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Design and Optimization of Multipoint Sampler for Seafloor Sediment Carried by a Deep-Sea Landing Vehicle

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Abstract: The present study proposes a low-energy consumption multipoint sampler carried by a deep-sea landing vehicle (DSLTV) to meet the requirements of time series sampling in local areas and location series sampling in wide areas, and an optimization method of sampling structure based on least-squares support-vector machine (LSSVM) surrogate model and a multi-objective particle swarm optimization (MOPSO) algorithm. First, the overall structure and core components, such as the multipoint sampler's sampling structure, were designed. The optimization variables were the cone angle, sampling tube inner diameter, and sampling tube inner hole length, which were determined by considering the force with which the sampling structure penetrates the seafloor sediment. Then, the sampling process was simulated by the finite element method-smoothed particle hydrodynamics (FEM-SPH) method, while the accurate LSSVM model of force required for sampling and sampling tube volume was established. Finally, the MOPSO algorithm was used for multi-objective optimization of model parameters of sampling structure. The optimal model of sampling structure that can provide theoretical support for the optimal design of multipoint sampler effectively reduces energy consumption and improves sampling efficiency by force required for sampling 25.89% lower and sampling tube volume 34.81% higher than the original model.

Keywords: deep-sea landing vehicle; multipoint sampler; sampling structure; low energy consumption; FEM-SPH method; multi-objective optimization



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1. Introduction

Sediment samples from the deep seafloor are critical for understanding changes in the marine environment, developing seafloor mineral resources, predicting long-term future climate changes, studying the diversity of marine extremophiles, and building submarine projects [1–4]. Sediment samplers, which are based on operational platforms such as research vessels and underwater vehicles, are used as operational tools for collecting sediment samples from the seafloor [5].

Sediment samplers based on the underwater vehicle have been widely used in recent years due to their advantages of minimal disturbance, refinement, and automation in the operation process, as well as the advancement in underwater vehicle technology [6–8]. Guo et al. proposed a low-disturbance in-situ encapsulation and pressure-retaining sampler for the remote-operated vehicle (ROV) platform that can separate and transfer sediment and overlying water under pressure. The sea trial is used to validate the device's feasibility [9]. Chen et al. proposed a novel sediment pressure sampling device based on a hadal-rated lander and powered by an underwater oil-filled motor. The sampling structure of the device was optimized based on the simulation results of the sampling process, and the device's feasibility was verified through field tests [10]. Liu et al. proposed an airtight sampler that can hold pressure and depends on the human-occupied vehicle (HOV) manipulator to complete the sampling operation. A design plan was released after a study of the pressure

compensation and sediment sampling rate issues. Internal pressure, high-pressure cabin, and sampler-to-manipulator adaptation tests were used to assess its viability [11]. In recent years, for different underwater operation platforms, the research on seafloor sediment samplers has advanced significantly for various underwater operation platforms, which has promoted the development of seafloor sediment sampling technology. Furthermore, most seafloor sediment samplers that have commercial applications are carried by research vessels, or HOV and ROV. Manually placed samplers or manually operated manipulators are used in sampling operations, which can meet the sampling needs of most workplaces. However, there has been little research on the automatic sampling operation of commercial seafloor sediment samplers. Deep-sea working conditions are complex and harsh, and the commercial seafloor sediment samplers are difficult to adapt to the deep-sea unmanned or cableless and mobile underwater vehicle platform. Currently, scientific research necessitates multipoint sampling of seafloor sediments to study sediment distribution characteristics in location and time series. As a result, there is still a lack of a seafloor sediment sampler and corresponding carrying platforms that can perform automatic and multipoint sampling in order to meet the requirements of time series sampling in local areas and location series sampling in wide areas.

Several scholars have studied the seafloor sediment sampler operation process by employing a simulation method to better understand its movement mechanism and stress state and minimize the test costs. Using an elastoplastic model, Chen et al. defined the sediments and simulated the sampling process using coupled Eulerian-Lagrangian (CEL) method. The effects of the installation position and the opening diameter of the core keepers in the sampling device were researched [10]. He et al. used the volume of fluid (VOF) method to simulate the sampling process. The effects of sampling speed, sampling tube diameter, drainage discharge, and dynamic sediment viscosity on coring rate and sampling volume were successfully simulated and verified by tests [12]. In addition, seafloor sediments are regarded as a solid-liquid two-phase granular mixture under loose accumulation [13]. Under disturbances, some of the particles exhibit fluid phenomena [14]. Because of its ability to discretize the model into interacting microscopic particles, the smoothed particle hydrodynamics (SPH) method approach is well suited for dealing with dynamic issues involving significant deformation and disconnected media. As a result, the solid-liquid two-phase granular model of seafloor sediments may be more accurately and convergently simulated using the FEM-SPH method [15–17]. It can be seen that it is particularly important to analyze the operation process of the seafloor sediment sampler by simulation and obtain a high-precision calculation model and then carry out the design of its model parameters to better meet the needs of scientific research.

This study proposed a low-energy consumption multipoint sampler carried by a deep-sea landing vehicle (DSL) [18–20] to meet the requirements of time series sampling in local areas and location series sampling in wide areas. The multipoint sampler uses the underwater stepping motor to drive its core component, namely the sampling structure, to penetrate the seafloor sediments for sampling. Due to the high operating cost of the DSL, which imposes stringent energy consumption restrictions and needs to reduce the operation energy consumption of the multipoint sampler, the DSL and sediment sampler are powered by the battery pack carried by the DSL. Furthermore, the volume of sediment samples is increased to improve sampling efficiency.

The rest of this study is structured as follows: Section 2 defines the design and functioning of the multipoint sampler. The optimization variables can be determined by considering the force with which the sampling structure penetrates the seafloor sediments. Section 3 uses the FEM-SPH method to obtain the test data of the force required for sampling, the sampling tube volume corresponding to each optimization variables combination, and the least-squares support-vector machine (LSSVM) model is established according to the test data. Then, the sampling structure of the multipoint sampler is optimized by the multi-objective particle swarm optimization (MOPSO) algorithm. Section 4 provides a conclusive summary of the content of this study.

