autonomous mobile water sample collection device equipment for ecological floating islands: The main function of this equipment in the process of use is to collect water samples from ecological floating islands in a directional manner. This is shown in Figure 1. The input quantity on the left side of the figure is the water sample, sampling information, driving energy and driving signal of the ecological floating island respectively, the output quantity measured on the right side of the figure is the sampling tube and the display sampling information respectively, the lower part of the figure is the influence of the external environment on the autonomous mobile water sample collection device equipment of the ecological floating island, its content mainly includes water waves, humidity and temperature, etc., the top of the figure is the influence of the ecological floating island autonomous mobile water sample collection device equipment on the external environment, and its content is mainly biological invasion, noise, vibration and peculiar smell.

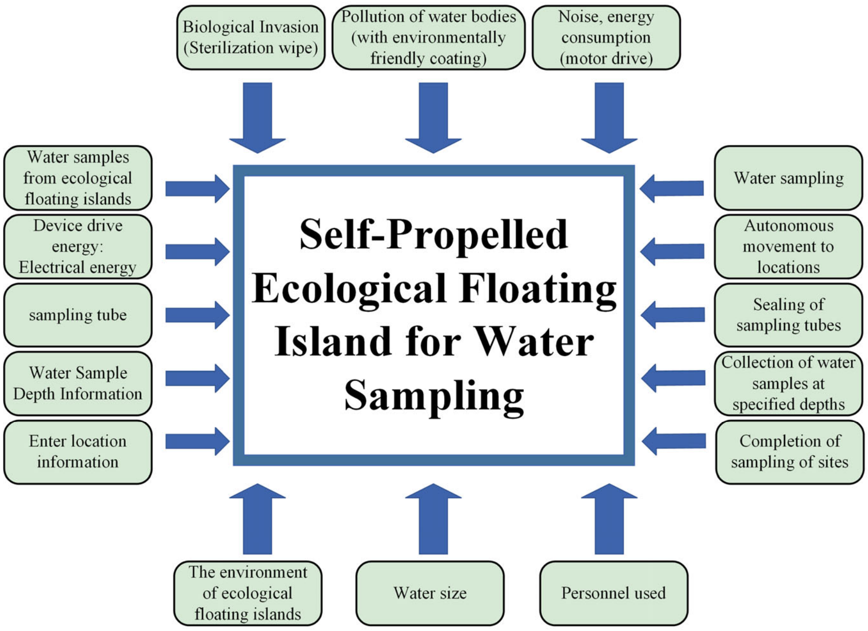

Figure 1. Schematic diagram of the black box of the autonomous mobile water sample collection device on the ecological floating island

The total function of the autonomous mobile water sample collection device equipment of the ecological floating island is to collect water samples at a designated place and a specified depth, and the total functions are roughly divided into: water sample collection function, depth adjustment function, sampling tube sealing function, control function and position movement function. The total function diagram is shown in Figure 2.

