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Article

Design and simulation of reconfigurable modular snake robots with bevel gear transmission

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Abstract: With the advancement of technologies, robotics is playing an increasingly important role in various fields. The snake robot has attracted widespread academic attention due to its efficient and flexible movement characteristics. Nevertheless, its popularity and application range are constrained by complex control, low durability, and high cost. Given this, this study proposed a modular design framework based on the concept of modular design and a reconfigurable modular snake robot using bevel gear transmission. The snake robot consists of several basic module units with the same structure, which are restructured and reconfigured to achieve different shapes and functions. A standardized interface and communication protocol were optimized and designed, with each module containing an autonomous control unit and several execution units. The robot realized motion and tasks through the collaborative work of multiple modules to adapt to various work and environmental requirements. In addition, the research analyzes distributed control, improved motion control (using PID algorithm), energy management, safety design and other aspects, based on the cost data, improvement measures were proposed. At the same time, the work risks of the robot are analyzed, such as mechanical damage to the human body, adverse environment and electromagnetic interference, and corresponding solutions are proposed, and problems are found through durability testing and material improvement measures are proposed. Finally, based on SolidWorks software, a three-dimensional modeling and simulation analysis was conducted on the robot to verify its correctness. This study can provide inspiration for the design and research of snake robots.

Keywords: bevel gear transmission; modularization; snake robot; reconfigurable

1. Introduction

The application fields of snake robots are very broad. Due to their unique shape and motion mode, snake robots have specific application value in many fields. Firstly, snake robots play an essential role in rescue and search missions. With high flexibility and reconfigurability, snake robots can adapt to various complex terrains and environments, such as collapsed buildings and other hazardous areas. Importantly, they can traverse narrow passages, crawl on uneven grounds, and undergo shape reconstruction when needed to enter narrow or difficult-to-reach areas for searching and rescuing trapped individuals. Secondly, snake robots have potential application value in the medical field. It can play an important role in medical surgery by adjusting modules and reconfiguring its own structure. For example, they can pass through narrow passages in the human body for minimally invasive surgery or examination. In addition, snake robots can be used for the development of medical equipment, such as endoscopes and interventional surgeries.

Thirdly, snake robots can be applied in the industrial field. They can perform specific industrial tasks in cramped and mazy environments, such as inspecting and repairing pipelines or diagnosing and maintaining machinery and equipment. The modularity and reconfigurability of snake robots enable them to adapt to diverse industrial needs with efficient, flexible, and precise operational capabilities. Finally, snake robots can be applied in scientific research fields. Snake robots can simulate and study the motion characteristics of biological snakes utilizing their modular structures and reconfigurable properties. Moreover, by studying the control and motion of snake robots, scientists can further recognize and simulate the behavior of snake animals, thus promoting the development of robotics technology.

In the 1970s, Professor Hirose from Tokyo Institute of Technology in Japan began to study snake robots. He developed the first snake robot (Active Cord Mechanism-ACMIII) in 1972. The robot has 20 joints with a total length of 2m, driven by servo mechanisms to swing left and right. To make effective contact with the ground, the robot was equipped with casters on its abdomen [1,2]. With a maximum speed of 40 cm/s, it can only move on the plane. Dr. Gavin Miller from the United States has also made significant contributions to the development of biomimetic multi-joint snake robots. Since 1987, his team has developed a series of biomimetic multi-joint snake robots, among which the most representative is the S5 in the S series [3]. This snake robot uses passive wheels under joints for motion. Although it cannot move in three-dimensional space, its two-dimensional motion is considered to be closest to biological snakes.

Howie Choset from Carnegie Mellon University in the United States developed and produced a snake robot, "Uncle Sam". The snake robot adopted a modular design. By fixing the back of each module to the U-shaped shell of the previous module, screws connected the modules together. The back allowed the entire snake robot to be mechanically assembled. Each module only contained two screws. Modules could be completely separated by disassembling the two screws on the module and the two screws on the front module. This modular design can flexibly change the number of modules and the length of the snake robot according to actual needs, achieving various sophisticated two-dimensional or three-dimensional movements without altering the structure of the robot [4,5].

The well-known American company Tesla launched a snakelike car charger in August 2015 [6]. Simulating the structure of biological snakes, it had a fixed bottom and a head that could freely rotate and swing. It can achieve fast charging without manual operation, providing great convenience. The Norwegian University of Science and Technology developed a multi-joint snake robot for fire rescue, Anna-Konda [7], which was cleverly designed. The hydraulic drive was used to power the multi-joint snake robot and extinguish fires. Although this snake robot is a no-wheel style, it can realize multi-gait motion modes [8,9].

The first biomimetic multi-joint snake robot in China was jointly developed by Xianshi Cui and colleagues from Shanghai Jiao Tong University in 1999, and it was endowed with the winding function in 2008 [10]. Beijing University of Aeronautics and Astronautics created a control logic of "distributed bottom motion control—upper central decision-making". In 2002, a biomimetic multi-joint snake robot named Solid Snake II was developed using an orthogonal series structure [11].

With the continuous progress of science, snake robots have become increasingly advanced. Contemporary snake robots are mainly composed of several interconnected trunk modules, each of which has a similar structure and function. The motion mode of snake robots approximates the creeping of snakes, which can achieve efficient and flexible movement and turn and realize snakelike crawling, swimming, lateral movement, rolling, lifting, and obstacle crossing through recombination and reconfiguration.

Although snake robots can perfectly complete various tasks, there exist multiple limitations and technical challenges. Firstly, energy constraints. The slender physique of snake robots can limit their ability to carry energy, affecting their running time and operation efficiency. Secondly, complex control. The hyper-redundant degrees of freedom and a series-parallel structural design of snake robots challenge practical manipulation, requiring high for operators and increasing the difficulty of design and manufacture of the robot system. Thirdly, inadequate durability. Snake robots are usually used in cramped or complicated terrain, and they may be easily damaged due to environmental factors such as friction and impact. Fourthly, costly. The research and manufacturing costs of snake robots are relatively high, which may restrict the popularity and application range of snake robots.

In order to address the above issues, this paper develops a new generation of reconfigurable modular snake robots with bevel gear transmission. The snake robot adopts a transmission mechanism with bevel gears, which endows it with advantages such as high transmission efficiency, stable transmission, compact mechanical structure, small space occupation, low operating noise, and strong wear resistance. Meanwhile, the snake robot is composed of multiple basic trunk module units with the same structure, and each module contains an autonomous control unit and several execution units. Through the collaborative work of multiple trunk modules, the robot fulfills motion and tasks. Modularization provides the snake robot with a certain fault tolerance ability. When a module breaks down, it can be replaced or repaired without the need to displace the entire robot, reducing maintenance costs and time. Meanwhile, a standardized interface and communication protocol between torso modules is designed, which can enable modules to communicate and exchange data, promptly receive measurement data and information from the external environment, and fleetly accommodate diverse work and environmental requirements. This type of snake robot has broad application prospects in deep-sea operations, deep space exploration, emergency rescue, and rehabilitation medical fields, throwing insights into the application and development of snake robots.