2. Design of Multipoint Sampler

The DSLV can perform long-term, large-scale, and short-range fine operations on the seafloor as a new type of autonomous marine equipment. Currently, DSLV is in the stage of conceptual prototype design, and detailed parameters can be found in Refs. [11–13]. As shown in Figure 1, the multipoint sampler carried by a DSLV operation platform can meet the requirements of time series sampling in local areas and location series sampling in wide areas. DSLV operates in two modes: long period and long range. Under the DSLV's long-period working mode, the sampler can complete fixed-point observations and measurements for up to 6 months within a local range to meet the requirement that the sampler can measure the seafloor sediments over a long period, which aids in understanding the evolution process of seafloor sediments over time. DSLV can complete exploration and research in a wide area of about 10 km under the long-range working mode, meeting the requirements for the sampler to measure the characteristic position data of seafloor sediments in a wide range and helping to understand the spatial distribution of seafloor sediments. The multipoint sampler weighs 40.31 kg in air and has 25.85 kg of negative buoyancy in seawater. It has dimensions of 360 mm × 400 mm × 570 mm, installed on the chassis assembly of the DSLV bow with an installation space of 360 mm × 580 mm × 670 mm, connected to the central control cabin and battery pack of DSLV by the watertight connector, so its electrical specifications are the same as those of DSLV. The operation energy consumption of the multipoint sampler and the sampling tube size is required due to limitations such as battery pack power and bow installation space. Therefore, it is essential to minimize the force required for sampling (F_S) and enhance the sampling tube volume (V) to optimize the multipoint sampler.

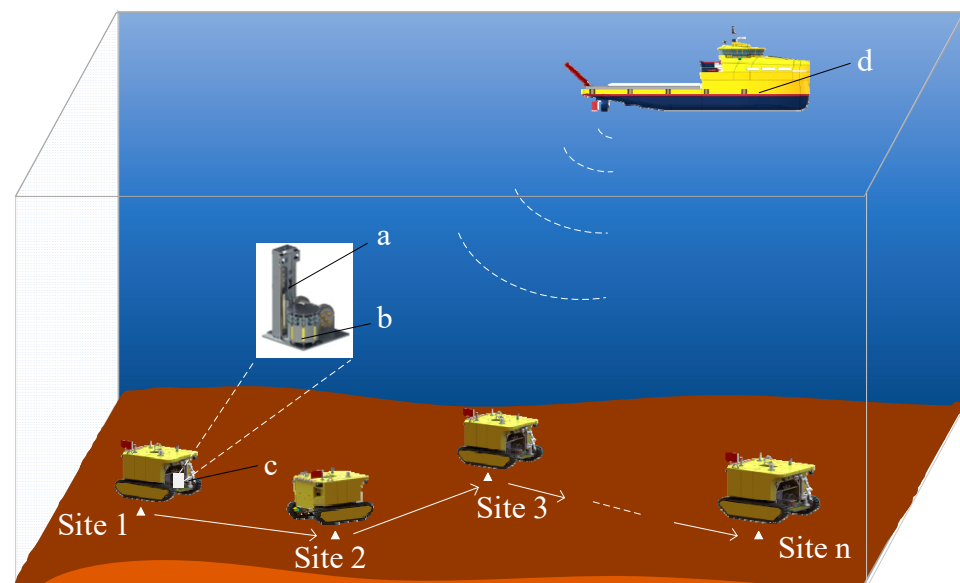


Figure 1. Schematic sketch of the demonstration mission. (Note: a—multipoint sampler; b—sampling structure; c—DSLV; d—research vessel).

2.1. Composition of Multipoint Sampler

In this study, the designed multipoint sampler investigates the sampling of eight different points by switching eight sampling structures. The multipoint sampler (Figure 2a), mainly constituting a base plate, support frame, rotary drive, sampling structure, mobile drive, and electronic cabin, is driven by two underwater stepping motors, mobile and rotary stepping motors. When DSLV reaches the sampling point, the mobile stepping motor controls the downward movement of the mobile drive through its transmission route. This enables the penetration of seafloor sediments for sampling operation by forming a linkage mechanism with the sampling structure. After that, the mobile stepping motor reverses, and the sampling structure moves upward. When it is recovered to the rotary

drive, the mobile drive is disconnected from the sampling structure. The rotary stepping motor rotates and controls the rotary drive to rotate $360^\circ/8 = 45^\circ$ clockwise to switch to the following sampling structure for the sampling operation at the next point. The process is repeated until the operation of the eight sampling structures is completed at eight points. The electronic cabin is a pressure-sealed cabin that can withstand deep-sea ultrahigh pressure and is used to install the control system of the multipoint sampler. In the future, the multipoint sampler structure will be further optimized, and more sampling structures will be added to better meet the requirements of multipoint sampling of seafloor sediments while improving the DSLV platform's operation capacity.

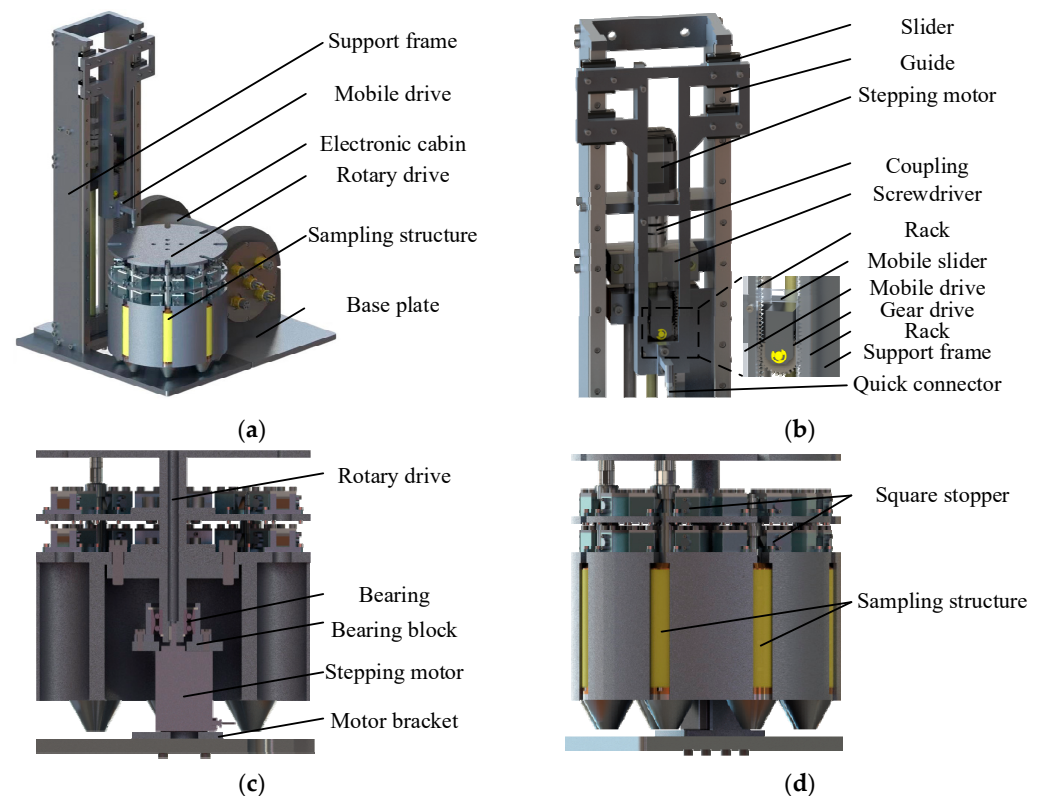


Figure 2. (a) The multipoint sampler; (b) The transmission route of mobile stepping motor; (c) The transmission route of rotary stepping motor; (d) The sampling structure location method.