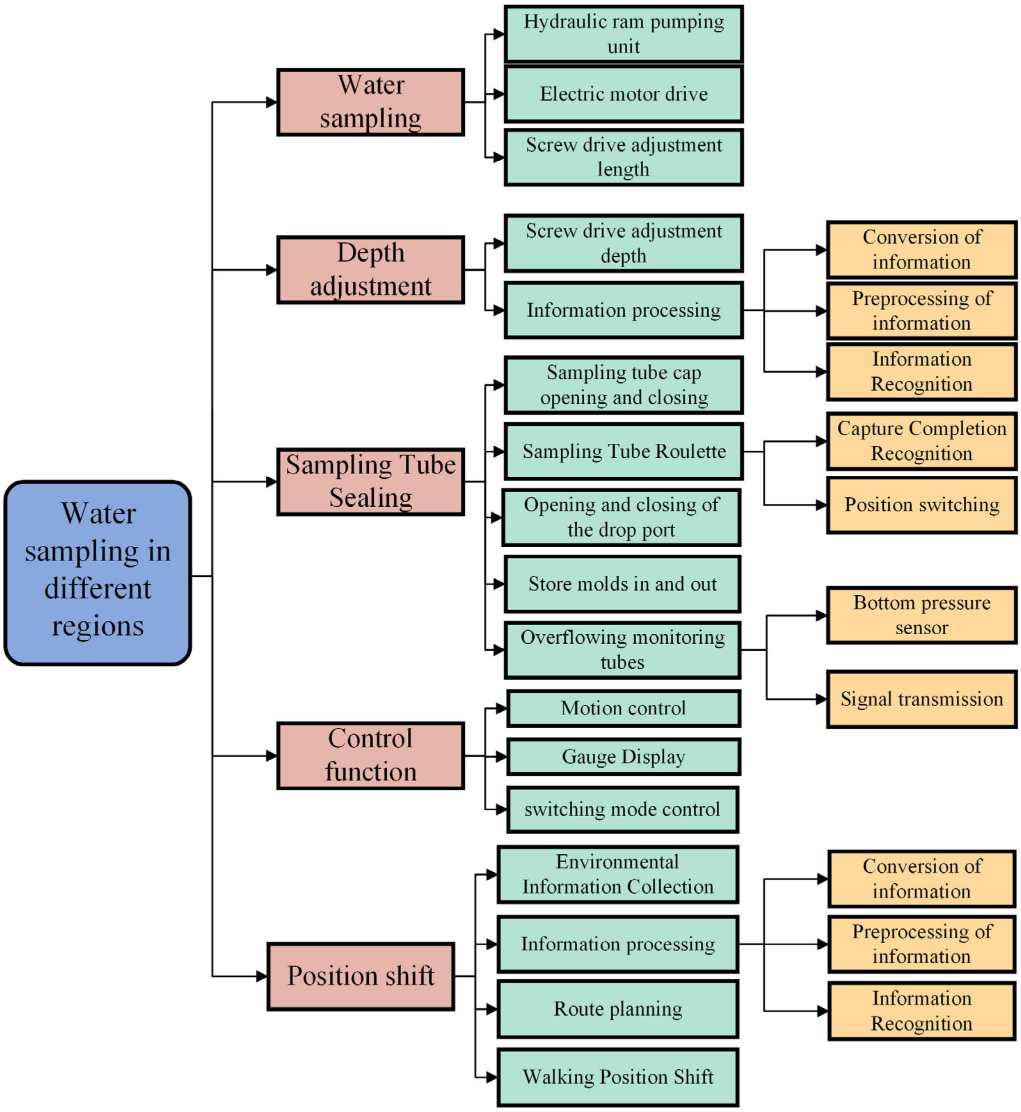

Figure 2. Diagram of the total function of the autonomous mobile water sample collection device for ecological floating islands

2.3. System composition

In order to meet the functional requirements of the autonomous mobile water sample collection device of the ecological floating island, the autonomous mobile system, water sample collection system, depth adjustment system, sampling tube sealing system and control system of the device were designed respectively. The system structure is shown in Figure 3, Autonomous mobile system: lithium battery is used as the power source, and the twin propellers are driven by brushless motors to generate thrust. According to the Beidou navigation function, the operator enters the sampling site for autonomous navigation movement. Water sample acquisition system: First, sound waves are generated into the water body through a single-wavenumber recovery detector; Then, the water depth is calculated based on the time interval; Finally, through the pumping pump cylinder, the pressure transmission power of the liquid is used to drive the actuator, and the pressure is generated to draw the water sample. Depth adjustment system: The water inlet depth of the conduit is adjusted by the lead screw mechanism and the transceiver mechanism of the device, so as to adjust the water intake depth and realize layered sampling. Sampling tube sealing system: First, the overflow of the sampling tube is monitored by the pressure sensor at the bottom of the sampling tube; Secondly, by the lead screw nut mechanism, the rotation of the motor is converted into the linear motion of the gland, thereby realizing the capping of sampling tube; Finally, the bottles are conveyed to the designated storage bin by means of a pusher-type dispensing device.