As a novel robot structure, snake robots have extensive application prospects in the field of robotics [12]. Its structural characteristics mainly manifest as modularity and reconfigurability. This article proposes an innovative transmission method for reconfigurable modular snake robots—bevel gear transmission. Moreover, a standardized interface and communication protocol are designed to facilitate efficient communication and data exchange between torso modules. On this basis, this article puts forward an improved motion control method. By real-time monitoring and adjusting the motion status of each module, the robot’s motion ability and flexibility can be effectively promoted. Meanwhile, the improved motion control method can profoundly enhance the control accuracy and robustness of the robot [13].

2. Design of snake robot system scheme

The modular biomimetic snake robot based on bevel gear transmission is a highly flexible and adaptive mechanical system. It is designed with SolidWorks 3D modeling software by imitating the motion form and characteristics of snakes. The robot consists of three modules: snake trunk, joint connection, and snakehead. The snake trunk part includes multiple standardized and interchangeable units, each integrated with a servo motor, achieving the precise control of the robot on multiple degrees of freedom. The joint connection module adopts a bevel gear transmission design, ensuring the smoothness and flexibility of the movement. Through reconfigurable modular design, the snake robot can change their length and shape according to task requirements, highlighting its advantages in adapting to different application scenarios. The use of SolidWorks for 3D modeling and simulation analysis optimizes the structural design and motion performance. In addition, distributed control systems and central coordination processors enable the robot to achieve precise control in complex tasks.

Snake robots present extensive application potential in fields such as search and rescue, pipeline inspection, military reconnaissance, and medical operations. Special attention is paid to the safety and reliability of the robot, such as the fault diagnosis system and redundant design, guaranteeing stable operation in various environments. Overall, this innovative snake robot, with its high flexibility, adaptability, and versatility, opens up new prospects for the development of robotics technologies and has the potential to change future lifestyles and work patterns. The holistic design of the snake robot is shown in **Figure 1**.

Figure 1. The holistic design of the snake robot.

The driven mode:

(1) Forward and backward advancement, as shown in **Figure 2**:

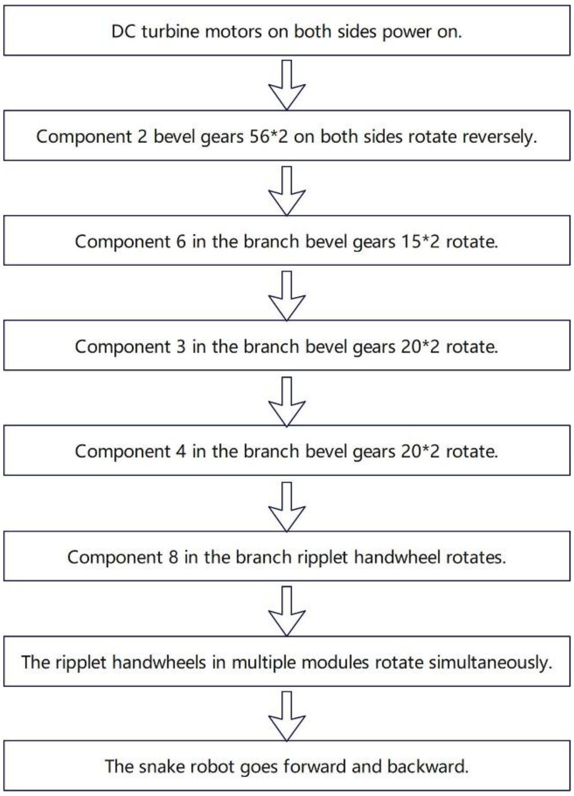


Figure 2. Forward and backward advancement.

(2) Left and right movement, as shown in **Figure 3**:

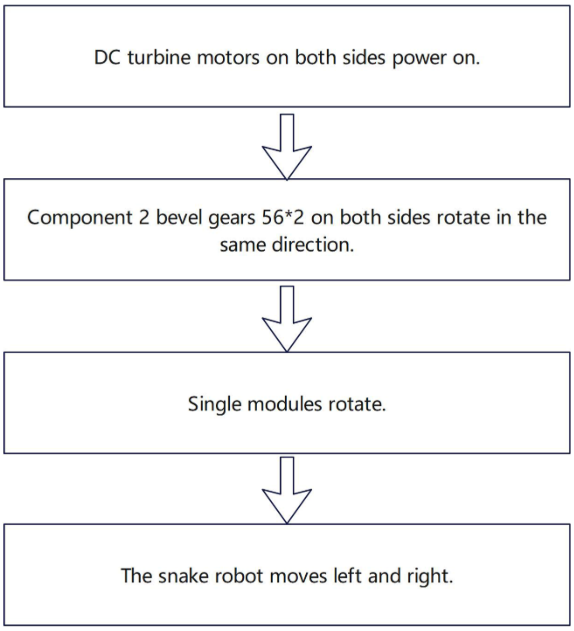


Figure 3. Left and right movement.

2.1. Design of the snake trunk module

The snake robot is composed of 16 torso modules, as shown in **Figures 4** and **5**. This modular design allows snake robots to quickly adjust and reassemble according to different task requirements and environmental conditions. The modular design of snake robots is the core of their adaptability, allowing robots to quickly adjust and reassemble according to different task requirements and environmental conditions.

Modular architecture: The modular architecture enables each module to be independently designed, manufactured, and maintained, favoring swift replacement or reconfiguration for specific applications.

Task-driven reconstitution: Based on task requirements such as search and rescue, pipeline maintenance, and geological exploration, the robot can optimize its performance by replacing modules.

Environmental adaptability: Modular design enables the robot to adapt to complex environments such as narrow spaces and rugged terrain, heightening its ability to operate in ever-changing environments.

Rapid deployment: Modular design allows snake robots to quickly respond to various operating environments and task requirements, enhancing work efficiency.

Standardized interfaces: The standardized mechanical and electrical interfaces between modules render interchangeability and interoperability, making it easy to promptly replace modules.

Bearing configuration: The jackscrew with an outer spherical ball bearing UC 201S of the GB/T 3882-2017 standard is adopted to fasten the gear guide shaft, ensuring the stability and reliability of the transmission system.

Power transmission: Through transmission components such as bevel gears, power is effectively transmitted from the motor to the joints of the robot, achieving precise control.