The mobile stepping motor is installed in the support frame and coupled with the screwdriver to control the movement of the screwdriver's mobile slider, shown in Figure 2b. In addition, a gear drive installed on the mobile slider and the racks on both the support frame and the mobile drive increase the stroke of the mobile drive. The displacement and speed of the mobile drive are twice that of the mobile slider of a screwdriver. The mobile drive is equipped with four sliders on the support frame's two guides. The male head of a quick connector on the mobile drive is used in conjunction with the female head on the sampling structure to realize the function of connecting and disconnecting the mobile drive and the sampling structure. Therefore, the direction and speed of the mobile drive and the sampling structure were controlled by adjusting the steering and speed of the mobile stepping motor. The rotary stepping motor is installed in the motor support of the base plate and connected with the rotary drive by the flat key to switch to another sampling structure, and its transmission route is shown in Figure 2c. The damage to the motor shaft is reduced by installing a double-row angular contact ball bearing block at the motor support using screws and circlips, which can bear the rotary drive's weight. The sampling structure location method is shown in Figure 2d. The rotary drive has two layers of the square stopper in which the lower square stopper is used to locate the unsampled sampling structures while the upper square stopper is used to locate the sampled sampling

structures. The square stopper has a self-locking function. The square stopper head no longer pops up and cancels the location on the sampling structure when it is forced into the square stopper shell. The most significant advantage of the multipoint sampler's structural design is that only two stepping motors are required to complete the automatic multipoint sampling operation of seafloor sediment sample collection and storage. Furthermore, the operation sequence of the two-stepping motors is different, which reduces the difficulty in motor control and increases the feasibility of the multipoint sampler system design scheme.

2.2. Composition of Sampling Structure

The core component in the multipoint sampler is the sampling structure which enables penetration of the seafloor sediments for sample extraction by force exerted by the mobile stepping motor on its top. The sampling structure is mainly composed of a quick connector, sampling tube, syntactic shell, cylindrical shell, conical shell, catcher, circlip, ball valve, and torsion spring, as shown in Figure 3. The female connector is the sampling structure's quick connector. It is connected to the mobile drive's male connector via positioning balls stuck in the male connector's slot. When the female connector's lock sleeve moves downward, the positioning balls move outward, canceling the positioning effect on the male head and disconnecting the quick connector. The sampling tube stores seafloor sediment samples, and the drainage holes are evenly spaced on the upper sidewall. During the entry of the sediments into the sampling tube, internal seawater is discharged through the drainage holes. The basic components of the sampling structure are the syntactic, cylindrical, and conical shells. The syntactic shell can reduce the weight of the sampling structure in water, while the conical shell can reduce the sampling structure's resistance in the operation process. The cylindrical shell connects the two shells and houses other components. The circlip holds the catcher in place in the sampling tube. The catcher is made of metal flakes and will remain closed in the absence of external force. The catcher remains open when the sediments enter the sampling tube from the outside. The ball valve is installed at the connection between the cylindrical shell and conical shell, and the torsion spring is used to control the rotation to achieve a locking or sealing function of the sampling tube.

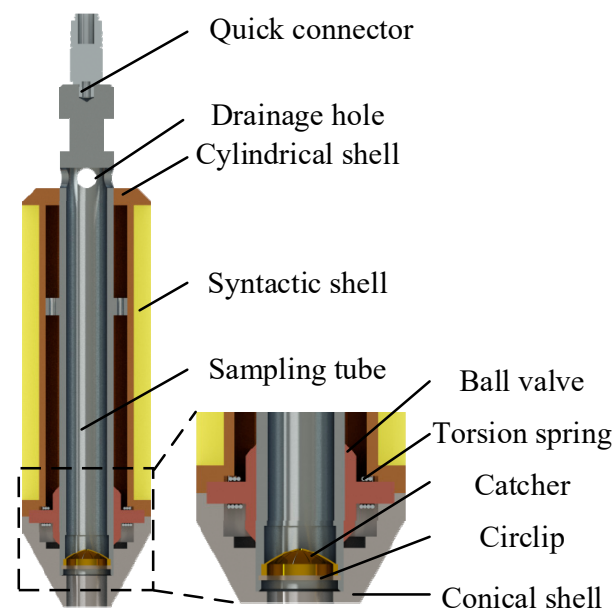


Figure 3. The sampling structure.

2.3. Operation Process of Multipoint Sampler

The penetration of the multipoint sampler into the seafloor sediments to obtain the samples is based on the sampling structure, and its operation process includes five stages, as shown in Figure 4.

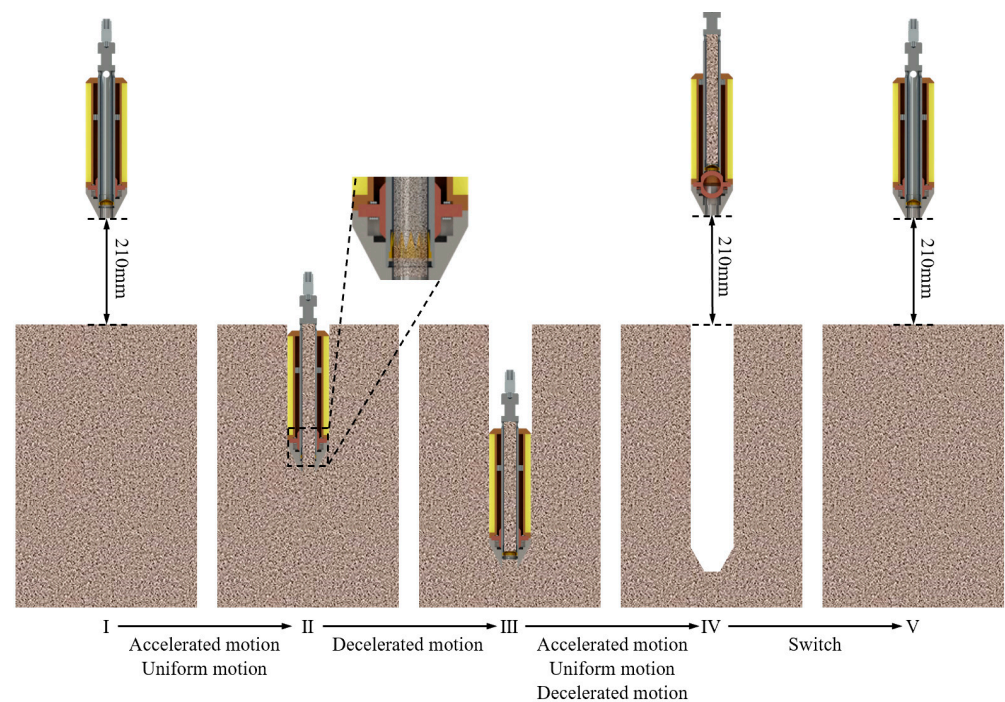


Figure 4. The operation process of the multipoint sampler.