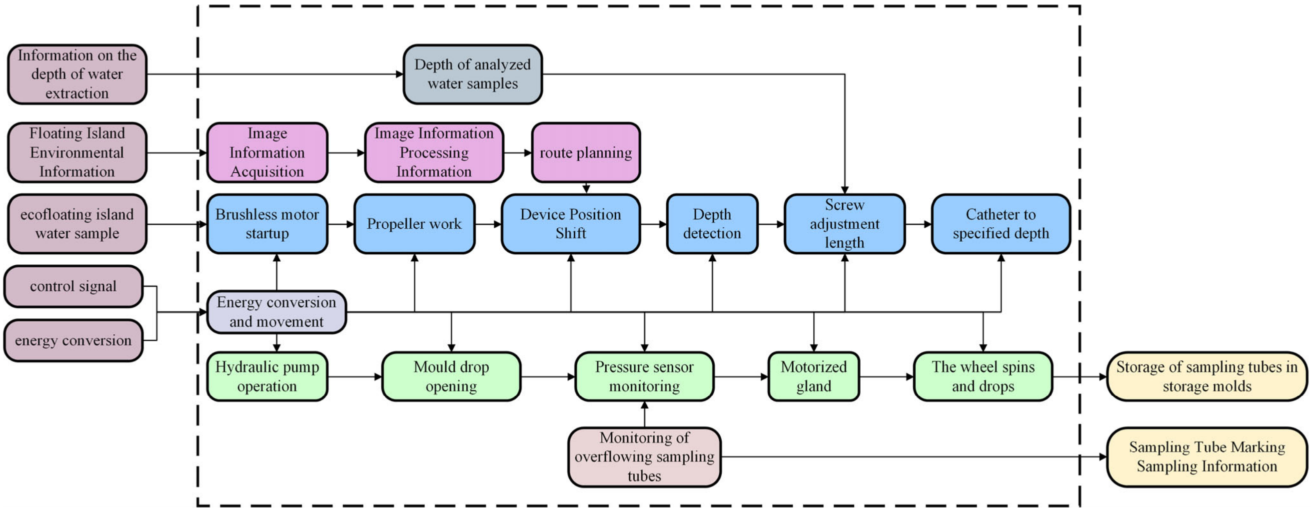

Figure 3. System structure diagram of the autonomous mobile water sample collection device for ecological floating islands

3. Process Design Scheme

3.1. Process method design

(1) When the specified depth is reached, the motor stops working, the pumping pump starts to run, the water is pumped into the sampling bottle and the collection is completed, the motor reverses, drives the workbench back to the initial position, and completes a sampling. Because the water quality monitoring of the ecological floating island has a high accuracy to the water entry, the transmission accuracy of the ball screw is high, the rotary motion can be accurately converted into linear motion, and the positioning accuracy can usually reach ±0.01mm or even higher, and is suitable for the equipment that requires high position accuracy, so the displacement legend sense measurement platform moving length is installed at the head of the workbench, so that the depth of water entry is directly obtained, and the error of the depth of water is $\leq$ 10mm, and the quality of water sample collection is guaranteed.

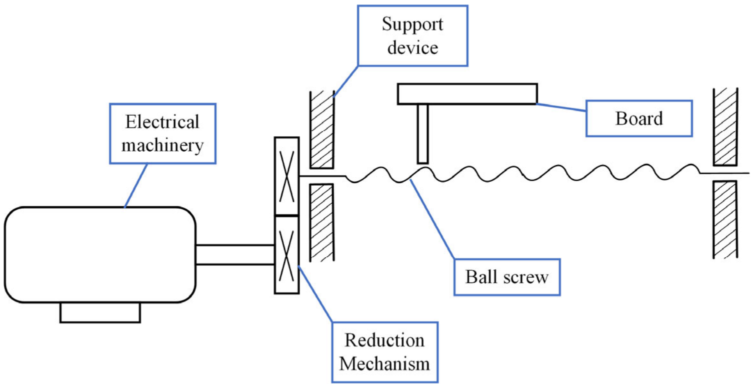

Figure 4. Schematic diagram of the principle of adjusting the depth of the ball screw mechanism