Distributed power system: Each module can be equipped with an independent power system, promoting the robot’s flexibility and redundancy.

Control system: With the distributed control system, each module has its own control unit while communicating with the central control unit, realizing coordination control.

Maintenance and upgrade: Modular design simplifies the maintenance and upgrade process, allowing for quick replacement of damaged modules or upgrading to new technologies, which lowers long-term operating costs.

Energy efficiency: By optimizing the weight and power distribution of modules, the entire energy efficiency of the robot is improved, especially in long-term exploration tasks.

In major applications such as search and rescue, snake robots can quickly enter narrow or dangerous spaces and utilize their flexibility and equipped sensors for life sign detection. In pipeline maintenance, robots can traverse mazy pipeline networks, detect leaks, blockages, or corrosion, and conduct necessary repairs. In geological exploration, modular design enables robots to replace corresponding sensor modules according to different terrains to adapt to changing geological conditions. This modular design significantly advances the practicality and application range of snake robots.

The design of the snake trunk module is crucial for the flexibility and adaptability of snake robots. This module adopts the modular design and achieves prompt replacement and maintenance through standardized interfaces, enhancing the system’s scalability and reliability. Each module serves as a repeating unit, following a unified design principle to ensure consistency and coordination of the entire snake body. In terms of driving, each module is equipped with a servo motor. Its torque τ can be obtained from the following formula: $\tau = Kt \cdot I \cdot V$, where Kt represents the motor constant, I denotes the current, and V stands for the voltage. These motors provide the necessary power for the motion of modules on multi-joint degrees of freedom. Torque transmission is achieved through drive mechanisms such as bevel gears, ensuring effective torque transmission. The formula Tout = i/Tin illustrates the relationship between output torque, input torque, and transmission ratio i. Distributed control allows the microcontroller of each module to independently manipulate its actions based on the received signal S, which is transmitted through the communication bus and represented as $ui = f(S)$.

The design of mechanical interfaces must meet the requirements of mechanics and kinematics to ensure structure stability and motion coordination. Its strength M concerns the yield strength σy and the cross-sectional area A of the material, denoted by $M \leq \sigma y \cdot A$. Kinematic modeling can characterize the relative motion between modules. For example, the angle θ of the rotating joint is related to the angular displacement $\Delta\theta$ of the motor, expressed as $\theta = \Delta\theta \cdot r$, where r represents the radius. Dynamic simulation is used to predict the performance of the robot under different loads, and $F = m \cdot a$ reflects the relationship among force, mass, and acceleration.

Fault tolerance is a key consideration during the design. Additional driver modules are incorporated for system redundancy. The design of thermal management needs to take into account the thermal effect of the motor. For example, the formula $Q = k \cdot A \cdot \Delta T$ is used for calculating thermal conduction, where k is the thermal conductivity. Regarding material selection, the ratio of material strength to density $\sigma Y/\rho$ is the crux of choosing lightweight and high-strength materials. The design of maintenance interfaces aims for the convenience of maintenance and simplifies the maintenance process by lessening junction points between modules.

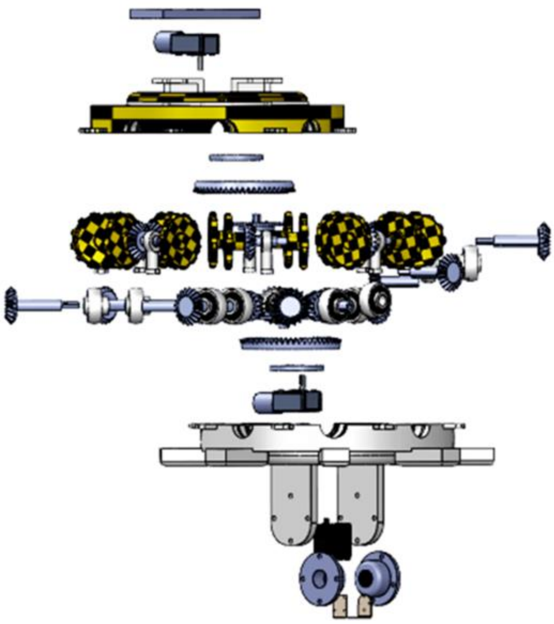


Figure 4. The exploded view of the snake trunk module.

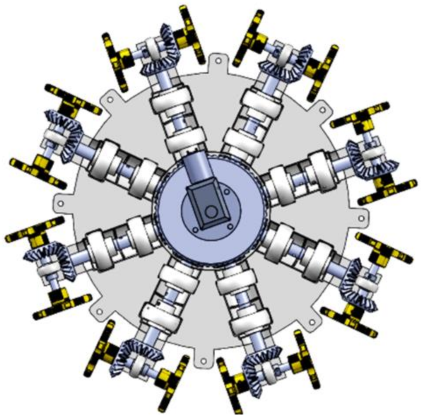


Figure 5. Internal mechanism of the snake trunk module.

2.2. Design of the joint connection module

The joint connection module is the key to modular design and the core of the entire system. This study adopts a series connection method, linking each dual shaft servo in series to form a continuous chain.

Series connection: The joint modules are connected in series to establish the main structure of the snake robot. The serial structure allows for the transfer of force and motion between modules.

Bending range: The steering engine can bend between −180° and +180°, providing a broad operating space.

Torque output: The torque T provided by the dual shaft servos equals to the torque τ of the motor. At the maximum output, T = 15 kg·cm.

Modular connectors: The design of connectors must satisfy mechanical equilibrium, such as $\sum M = 0$, where M is the torque on the connectors.

Control algorithm: The PID (Proportional Integral Differential) control algorithm is used to accurately adjust the position of the servo: $u(t) = Kp \cdot e(t) + Ki \cdot \int e(t)\, dt + Kd \cdot dt/de(t)$.

Mechanical limit: The mechanical limit design employs limit switches or limit screws to avert joint over stroke.

The design of the joint connection module adopts the jackscrew with an outer spherical ball bearing UC 201S of the GB/T 3882-2017 standard to fix the gear guide shaft, ensuring the stability and reliability of the transmission system. Moreover, the precise control of dual shaft servos enables the snake robot to fulfill continuous chain motion, enhancing its adaptability in complex environments. Through the design of this joint connection module, the snake robot can achieve highly flexible movement and adapt to diverse working environments, such as exploring narrow spaces, traversing complex terrains, and performing fine operations, significantly enhancing its effectiveness and reliability in practical applications. As shown in **Figure 6**, the dual shaft servos control the posture bending of the snake robot within a range of 180° and a maximum torque of 15 kg. Multiple modules are linked by connectors to compose the whole body of the snake robot, allowing the robot to bend and twist like a snake. Part of the specific parameters of the servos are listed in **Tables 1** and **2**, and PWM Control is shown in **Figure 7**.