Stage I: The eight sampling structures are positioned in the rotary drive by the lower square stopper, followed by the rotation of the torsion spring by 90° , driven by the ball valves. Further, the sampling tube passes through the ball valve. The ball valve keeps the sampling tube locked using the tension torsion spring.

Stage II: The mobile stepping motor rotates clockwise, and the mobile drive moves downward, connected with the sampling structure through the quick connector. The mobile stepping motor rotates anticlockwise to upward move the mobile drive sampling structure. The lower square stopper head is pressed into its shell to cancel the positioning effect on the sampling structure. Then, the mobile stepping motor rotates clockwise, pressing the sampling structure into the seafloor sediments. There are two stages of movement: accelerated motion and uniform motion. The bottom of the sampling structure is roughly 210 mm distant from the seafloor sediments as the multipoint sampler is mounted on the chassis assembly at the bow of DSLV, and the accelerated motion is finished in the seawater. The sampling structure penetrates the seafloor sediments at a constant speed of 30 mm/s until the sampling tube's inner hole is completely immersed in the seafloor sediments. The seafloor sediments enter the sampling tube through the opening at the bottom of the sampling structure, and associated seawater is discharged through the upper drainage hole. At this time, the catcher is in the open state. When the sampling structure moves in the seafloor sediments at a uniform speed, the largest is the F_S .

Stage III: The mobile stepping motor controls the sampling structure to slow down, and the sediment samples in the sampling tube are further compressed, which is conducive to improving the sampling rate [11] (ratio of the sample retrieved by the sampling tube to the insertion depth of the sampling tube) until itself the sampling structure no longer moves. At this point, the sediments will stop entering the sampling tube, and the holding tank will return to the closed state to pre-seal the sediment samples in the sampling tube.

Stage IV: The mobile stepping motor rotates counterclockwise, and the mobile drive moves the sampling structure upward. The movement process is also divided into acceleration motion, uniform motion, and deceleration motion. The seafloor sediments have cohesion and compressibility, and the catcher is closed. Therefore, most sediment samples are retained in the sampling tube. When the sampling structure is returned to the rotary drive, the sampling tube moves vertically upwards while the cylindrical shell is constrained

by the rotary drive and stops moving. At this time, the sampling tube is extracted from the ball valve. The ball valve is reversed by 90° under the action of the tension torsion spring to complete the reset, forming the seal on the opening at the bottom of the sampling tube to prevent the leakage of seafloor sediment samples. At the same time, the quick connector continues to move upward while the lock sleeve of the female head is restricted by a rotary drive and no longer moves. At this time, the sampling structure and mobile drive will be disconnected, and the sampling structure that has completed the sampling operation will be positioned in the rotary drive.

Stage V: The rotary drive rotates 45° clockwise to switch to the following sampling structure and carry out the sampling operation at the next point.

2.4. Force Analysis of Sampling Structure

The force applied to the top of the sampling structure by the mobile stepping motor must be greater than or equal to F_S . As can be seen, F_S determines the power output of the mobile stepping motor. Under the condition that the working time does not change, reducing the F_S can reduce the energy consumption of sampling. F_S is related to the model parameters of the sampling structure. Therefore, to determine the optimization variables, it is necessary to analyze the force of the sampling structure during operation.

From Section 2.3, the maximum value of the F_S occurs at the uniform motion stage of the sampling structure penetrating the seafloor sediments in stage II, at which time the F_S is expressed as follows:

$$F_S = F_f - F_G + F_Q \quad (1)$$

where F_f is the sampling resistance; F_G is the sampling structure gravity, and F_Q is the sampling structure buoyancy. The F_f is expressed as follows:

$$F_f = F_{fr} + F_{fa} \quad (2)$$

where F_{fr} is the restoring force caused by sediment deformation, and F_{fa} is the adsorption force caused by sediment cohesion. The schematic diagram of F_{fr} is shown in Figure 5.

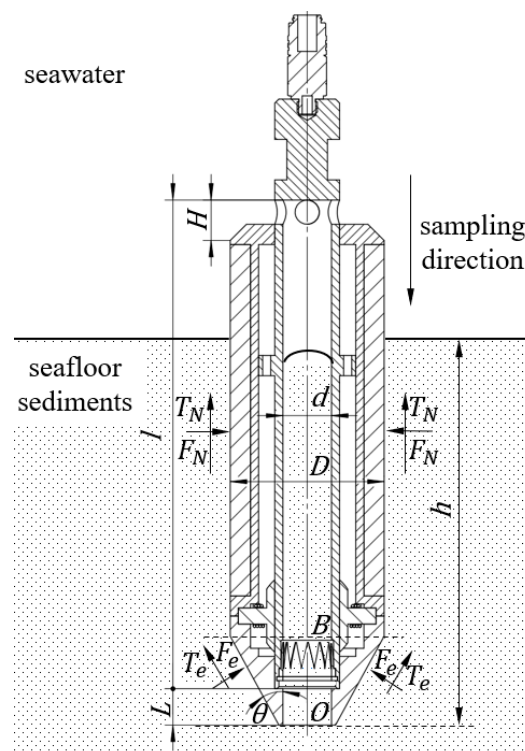


Figure 5. Schematic diagram of F_{fr} .

In Figure 5, F_e is the conical surface normal force; T_e is the conical surface tangential force; F_N is the cylindrical surface normal force; T_N is the cylindrical surface tangential force; h is the length of the sampling structure penetrating into the sediments; θ is the cone angle; d is the sampling tube inner diameter; l is the sampling tube inner hole length; D is the sampling structure diameter, and H and L are the positioning dimensions of parts during assembly. The F_{fr} is expressed in the following relation:

$$F_{fr} = F_{Q1} + F_{Q2} \quad (3)$$

where F_{Q1} is the penetration resistance, and F_{Q2} is the frictional resistance. The F_{Q1} is expressed as follows:

$$F_{Q1} = 2F_e \sin \theta + 2T_e \cos \theta = 2F_e \sin \theta + 2\mu F_e \cos \theta \quad (4)$$

The expression of F_{Q2} is expressed as follows:

$$F_{Q2} = 2T_N = 2\mu F_N \quad (5)$$

where μ is the friction coefficient between the sampling structure and the seafloor sediments.