(2) Electric capping and sealing process method: As shown in Figure 5, the bottle enters the working area of the capping machine through the conveyor belt system. When the bottle reaches the work area, the sensor detects the position of the bottle and triggers the cap positioning device to ensure that the lid is accurately aligned with the bottle finish. The lid is stored in the feeder to deliver the lid to the correct location. The cap positioning device places the cap precisely above the bottle finish, preparing it for the subsequent capping operation. The lid device consists of an electric motor and a lid gripper. The electric motor rotates the cap gripper via a gear drive to place the cap on the bottle mouth. The cap gripper continues to rotate, screwing the cap into the mouth of the bottle. The force and angle of the capping can be adjusted by means of a mechanical torque adjustment function to suit different types of bottles and caps. When the cap is completely screwed into the bottle mouth, the motor stops rotating, and the bottle continues to move along the system, leaving the capping machine and entering the next process.

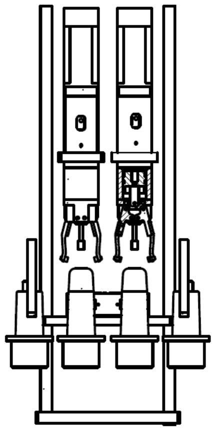

Figure 5. Schematic diagram of the principle of motorized capping sealing

3.2. Process design

(1) Action analysis of ball screw adjustment depth When the external force drives the screw to rotate, according to the principle of spiral transmission, the nut will move in a straight line along the axis direction of the screw. For example, in the feed system of machine tool, motor drives the screw rod of ball screw to rotate, makes the workbench that is arranged on the nut realize the precise linear feed movement, thereby realizes the precise water depth of adjusting workbench, and the ball screw adjustment action diagram is shown in Figure 6.

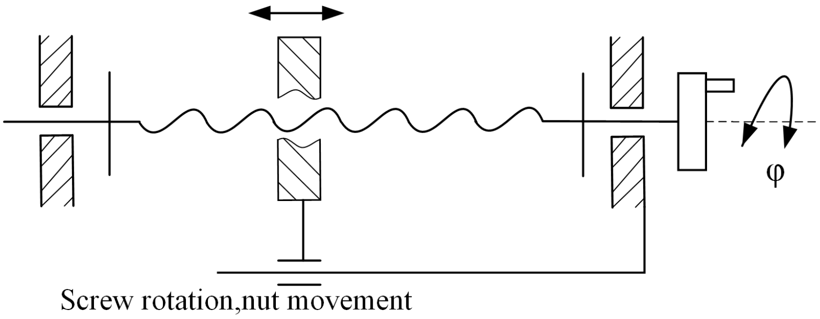

Figure 6. Ball screw adjustment action diagram

(2) Action analysis of the position conversion part of the sampling bottle

There are 12 stations on the roulette conversion position, and the position change is realized by the roulette wheel. After the screw adjusts the depth, the hydraulic pump starts to work, put the water at the specified depth on the station 1. as the sampling bottle, when the sampling bottle is full on the station I., the roulette wheel wheel can rotate, do the rotary intermittent movement, the sampling bottle that is divided on the station is transferred to the station II., realize the rotary capping. The specific process action is shown in Figure 7, and the roulette wheel does a rotary intermittent movement.