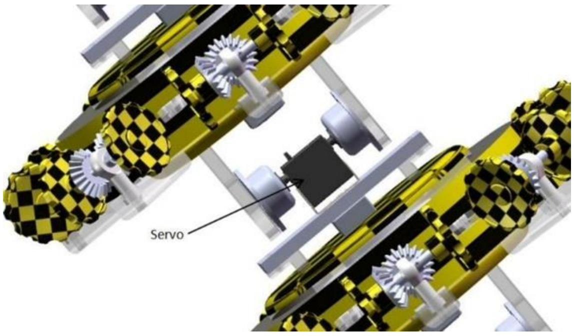


Figure 6. The joint connection module.

Table 1. Electrical Specifications.

No.	Item	Specification	
1-1	Operating Voltage	5 V	6.8 V
1-2	Idle current (at stopped)	4 mA	5 mA
1-3	Operating speed (at no load)	0.16 sec/60°	0.14 sec/60°
1-4	Stall torque (at locked)	15 kg·cm	17 kg·cm
1-5	Stall current (at locked)	1.8 A	2.2 A

Table 2. Control Specifications.

No.	Item	Specification
2-1	Control System	PWM (Pulse width modification)
2-2	Pulse width range	500–2500 µsec
2-3	Neutral position	1500 µsec
2-4	Running degree	180° (when 500–2500 µsec)
2-5	Dead bandwidth	3 µsec
2-6	Operating frequency	50–330 Hz
2-7	Rotating direction	Counterclockwise (when 500–2500 µsec)

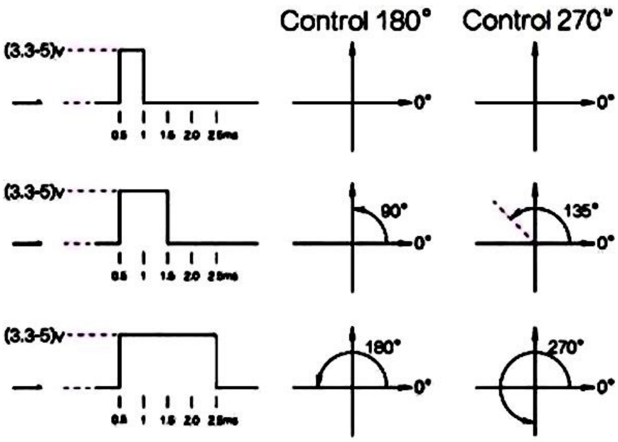


Figure 7. PWM control.

2.3. Design of the snakehead module

The snakehead module of the snake robot adopts a four-finger mechanical gripper mechanism, which endows the robot with strong grasping ability and high flexibility to grab objects of different shapes and sizes. The detailed design of the snakehead module is shown in **Figures 8** and **9**, mainly including part ① the motor and part ② screw control. First, four-finger grasping can achieve various grasping modes, such as parallel grasping, diagonal grasping, circular grasping, and triangular grasping, suitable for objects of different shapes 14. Second, it can realize multiple grasping forces, including point contact force, line contact force, and surface contact force, fit for objects of different sizes. Third, four-finger grasping can achieve diverse grasping postures, such as horizontal grasping, vertical grasping, and inclined grasping, applicable to objects in different positions.

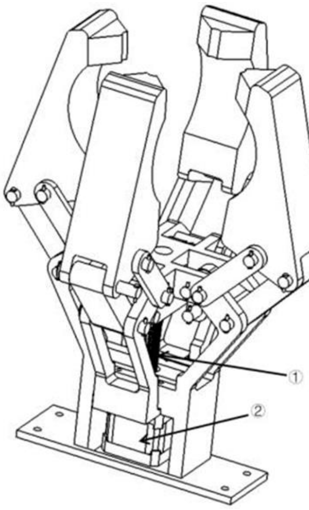


Figure 8. The snakehead module design a.

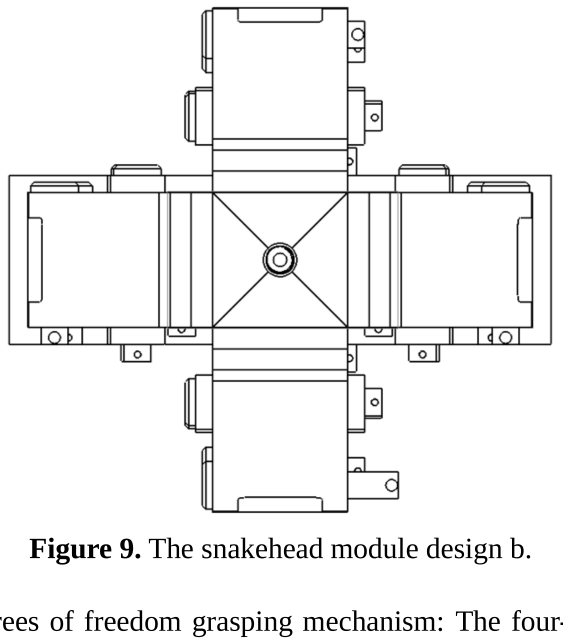


Figure 9. The snakehead module design b.

Multiple degrees of freedom grasping mechanism: The four-finger mechanical gripper of the snakehead module provides multiple degrees of freedom, allowing for sophisticated grasping operations. The independent control ability of each finger enables the robot to achieve precise grasping movements.

Accurate motion control: The precise combination of the motor and screw control system guarantees the accurate control of finger movement. The selection and control strategy of motors are crucial for efficient grasping actions.

Force-position hybrid control: By integrating force and position sensors, force-position hybrid control is realized, improving adaptability and robustness during the grasping process.

Diversity of gripping modes: The four-finger gripper has multiple gripping modes, such as parallel gripping, diagonal gripping, circular gripping, and triangular gripping, which are suitable for objects of different shapes.

Controllability of gripping force: By precisely controlling the output of the motor, the mechanical gripper can apply different types of gripping force, including point contact force, line contact force, and surface contact force, adapting to objects of different sizes and weights.

Dynamic modeling and simulation: During the design, detailed dynamic modeling and simulation are conducted on the four-finger mechanical gripper to predict and optimize its performance under various working conditions.

Through the design of this snakehead module, the snake robot can demonstrate superior performance and high adaptability in tasks such as search and rescue, precise assembly, hazardous material handling, and daily item handling. This design reflects the in-depth research and innovation ability of doctoral students while providing a solid foundation for the universality and effectiveness of snake robots in practical applications. The Motor parameters are listed in **Table 3**.

Table 3. Motor parameters.