The deformation-specific resistance of seafloor sediments was used to describe the normal force of seafloor sediments on the sampling structure per unit area. According to Kostratsyn soil resistance theory [21,22], the F_e is expressed as follows:

$$F_e = (k_{e1} + k_{p1}) A_1 \quad (6)$$

The F_N is expressed as follows:

$$F_N = k_{e2} A_2 \quad (7)$$

where k_{e1} is the specific resistance of elastic deformation of seafloor sediments on the conical surface; k_{p1} is the specific resistance of plastic deformation of seafloor sediments on the conical surface; A_1 is the contact area between the conical surface and seafloor sediments; k_{e2} is the specific resistance of elastic deformation of seafloor sediments on the cylindrical surface, and A_2 is the contact area between the cylindrical surface and the seafloor sediments.

When the sampling structure comes into contact with seafloor sediments, the F_{fa} can be expressed by the following equation:

$$F_{fa} = A_c P_{ct} \quad (8)$$

where A_c is the contact area between the sampling structure and the seafloor sediments; P_{ct} is the tangential adsorption strength between the sampling structure and the seafloor sediments. The F_f is expressed as follows:

$$F_f = \begin{cases} 2(k_{e1} + k_{p1}) A_1 (\sin \theta + \mu \cos \theta) + A_c P_{ct} & h < OB \\ 2(k_{e1} + k_{p1}) A_1 (\sin \theta + \mu \cos \theta) + 2\mu k_{e2} A_2 + A_c P_{ct} & h \geq OB \end{cases} \quad (9)$$

The sampling tube must be fully immersed into the seafloor sediments during the uniform penetration of the sampling structure into the seafloor sediments, as shown in stage II of the operation process of the multipoint sampler. The sediment penetration length of the sampling structure during this stage is greater than the conical shell height ($h \geq OB$), the maximum value of F_f appears in this process, and it is expressed as follows:

$$\begin{aligned}
F_f &= 2(k_{e1} + k_{p1})A_1(\sin \theta + \mu \cos \theta) + 2\mu k_{e2}A_2 + A_c P_{ct} \\
&= \frac{\pi(D^2 - d^2)}{2} \cdot k_{e1} + \frac{\pi(D^2 - d^2) \cot \theta}{2} \cdot \mu k_{e1} + \frac{\pi(D^2 - d^2)}{2} \cdot k_{p1} \\
&\quad + \frac{\pi(D^2 - d^2) \cot \theta}{2} \cdot \mu k_{p1} + 2\pi D \left(l + L - H - \frac{(D-d) \cot \theta}{2} \right) \cdot \mu k_{e2} \\
&\quad + \left[\frac{\pi(D^2 - d^2) \csc \theta}{4} + \pi D \left(l + L - H - \frac{(D-d) \cot \theta}{2} \right) + \pi d(l + L) \right] \cdot P_{ct}
\end{aligned} \tag{10}$$

where D is limited by the DSLV installation area, and H and L are constant in the preliminary design. Therefore, F_f depends on the model parameters, θ , d , and l , which are related to F_G and F_Q . Therefore, θ , d , and l are the optimization variables of the sampling structure. The preliminary design parameters are shown in Table 1.

Table 1. Preliminary parameters design of sampling structure.

θ (°)	d (mm)	l (mm)	D (mm)	H (mm)	L (mm)
30	12	120	39	10	10

3. Optimization of Sampling Structure

The FEM-SPH method was used in this study to simulate the operation of the sampling structure penetrating the seafloor sediments. Through the design of the test of each optimization variables combination, the corresponding F_S and V data were solved. The LSSVM model was used as the surrogate model of the test data of each optimization variable (θ , d , and l) combination, and the model parameters of the sampling structure were optimized using the MOPSO algorithm based on Pareto dominance for reducing F_S and increasing V .

3.1. Establishment of FEM-SPH Coupled Model

The F_G and F_Q are directly measured during the model building while F_f is obtained during the operation process simulation. The model was simplified for simulation purposes by ignoring components that had a minor impact on the simulation results, such as a quick connector, catcher, circlip, ball valve, and torsion spring. The conical shell and syntactic shell were made of 304 stainless steel and syntactic foam, respectively, following the design requirements and technical indicators. In contrast, the sampling tube and cylindrical shell were made of 6061 aluminum alloy. Because there has not been much research on some mechanical properties of seafloor sediments that are generally saturated clay [23], the sediments are defined using saturated clay mechanical property parameters, and the results are shown in Table 2. The modified Drucker-Prager (D-P) nonlinear elastoplastic constitutive model [24] was chosen as the sediment strength criterion.

Table 2. Mechanical property parameters of seafloor sediment (note: the data was from [25,26]).

Young's Elastic Modulus (MPa)	Poisson's Ratio	Cohesive Force (kPa)	Interior Friction Angle (°)	Compressive Strength (kPa)	Tensile Strength (kPa)
1.67	0.49	7.31	2	27.04	77.12

The F_S , which determines the power output of the stepping motor, reaches its highest value during the uniform motion stage of sampling structure penetrates the seafloor sediments; it is necessary to conduct simulation analysis in this stage. During grid division, FEM units were used for sampling structure and external (surrounding and bottom) sediments, while SPH particles were used for internal sediments. The model debugging shows that the FEM units size of sediments was 180 mm × 180 mm × 210 mm, and the SPH particles size of sediments was 160 mm × 160 mm × 200 mm. Figure 6 depicts the generated FEM-SPH coupled model of the sampling structure and seafloor sediments.

The point-to-surface erosion contact was defined between the FEM units of the sampling structure and the SPH particles of sediment. The point-to-surface solid contact between the FEM units of the surrounding and bottom sediments and the SPH particles of the internal sediments was defined. The operating speed of the sampling structure was established as 30 mm/s. The sampling tube was moved vertically downward until its inner hole was fully buried in the seafloor sediments. All free degrees of the nodes on the side and bottom of the seafloor sediments were limited to simulate and analyze the coupled model.

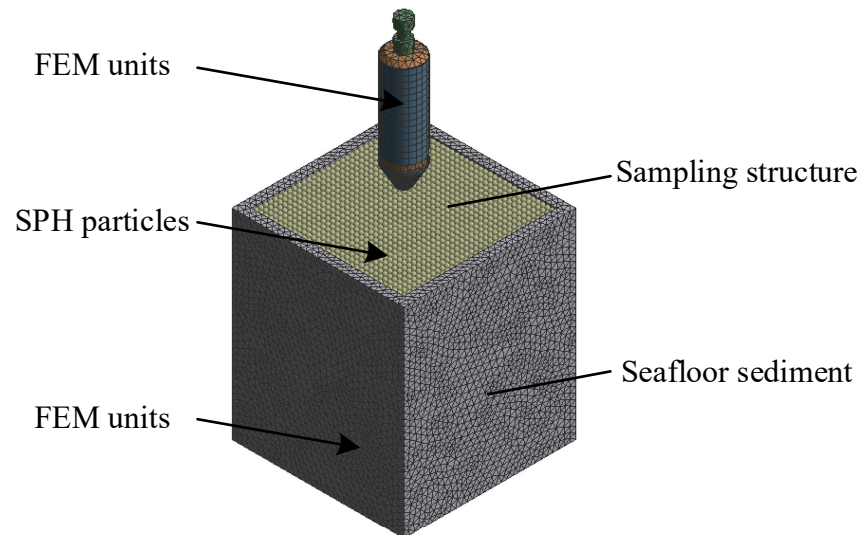


Figure 6. The FEM-SPH coupled model.