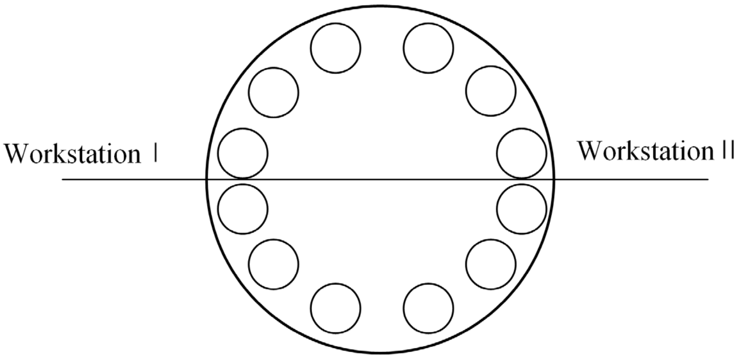

Figure 7. Interchange rotation process action

(3) Action analysis of capping of electric capping machine

When the cap is conveyed to the capping position, the positioning mechanism of the capping machine will work quickly to accurately position the cap on the bottle mouth. This is usually done through a mechanical fixture when the two are aligned, a signal is sent to start the capping action, to ensure the concentricity of the cap and the bottle mouth, and to provide a good basis for subsequent tightening. The capping head is usually driven by a motor, which drives the capping head to rotate through a transmission device (such as gears, belts, etc.). The capping head is generally made of an elastic material capping clip or capping claw, which can firmly grasp the cap. When the capping head rotates, the cap is driven to rotate by friction, and the cap is gradually tightened on the bottle mouth. During the tightening process, the speed and torque of the motor need to be precisely controlled according to the material, size and tightening requirements of the cap to ensure that the tightening force is moderate, and it will not be too tight to cause damage to the cap or deformation of the bottle, nor too loose to affect the sealing effect.

3.3. Process flow diagram design and drawing

The process of the device is divided into 5 steps, using a rotary and linear process route. The workbench moves with the lead screw and constantly adjusts the depth of water intake. Then, when the lead screw is moved to the specified position, the hydraulic unit starts to work, and the water is pumped out at the specified depth through the plunger pump, and then injected into the sampling bottle below. When the detection sampling bottle is full, the indexing mechanism under the sampling tube works, and the sampling bottle is rotated to the next station. At that time, the electric capping machine works to seal the sampling bottle. Finally, when the sampling is completed, there is a pusher feeding mechanism, and all the sampling bottles are pushed into the storage bin. The process flow diagram is shown in Figure 8.

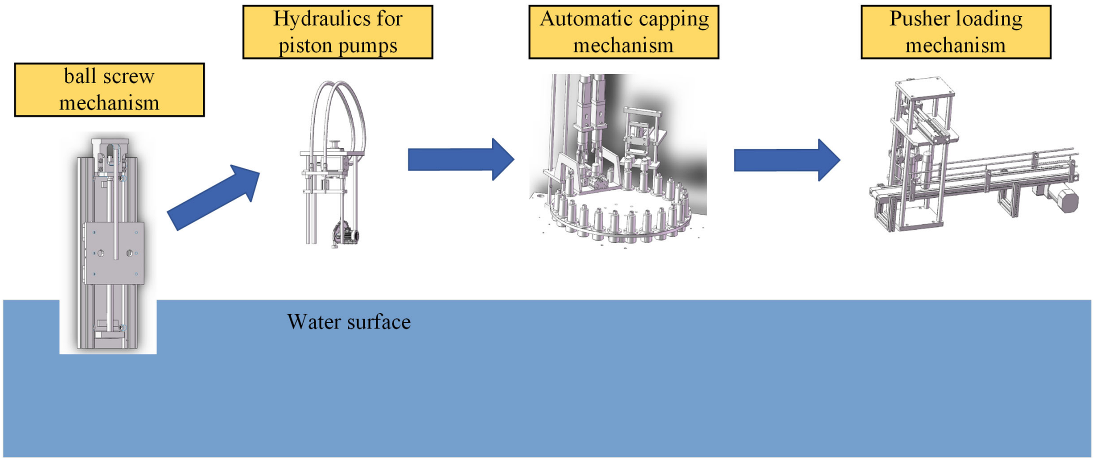

Figure 8. Process flow diagram of an autonomous mobile water sample collection device for an ecological floating island

According to the water sample collection process determined in the process plan, determine the main mechanism in the motion cycle diagram as: lead screw lifting and lowering mechanism, sampling mechanism, turntable mechanism, capping mechanism, storage mechanism, carry out time allocation to each mechanism, and the motion cycle diagram is shown in Figure 9, and the minimum time to complete the whole work cycle:

$$Tp_{min} = Tk_1+Ts_2+Td_1+Tk_2+Tk_3+3*Tk_4+Tk_5+Ts_5+Td_5+Tk_6+Ts_6. \quad (1)$$