Item	**Specification**
Motor model	42BYGH3401
Step angle	1.8°
Trunk length	40
Rated current (A)	1.65
Resistance (Ohm)	1.5
Inductance (mH)	2.7
Static distance (N·m)	0.35
Rotor inertia	0.054
Number of lead wires (NO.)	4
Weight (g)	250

2.4. Design of the power system

The snake robot is powered by the GW4632 right angle worm gear DC 370 reduction motor with an auto-lock 6 V motor. The maximum output power is 3.5 W, the maximum no-load speed is 180 rpm, and the rated torque is 0.12 N·m. It drives the two bevel gears in the middle of the joint to rotate. Through gear transmission, the gears at the link of the snake robot are propelled to revolve, thus realizing the basic motion. Partial parameters of the motor are listed in **Table 4**.

Table 4. Partial parameters of the motor (rated voltage: DC 6.0 V).

Item	Specification
Reduction ratio (transformation ratio)	1:32.5
No-load current (mA)	≤ 120
No-load speed (rpm)	180
Rated torque (kg·cm)	1.2
Rated torque (N·m)	0.12
Rated speed (rpm)	132
Rated current (A)	≤ 1.3
Locked torque (kg·cm)	5.00
Locked current (A)	≤ 2.7

2.5. Safety design

The modular reconfigurable snake robot studied in this paper, due to the complexity of its working environment and the diversity of tasks, robots may face various failures and dangerous situations during operation. In order to ensure the safe operation of the robot and improve its reliability and stability, it is very important to predict its safety risk.

During the safety test, it was found that the robot may be subject to the following risks when working:

(1) Mechanical damage to the human body: If the fingers or other body parts are within the grasp range when grabbing objects, they may be mistakenly pinched by the manipulator claw, causing injury.

(2) Risk of harsh environmental impact: If the robot works in a harsh environment such as high temperature, humidity, dust, corrosive gases, its mechanical structure and electrical system may be corroded and damaged, affecting its performance and life.

(3) Electromagnetic interference risk: In some industrial environments or specific sites, there may be strong electromagnetic interference, affecting the normal work of the robot's electronic components and control systems.

In response to the complexity of their working environment and the diversity of tasks, this paper designs the following countermeasures for robots.

(4) Countermeasures for mechanical damage to the human body: Due to the existence of weak bioelectrical signals on the surface of the human skin, such as ECG and myoelectric. In this paper, the snake robot is equipped with a bioelectric sensor, which contacts with the skin through the electrode to collect these bioelectrical signals, and then amplifies and filters them, so that the robot can respond in time and avoid causing harm to the human body.

(5) Risk response to harsh environmental impacts: For the GPS module and position sensor in the snake robot, a sealed design is adopted, such as the use of sealing rubber rings to seal the joint of its housing to prevent moist air and moisture from entering. In terms of the heat dissipation design of the sensor of the snake robot, appropriate heat sinks are added to ensure that the module will not deteriorate or be damaged due to overheating in high temperature environments. The shell of the

sensor adopts chemical anticorrosive coating and electroplating to enhance its corrosion resistance and sand erosion resistance. At the same time, some key components inside the sensor are sealed to further prevent the erosion of corrosive gases.

(6) In order to ensure the reliability of wireless communication, select a wireless communication frequency band with strong anti-interference ability, and use error correction coding technology to encode transmitted instructions. This can correct the errors in the communication process to a certain extent and improve the accuracy of instruction transmission. Hamming code is applied to detect and correct single bit errors in a certain range, which is suitable for relatively simple instruction transmission scenarios that require high real-time performance.

For Hamming codes, the encoding parameters need to be determined according to the bit length of the instruction. Assuming that the emergency stop instruction is represented by 8 bits of binary data (for example, the instruction may contain the stop identification of different functional areas of the robot and verification information, etc.), the number of check bits needs to be calculated according to the coding rules of Hamming code.

For data with a total length of bits (including information bits and check bits), the number of check bits satisfies the inequality. For the case, by calculation can be obtained. That is, 4 check bits need to be added, and the length of the final encoded instruction is a bit.

The following check bits are generated:

Let the original 8-bit emergency stop instruction be designated as D7, D6, D5, D4, D3, D2, D1, and D0.

According to the rule for generating check bits in Hamming code, the 4-bit check bits P3, P2, P1, and P0 are computed as follows:

$$P0 = D_7 \oplus D_6 \oplus D_5 \oplus D_3 \oplus D_2 \oplus D_0$$
$$P1 = D_7 \oplus D_6 \oplus D_4 \oplus D_3 \oplus D_1 \oplus D_0$$
$$P2 = D_7 \oplus D_5 \oplus D_4 \oplus D_2 \oplus D_1 \oplus D_0$$
$$P3 = D_6 \oplus D_5 \oplus D_4 \oplus D_3 \oplus D_2 \oplus D_1$$

The calculated check bit is combined with the original instruction to obtain the encoded 12-bit instruction: D7 D6 D5 D4 D3 D2 D1 D0 P3 P2 P1 P0.

Transmit the encoded instruction: The encoded 12-bit instruction is sent out through the wireless communication module. During the transmission process, various interference may cause some bit errors, by calculating the difference between the check bit of the received data and the check bit of the original data. According to the error correction rules of Hamming code, if only one check bit is inconsistent, it can be determined that the corresponding data bit has an error and be corrected. If multiple check bits are inconsistent, it may indicate that an error has occurred that cannot be corrected. In this case, appropriate measures can be taken, such as requesting resending the command or triggering the security protection mechanism to ensure that the robot does not perform the wrong operation because of the wrong command.

By using the error correcting coding technology such as Hamming code, the accuracy and reliability of remote emergency shutdown instruction transmission can be improved to a certain extent, and the errors in the communication process can be corrected to ensure the safety of the robot in the remote operation process.

At the same time, the effective fault detection system and emergency shutdown mechanism are designed.

Fault detection system: Through the sensors installed in various parts of the robot, such as the force sensor installed on the manipulator claw, real-time monitoring of the grasping force, when the grasping force exceeds the safety threshold, automatically adjust the grasping action to avoid nip injuries. There are also temperature sensors, pressure sensors, displacement sensors, etc., real-time monitoring of the operating status of the robot to analyze the operating data of the robot, such as motor current, speed, position, etc., through the change trend of the data to determine whether the robot has faults. The troubleshooting process is shown in **Figure 10**. If the motor located in a module of the robot emits an abnormal signal, the fault can be located in that module and its associated connection. This also helps to narrow the scope of troubleshooting and improve maintenance efficiency, as shown in **Figure 11**.