3.2. Solution and Analysis of Force Required for Sampling

As described in Section 2.4, the relationship between the input parameters, which include θ , d and l , and the two optimization objectives of F_S and V were explored by simulating the model. Therefore, a three-factor test was designed for simulation analysis. Due to the limitation of the size of the DSLV installation area and the volume index of the multipoint sampler, the ranges of θ , d , l are $20^\circ \sim 30^\circ$, 12~14 mm, and 120~135 mm, respectively. The test parameters values of a total of $4 \times 3 \times 4 = 48$ groups of tests are shown in Table 3.

Table 3. The values of the test parameters.

θ ($^\circ$)	d (mm)	l (mm)
21	12	120
24	13	125
27	14	130
30		135

The F_f change curve corresponding to each group of tests was obtained after the test simulation of 48 groups. The maximum value of F_f was obtained after low-pass filtering was used to remove the high-frequency noise from the results. The F_G and F_Q were directly calculated by the model parameters, and the corresponding F_S under each group was subsequently calculated by Formula (1), as shown in Figure 7. The results show that θ , d and l have an influence on F_S , with a minimum of F_S is 5.85 N, and the corresponding structural parameters such as the θ of 24° , d of 13 mm, and l of 120 mm. Similarly, the V is calculated from the d and l . The maximum of V is 20.77 mL, with the corresponding structural parameters such as the d of 14 mm and l of 135 mm. There is a mutual constraint relationship between the structural parameters that correspond to the minimum value of F_S and the maximum value of V . Thus, multi-objective optimization must be used to select the optimal model parameters.

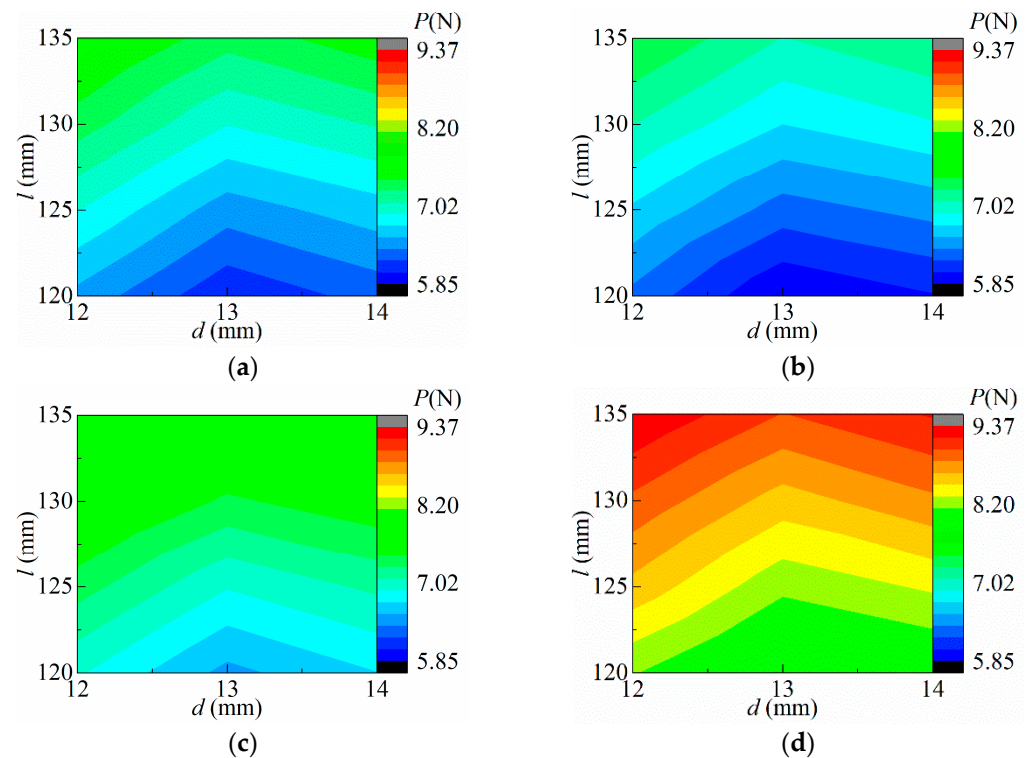


Figure 7. The simulation data of F_S to correspond to each group of tests: (a) $\theta = 21^\circ$; (b) $\theta = 24^\circ$; (c) $\theta = 27^\circ$; (d) $\theta = 30^\circ$.

3.3. Optimization Algorithm for Model Parameters of Sampling Structure

In this study, the optimization can be expressed by the following mathematical equation:

$$\left. \begin{array}{l} \min F_S(\theta, d, l) \\ \max V(\theta, d, l) \end{array} \right\} \quad 20^\circ \leq \theta \leq 30^\circ \quad 12 \text{ mm} \leq d \leq 14 \text{ mm} \quad 120 \text{ mm} \leq l \leq 135 \text{ mm} \quad (11)$$

The MOPSO algorithm steps:

Step 1: The basic parameters of the MOPSO algorithm are shown in Table 4. The position P_j and velocity v_j of particle j was initialized based on the basic parameters, where $j = 1, 2, 3 \dots K$, is the indexed particle. The functions of the LSSVM model predicting F_S and V were considered as the fitness functions. The fitness value of each particle is calculated, and the non-inferior solutions were saved in the Archive set as per the Pareto dominance principle.

Table 4. The basic parameters of the MOPSO algorithm.

Iterations	Number of Particles	Pareto Solutions
500	300	200

Step 2: The local leader was determined based on the fitness values of particles. During uncertainties in the determination of the personal best position, the solution was randomly selected as p^{best} , which is the personal historical best position. The global leader was determined based on the crowding degree of the particles in the Archive set. The lower the crowding degree, the greater the probability of particle selection as g^{best} .

Step 3: The speed and position of particles were updated, and the expressions are as follows:

$$v_j^{(k+1)} = wv_j^{(k)} + c_1r_1(p^{best} - x_j^{(k)}) + c_2r_2(g^{best} - x_j^{(k)}) \quad (12)$$

$$x_j^{(k+1)} = x_j^{(k)} + v_j^{(k+1)} \quad (13)$$

where k is the current iteration number; w is the inertia weight, $w^{(k+1)} = C_0 w^{(k)}$, C_0 is the weight attenuation factor; c_1 is the cognitive learning factor; c_2 is the social learning factor, and r_1 and r_2 are the random numbers from 0 to 1. After debugging the basic parameters of MOPSO, when the value of w is 0.8, the value of C_0 is 0.99, the value of c_1 is 1.5, and the value of c_2 is 2, the comprehensive performance of MOPSO is the best. Further, the p^{best} in the current iteration process was updated.