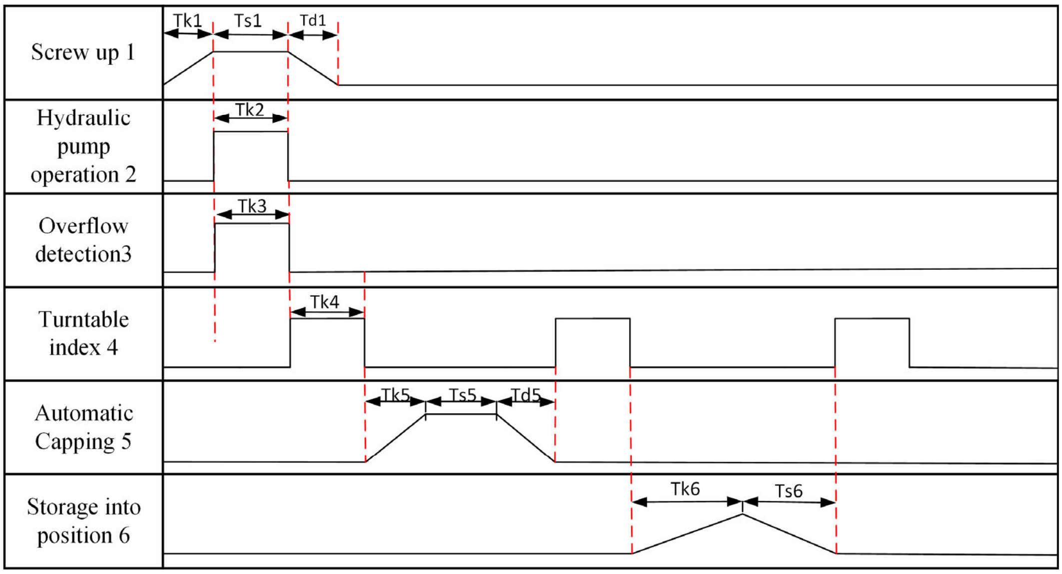

Figure 9. Diagram of the motion cycle of an autonomous mobile water sample collection device on an ecological floating island

4. Mechanical Structure Design

The table begins to do a linear reciprocating motion driven by the motor, moving towards the water area at a specified depth. The workbench on the lead screw is connected to the PU conduit and tape measure. The tape measure shrinks into the cavity and the outlet is equipped with a displacement sensor, which can monitor the length of the tape measure in real time, that is, the depth of the water under the table. When the workbench is vertically displaced to the water area that the preset hydrological layer reaches the specified depth, the lead screw stops moving, and the pumping pump starts to work at this moment, and the motor drives the impeller of the water pump, and the water is pumped to the upper container by air pressure, and the output conduit below the container is facing the sampling bottle, and the sample filling is realized. There is a pressure sensor at the bottom of the turntable fixture, which can monitor the change of the quality of the sampling bottle in real time, and when the specified sampling capacity is reached, the pumping pump stops working and the sampling ends. The servo motor of the turntable indexing mechanism starts to work, and the turntable begins to turn back to the capping station, and the capping machine realizes capping by linear motion of the cylinder. After the capping is completed, the turntable indexing mechanism works again and is transmitted back to the capping station. The mechanical structure design of the autonomous mobile water sample collection device of the ecological floating island is shown in Figure 10, and the overall layout is shown in Figure 11. When the sampling boat arrives at the designated sampling position of the ecological floating island, the sampling device is started, and the ball screw workbench on the sampling mechanism begins to do linear reciprocating motion under the drive of the motor, and moves towards the water area of the specified depth. The workbench on the lead screw is connected to the PU conduit and tape measure. The tape measure shrinks into the cavity and the outlet is equipped with a displacement sensor, which can monitor the length of the tape measure in real time, that is, the depth of the water under the table. When the workbench is vertically displaced to the water area that the preset hydrological layer reaches the specified depth, the lead screw stops moving, and the pumping pump starts to work at this moment, and the motor drives the impeller of the water pump, and the water is pumped to the upper container by air pressure, and the output conduit below the container is facing the sampling bottle, and the sample filling is realized. There is a pressure sensor at the bottom of the turntable fixture, which can monitor the change of the quality of the sampling bottle in real time, and when the specified sampling capacity is reached, the pumping pump stops working and the sampling ends. The servo motor of the turntable indexing mechanism starts to work, and the turntable begins to turn back to the capping station, and the capping machine realizes capping by linear motion of the cylinder. After the capping is completed, the turntable indexing mechanism works again and is transmitted back to the capping station. At this time, the automatic capping machine starts to work, and the capping machine head is driven by the motor, so that the capping machine head moves downward, and the capping gripper of the machine head begins to rotate, and the sampling cap is driven to rotate downward, so as to realize the capping. After the capping is completed, the capping head is returned to the initial position, and the turntable indexing mechanism works again to turn the sampling bottle back to the storage station. At this moment, the cylinder gripper begins to work, and realizes up and down and horizontal linear movement through the cylinder, so as to go to the area around the sampling bottle cap, realize positioning and grabbing, and then carry out positioning and put on the conveyor belt. The sample bottle is dropped into the sample chamber via a conveyor belt and the sample is sealed.