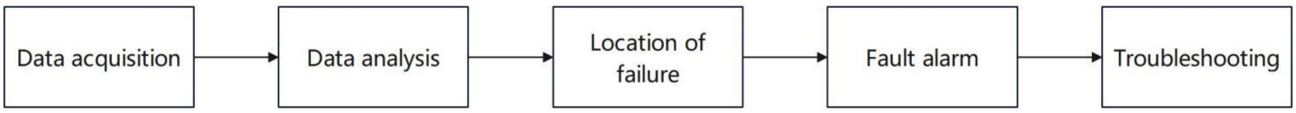


Figure 10. Troubleshooting flowchart.

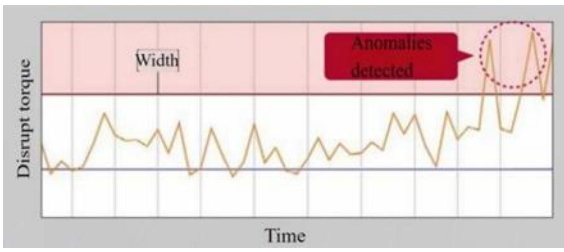


Figure 11. Diagnosis of servo motor.

Continuous monitoring and maintenance: Even after the robot are put into use, its performance and safety should be continuously monitored, with regular maintenance and necessary upgrades to address possible risk changes, as shown in **Figure 12**.

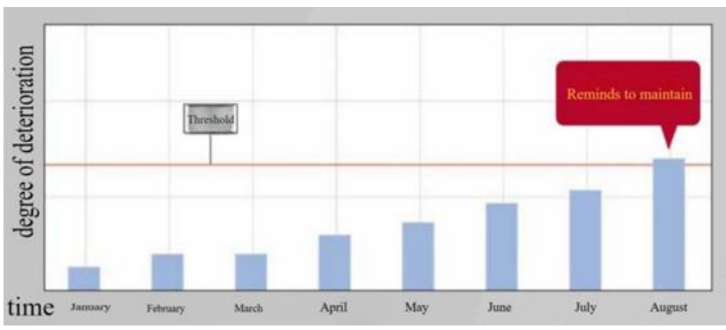


Figure 12. Reducer diagnosis.

Emergency stop mechanism: remote emergency stop is achieved by controlling the emergency stop button.

(1) Wireless communication module: Using wireless communication technology, such as Wi-Fi, Bluetooth or ZigBee, to integrate a wireless communication module on a remote control device (such as a remote control or remote console). This module is responsible for sending emergency shutdown instructions to the robot.

(2) Wireless receiving module: A wireless receiving module matching the remote control device is installed on the robot. After the operator presses the emergency stop button, the operator can receive the emergency stop command sent remotely.

2.6. Cost design

The following is the cost data model analysis and measurement research of this modular snake robot. Modular design is an advanced product design method, which can greatly reduce the research and development cycle and save costs. In this regard, the cost of the product can be tested and controlled by establishing the measurement model of the modular product.

2.6.1. Cost measurement model of modular products

In the process of modular design of snake robot, cost control is very important. Accurate cost prediction not only determines the market competitiveness of robots, but also the success or failure of project implementation. Therefore, accurate cost assessment is always a core issue in the design process. This study takes the basic module of the snake robot as the core and takes its cost as the benchmark cost. Use the cost database to make combined cost estimates and use these estimates as a basis for decision making. Standardize the cost of basic modules by analyzing the cost of multiple types of snake robots on the market or tracking the cost of individual modules in depth. For variant modules, their similarity is estimated by comparing their technical specifications with those of the base module, so that similar variant modules and those requiring independent cost estimation are identified. This contributes to a more accurate forecast of the total cost of complex products. Total cost includes elements such as direct materials, direct labor, and manufacturing expenses. For those variant modules that are similar to the basic module, the cost prediction can be made based on the cost data of the basic module, and consider the adjustment of technical parameters and the change of product structure in the variant design. If the variant modules differ significantly from the base modules, they will be considered entirely new designs. **Figure 13** shows a relational model for cost estimation of complex products in a modular design.