Step 4: The fitness of all particles in the current iteration process was compared to store the non-inferior solutions in the Archive set for maintaining and updating the Archive set to update further g^{best} . The elimination factor and mesh adaptive redivision rule were used to bring the number of non-inferior solutions down to the threshold number when it was higher than the threshold number.

Step 5: The program terminates when the number of iterations reaches the pre-determined number. Now, all the solutions stored in the Archive set are Pareto solutions. However, if the condition was not met, it would return to Step 1.

In this study, the multi-objective optimization process of model parameters of sampling structure is shown in Figure 8.

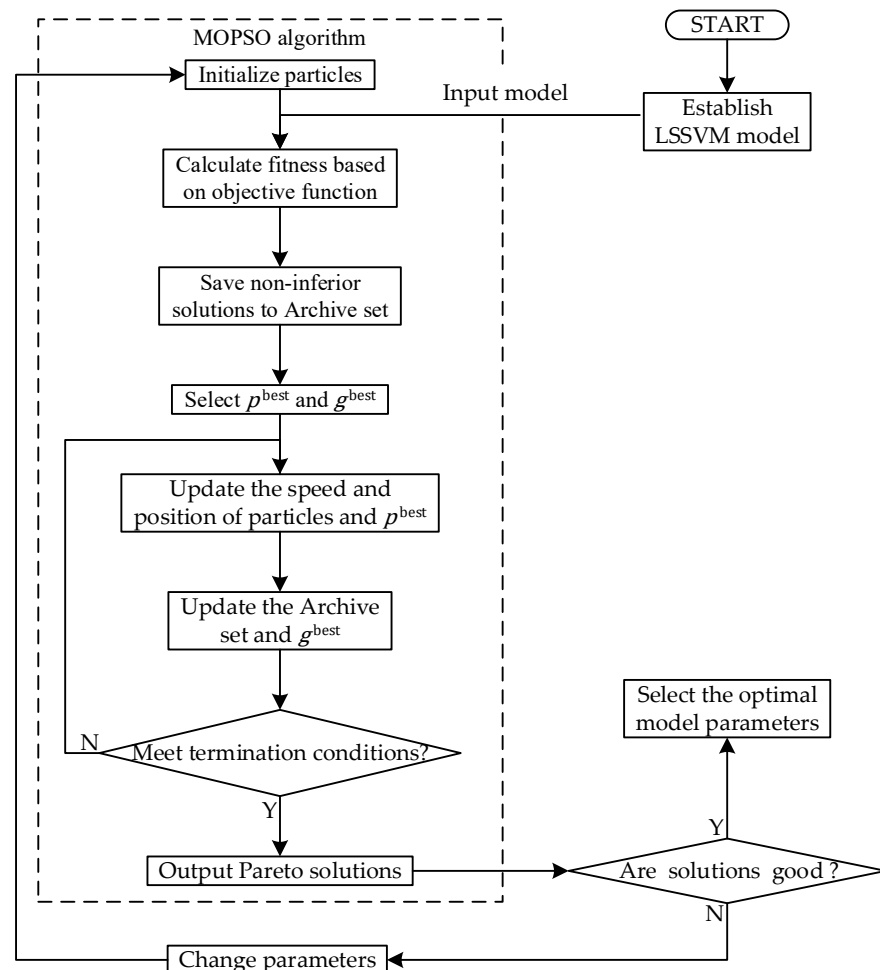


Figure 8. Schematic diagram of the multi-objective optimization process.

The 48 test values on F_5 and V were divided into 10 data groups after being randomly sorted. The 9 data groups were chosen at random to serve as a training sample for the LSSVM surrogate model to obtain the predicted values of the remaining data group. The procedure was then carried out 9 times to produce the predicted values for each data group. The comparison between the predicted values of the LSSVM model and the test values

is shown in Figure 9. The red line is a diagonal line, and 48 data points were generated according to the test and predicted values of F_S and V . The predicted values on the diagonal are equal to the test values, and all the points distribute around the diagonal with a good fitting effect.

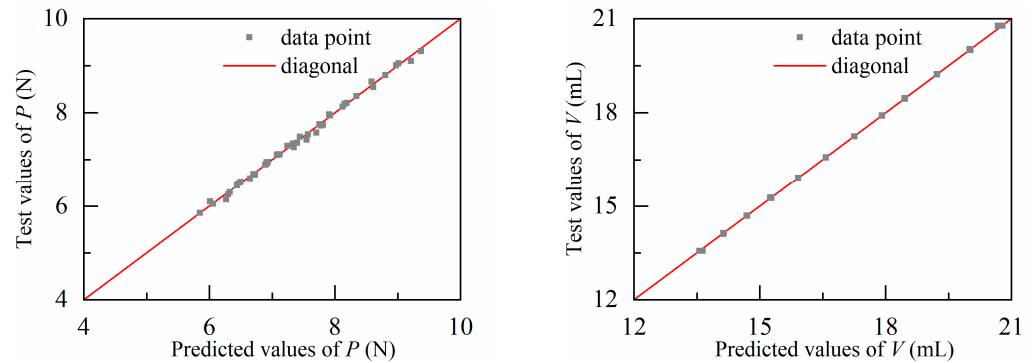


Figure 9. The comparison between predicted and test values.

The results of the model accuracy evaluation using the (mean square error (MSE), root mean square error (RMSE), the sum of squares for error (SSE), and determination coefficient (R^2)) were used to evaluate the accuracy of the LSSVM model, and the results are shown in Table 5. F_S and V have an R^2 determination coefficient that is greater than 0.97. It has been demonstrated that the LSSVM model has a low error rate and high accuracy. It also ensures the dependability of its optimization results in terms of MOPSO algorithm optimization.

Table 5. LSSVM model accuracy evaluation results.

Evaluation Result	F_S	V
MSE	0.002585	0.000719
RMSE	0.050841	0.026814
SSE	0.124066	0.0345
R^2	0.981395	0.990284

After inputting the LSSVM model and debugging the basic setting parameters, the MOPSO algorithm program was run, and the results after 500 iterations are shown in Figure 10. The Pareto solutions are the red points that are not dominated by other points. In Figure 10, the Pareto solutions are dense, continuously, and smoothly distributed on the convex curve, indicating the strong ability of the MOPSO algorithm to approximate Pareto solutions in the sample space. In addition, the spacing metric (SP) was used to evaluate the Pareto solutions using the following equation:

$$SP = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (d_i - \bar{d})^2} \quad (14)$$

where n is the number of Pareto solutions; d_i is the neighborhood distance between the adjacent Pareto solution, where $i = 1, 2, 3 \dots n$; $\bar{d}$ is the mean of all d_i . The smaller the SP value, the more uniform the distribution of Pareto solutions. The SP of Pareto solutions in this study is estimated as 0.001351, indicating that the Pareto solution distribution is relatively uniform, thus, verifying the effectiveness of the MOPSO algorithm.