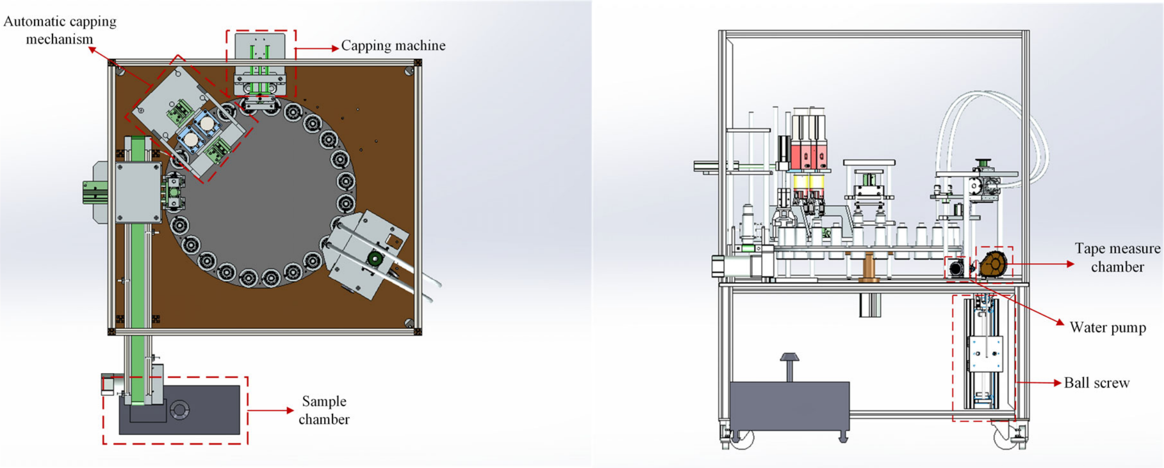

Figure 10. Overall structural design diagram

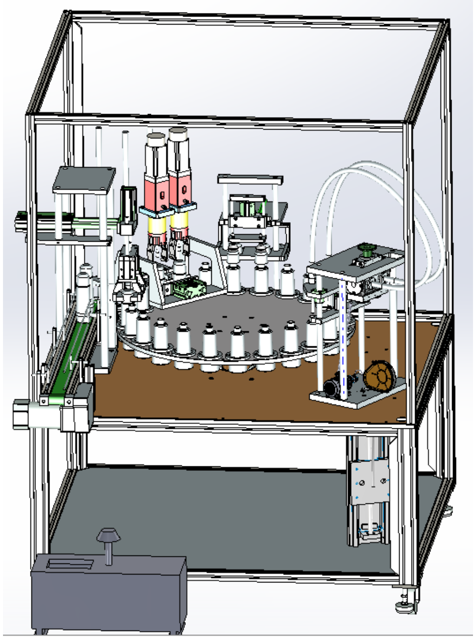

Figure 11. The general layout of the water sample collection device for the ecological floating island

5. Performance Evaluation

The torque and angle of the capping machine are analyzed, the sampling depth accuracy of the ball screw mechanism is shown in Figure 12, the deviation is shown in Table 1, and the torque and angle of the capping machine are shown in Figure 13.