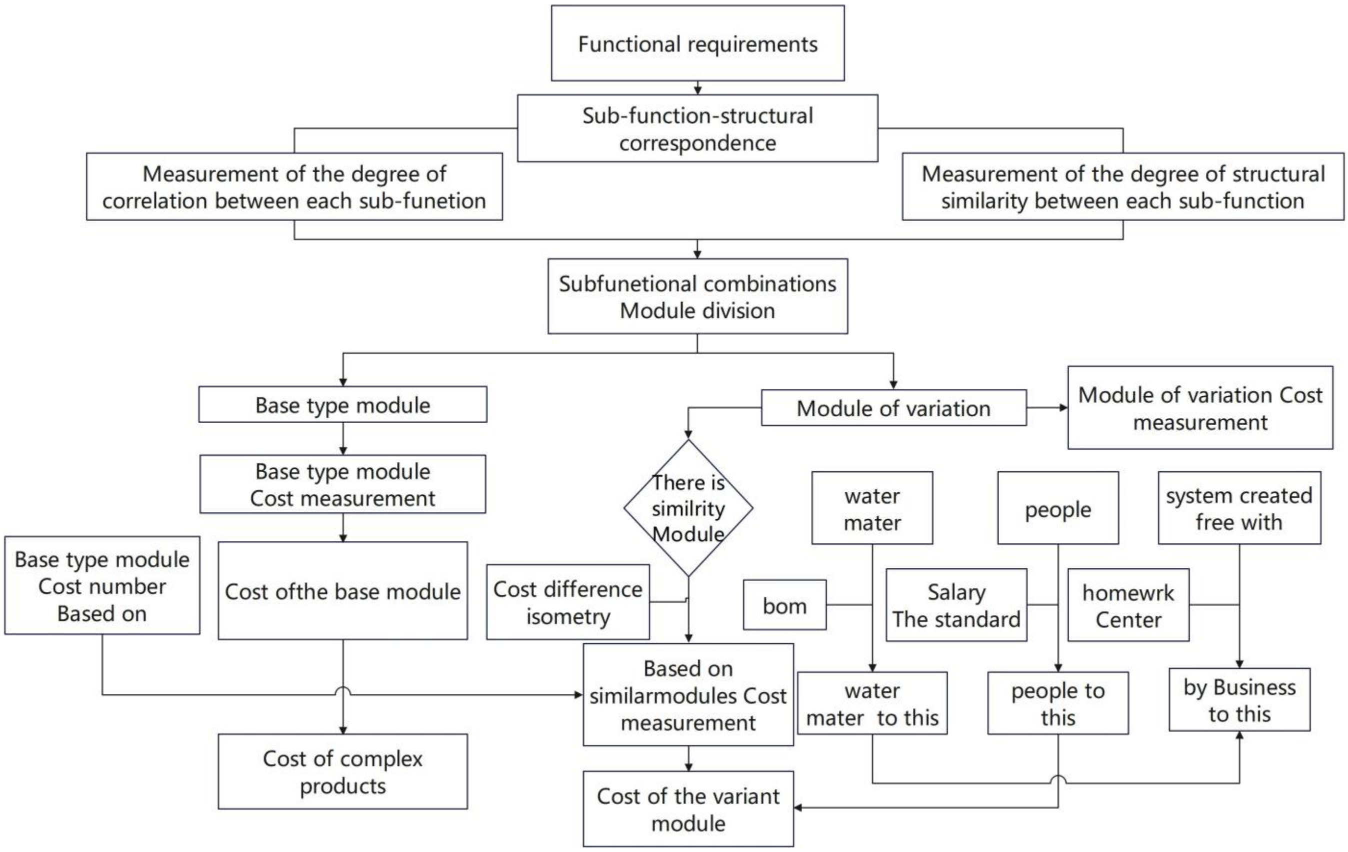


Figure 13. The relational model for cost estimation of complex products in modular design.

2.6.2. Cost data analysis of snake robot

Material cost

This product has a total of 15 torso modules, 1 snake head module, 3.6 meters long, with high strength 7075 series aluminum alloy will be connected between the modules, the price of the material per kilogram is about 200–500 yuan, the average weight of the connecting material between each module is 0.75 kg. The cost of aluminum alloy materials for 15 torso modules and 1 snake head module is between 2400 yuan and 6000 yuan.

In terms of sensors, the snake head module of the snake robot is equipped with a high-precision laser sensor, the price of high-precision laser sensor is 500–2000 yuan/piece, and the cost is between 500–2000 yuan. 15 torso modules are equipped with 4 infrared sensors, the price of infrared sensors is relatively low, the price range is 100–500 yuan, equipped with 60 infrared sensors, the cost is 6000–30,000 yuan.

In terms of drive, the snake-like robot is equipped with 15 high-torque motors to drive each joint, the price of miniaturized, high-torque motors is 200–1000 yuan, and the cost price of 15 individual motors is between 3000–15,000 yuan.

In terms of magnetic coil, the snake robot is equipped with a 24v coil of micro DC suction electromagnet, the price is about 20–30 yuan, and each torso module is equipped with 4 magnetic coils, the cost is about 1200 yuan to 1800 yuan.

Manufacturing and processing cost

High precision CNC machine tool processing costs, joints and other parts of the snake robot processing time is long, the processing time of each joint module is about 2–3 hours, the price is about 200–500 yuan per hour. The processing cost of 15 torso joint modules and 1 snake head module is between 3000–7500 yuan. Secondly, in the processing process, special processing processes such as laser cutting will be used, and the cost of each cutting is between 500–2000 yuan.

Testing cost

In terms of test equipment, this product needs to carry out mechanical testing and environmental testing, and in the test process, according to the test needs, it may be necessary to purchase a variety of test equipment, and the cost of consumables and energy consumption during the test process may be between 1000–5000 yuan per test. The specific cost analysis of each module is shown in **Table 5**.

Table 5. Material cost data analysis for each module.

Project	Unit price	Quantity	total (yuan)
7075 series aluminum alloy	500 yuan per kilogram	12 kilograms	6K
OD2-N30W04A2 high-precision laser sensor	2000 yuan	1 piece	2K
sps119ed1 infrared sensor	500 yuan per piece	4 pieces	2K
42BYGH340 high-torque motor and lead screw	150 yuan per piece	1 piece	0.15K
GW4632 right-angle worm gear and worm DC 370 reduction motor with self-locking 6V motor	50 yuan per piece	2 pieces	0.1K
36V coil of direct current suction cup electromagnet	50 yuan per piece	4 pieces	0.2K
18,650 lithium-ion battery	30 yuan per section	6 pieces	0.18K
Suction cup electromagnet	200 yuan per piece	2 pieces	0.4K
STS3215 servo	200 yuan per piece	2 pieces	0.4K
Spherical outside surface ball bearing with setscrew UC 201S in accordance with GB/T 3882-2017 standard	30 yuan per piece	16 pieces	0.48K
total	11.91K		

2.6.3. Improvement measure

Based on the budget and estimate of the cost of the above-mentioned snake robot, the magnetic modular design is proposed in this paper. As one of the key technologies in the design of the modular snake robot, it is of great significance to improve the manufacturing efficiency of the snake robot, mass production, reduce the production cost and optimize the machine performance.

Magnetic modular design

The core idea of magnetic modular design is to decompose the snake robot into multiple independent modules, each with a specific function and structure. These modules are assembled and disassembled by magnetic connection, which makes the assembly and maintenance of the robot simpler and more convenient.

The magnetic modular design can reduce the manufacturing and maintenance costs of the snake robot, and improve the performance and reliability of the snake robot. Traditional snake-like robots usually adopt integrated design, and the manufacturing process is complex and costly. The magnetic modular design allows the robot to be broken down into multiple independent modules, each of which can adopt standardized manufacturing processes and materials, thus reducing manufacturing costs. In addition, the modular design can also improve production efficiency, reduce production cycles, and further reduce manufacturing costs.

Magnetic modular design can promote the innovation and development of robots. Because the modular design allows the robot to be broken down into multiple independent modules, different technologies and solutions can be developed for different modules. These technologies and solutions can learn from and integrate with each other to promote the innovation and development of robotics.

Motor modular design

The modular design of the motor system brings significant advantages in reducing the cost of the snake robot. First of all, the modular design enables the production of motors to be standardized, improving production efficiency while reducing manufacturing costs. Different modules can be mass-produced under the same specifications, reducing the additional costs caused by special customization. Secondly, when the motor fails, only the corresponding module needs to be replaced, without the need for overall replacement, which greatly reduces the maintenance cost. In addition, the modular design is easy to upgrade and improve. With the development of the technology, individual modules can be easily upgraded without having to redesign the entire robot's motor system, extending the service life of the snake robot and further reducing long-term costs.

Lightweight design

The lightweight design of snake robot is of great significance to reduce the cost. First, stress analysis is performed on the material to arrive at the most appropriate thickness, reducing waste, as shown in **Figure 14**. In the production process, due to the weight reduction of parts, the difficulty of processing and assembly is correspondingly reduced, improving production efficiency and reducing labor and time costs. Secondly, the power required for the operation of the lightweight snake robot will also be reduced, thus reducing the cost of energy consumption. Moreover, the lighter weight makes transportation and installation more convenient, reducing logistics and installation costs. In addition, the lightweight design also helps to improve the flexibility and mobility of the robot, reducing the occurrence of wear and failure, which in turn reduces maintenance costs. In short, the lightweight design of the snake robot has achieved cost reduction from many aspects, laying the foundation for its wider application and promotion.