However, because every Pareto solution is optimal, each one has a different preference for the two optimization objective functions of F_S and V . In this study, the optimal model parameters of the sampling structure were determined by calculating the weights of the two optimization objective functions using the entropy weight method based on the distribution law of all Pareto solutions. The calculation results of the entropy weight method show that the weight coefficients of F_S and V are 55.74% and 44.26%, respectively. After

that, the comprehensive score of all Pareto solutions was calculated based on the weight coefficient, and the model parameter corresponding to the Pareto solution with the highest score is the optimal model parameter. The calculation indicates that the comprehensive score is maximum at points (6.02, 18.33), and the corresponding model parameters are θ (23.38°), d (13.93 mm), and l (120 mm). The optimization results show that, when compared to the initial design parameters, θ decreases, d increases, and l remains unchanged. On the basis of increasing the V , the F_S is reduced as much as possible to meet the requirements of the two optimization objectives.

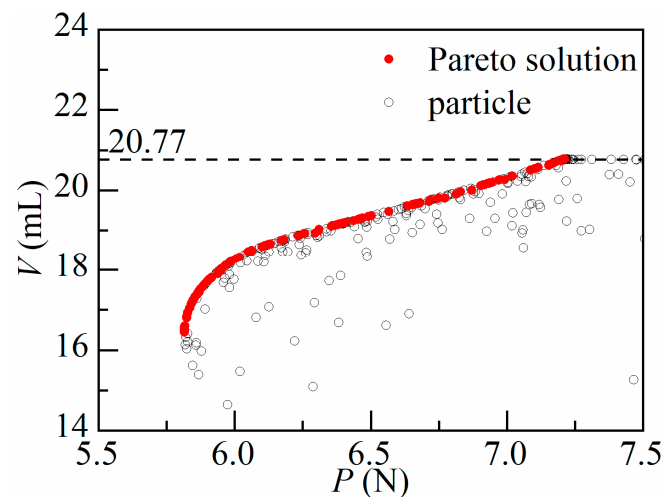


Figure 10. Pareto solutions of MOPSO algorithm.

3.4. Analysis of Optimization Results

An optimal model of the sampling structure was created using the optimal model parameters of Section 3.3 to verify the effectiveness of multi-objective optimization. The F_G of the optimal and original models are 2.40 N and 2.28 N, respectively. The F_Q of the optimal and original models are 0.96 N and 0.98 N, respectively. The F_f of the optimal model was obtained by FEM-SPH simulation, and its results were compared with the original model's sampling resistance, shown in Figure 11. As can be seen from Figure 11, the variation trend of sampling resistance of the optimal model is comparable to that of the original model. The F_f increases quickly when the sampling structure makes initial contact with the seafloor sediments and continues to rise until the conical shell completely penetrates into the seafloor sediments. Further, the F_f shows oscillation within a specific region and keeps increasing. The F_f of the optimal and original models are 7.48 N and 9.45 N, respectively, wherein the latter is 20.85% lower than the former. According to Formula (1), the F_S of the optimal and original models is 6.04 N and 8.15 N, wherein the latter is 25.89% lower than the former. The V of the optimal and original are 18.28 mL and 13.56 mL, respectively, wherein the latter is 34.81% higher than the former. The simulation value of F_S and the actual value of V of the optimal model has a small error compared to the results of multi-objective optimization, which verifies the reliability of the LSSVM model and the effectiveness of the MOPSO algorithm. Because simulation software technology is limited at the moment, there must be some errors between the simulation value and the actual value of most tests. Because of the constraints of scientific research conditions and the need to reduce test costs, the simulation method is used to collect test data to optimize the model parameters of the sampling structure. In the future, following this study's optimal model parameters, we will manufacture and test the sampling structure to validate its relevant actual test data.

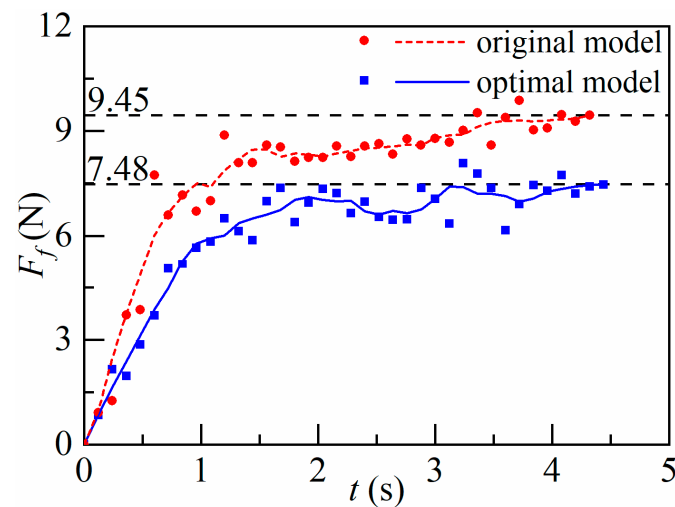


Figure 11. Comparison of sampling resistance between optimal model and original model.

4. Conclusions

This study proposes a low-energy consumption multipoint sampler for seafloor sediment based on the DSLV. When combined with the characteristics of the DSLV, the sampler can meet the requirements of time series sampling in local areas as well as location series sampling in wide areas. The sampler is powered by two underwater motors that can sample sediment without human intervention. In addition, an electronic cabin is designed to house the sampler's control system. The sampling structure is the main component of the sampler and is used to collect and store sediment samples. A torsion spring-controlled ball valve structure is intended to aid in sealing sediment samples. In order to reduce the energy consumption of the sampler and increase the sampling volume, we use the FEM-SPH method to obtain the sampling resistance test data to calculate the force required for sampling. The determination coefficient (R^2) of the LSSVM model of the force required for sampling and sampling tube volume based on test data is close to 1. Then MOPSO algorithm is used to find the optimal model parameters. Compared with the preliminary design, the force required for sampling is reduced by 25.89%, and the sampling tube volume is increased by 34.81%, which can provide theoretical support for the optimal design of a multipoint sampler.

We have currently manufactured and tested the prototype of the sampling structure's main components, and its primary functions, such as the rotation of the ball valve and the sealing of the sediment samples, have been validated. The multipoint sampler's overall prototype will then be manufactured and tested. Furthermore, we hope to investigate the multipoint sampler's control method and combine it with underwater image processing technology to achieve a better intelligent sampling effect and improve sampling structure protection. In the future, we hope that the multipoint sampler for seafloor sediment carried by the DSLV platform can be deployed in the 4500 m deep sea and the sampling effect of the system can be verified.

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