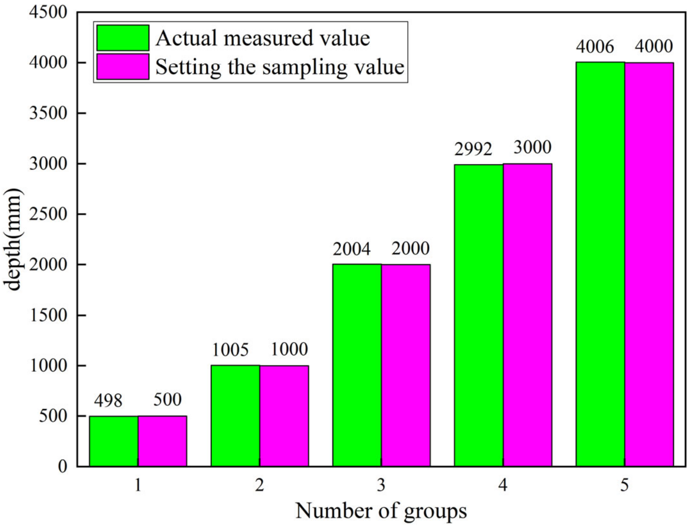

Figure 12. Comparison of sampling depth accuracy of ball screw mechanism

Table 1. The deviation between the actual water depth of the ball screw mechanism and the set depth

Numble	Set Depth (mm)	Mean Measured Depth (mm)	Maximum deviation (mm)
1	500	498	2
2	1000	1005	5
3	2000	2004	4
4	3000	2996	8
5	4000	4008	6

As can be seen from Figure 12 and Table 1, all measured points are within the error zone, with a maximum deviation of 8mm (<10mm), which proves that the lead screw mechanism meets the accuracy requirements.

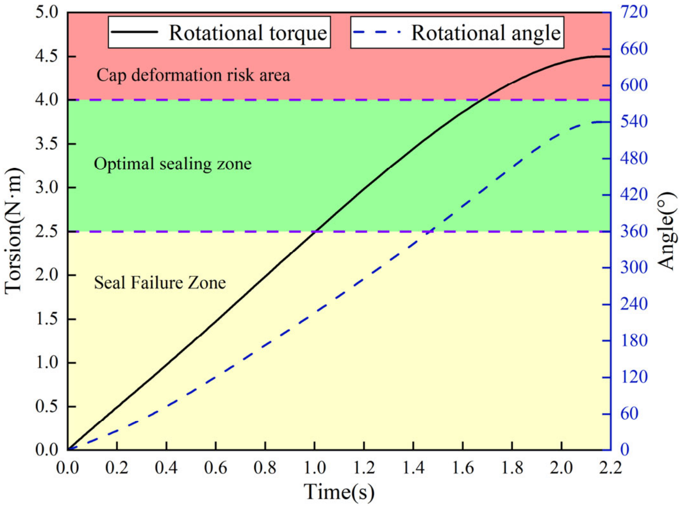

Figure 13. Torque and angle of capping machine capping over time

As can be seen from Figure 13, the capping torque of the capping machine is in the range of 2.5N-4N as the optimal sealing area, and the capping machine can ensure uniform compression of the sealing ring in the range of 360-570° rotation angle.

6. Conclusions

An autonomous mobile water sample collection device for ecological floating islands was designed. Firstly, the total functions of the device were analyzed, and the subsystem composition was determined. Secondly, the process scheme of each mechanism is formulated, and the motion process of each mechanism of the device is analyzed, and the motion cycle diagram is drawn. Finally, each part of the mechanism is integrated to form an overall structure, and the performance is evaluated from the aspects of sampling depth accuracy and torque and angle of the cap. Through the three core technologies of autonomous navigation, accurate depth sampling, and automatic packaging, the pain points of water sample collection on ecological floating islands are solved, and its modular design and low-cost structure have both engineering practicability and market competitiveness, providing innovative technical support for water ecological governance

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