Wireless power supply

The magnetic wireless charging design of the snake robot uses the principle of electromagnetic induction. The transmitting coil of the charging base generates an alternating magnetic field, and the receiving coil on the robot generates an induced current when it is near to realize charging. Coupled with the magnetic design, it can automatically align the adsorption to ensure stable and efficient charging. This design brings many advantages, no need to plug and unplug the line, high convenience, adapt to different angle position charging, strong flexibility, avoid the risk of electric shock, good safety. By optimizing the coil, magnetic structure and charge control circuit, the charging efficiency and stability can be improved, which lays a foundation for the wide application of snake robots.

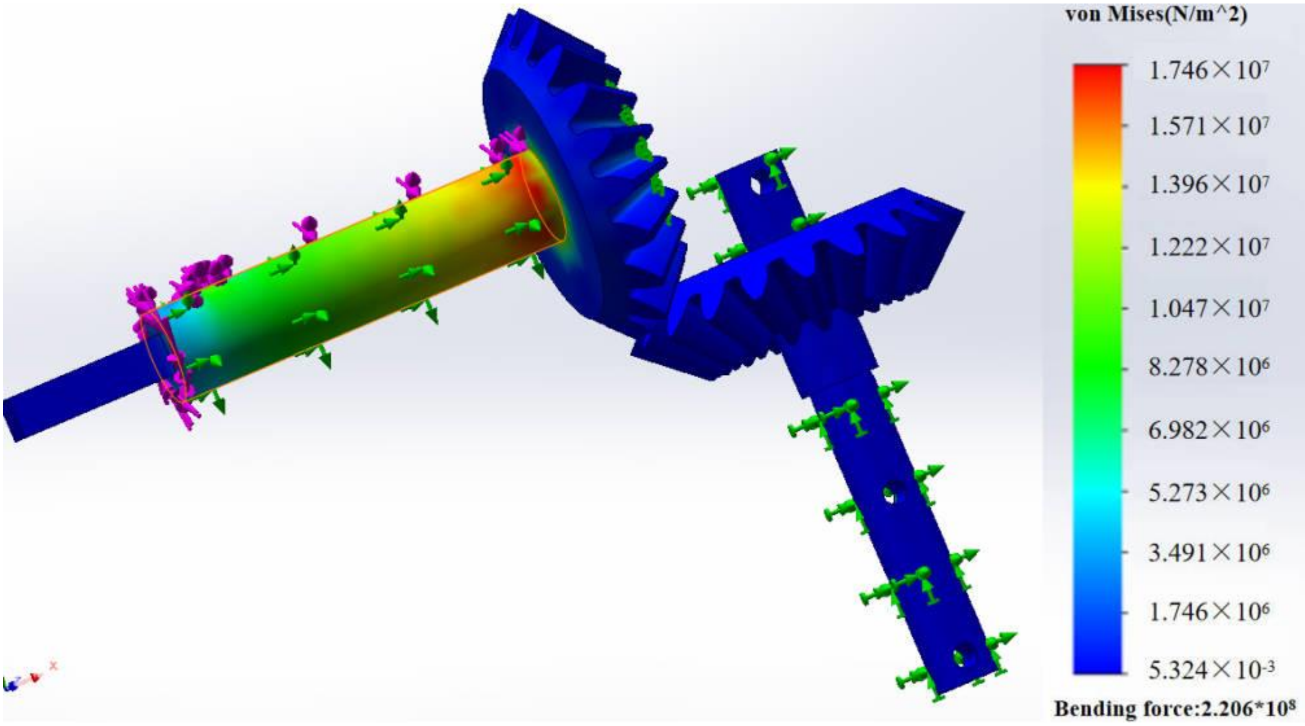


Figure 14. Stress analysis of gear materials.

3. Analysis of bevel gears

3.1. Mechanical parameters of bevel gears

The front view and top view of the single transmission part of a single module are shown in **Figures 15** and **16**. Basic parameters are shown in **Table 6**.

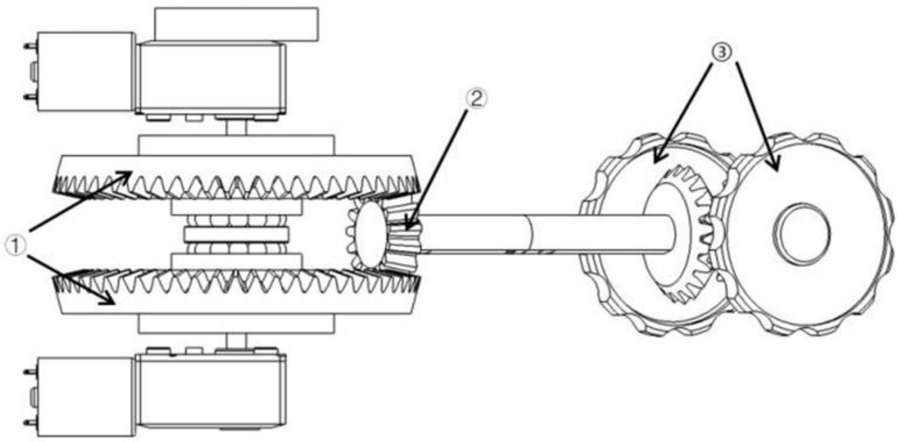


Figure 15. The single transmission part of a single module (front view).

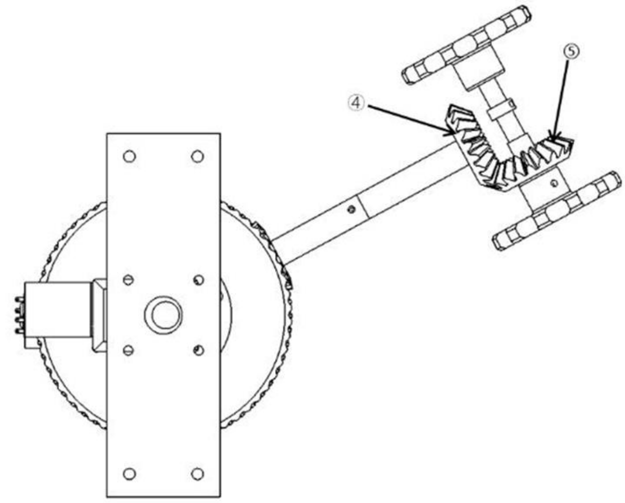


Figure 16. The single transmission part of a single module (top view).

Table 6. Basic parameters of each part.

Part name	Part parameter
Component ①	Bevel gear wheel: 56 × 2, modulus: *mn* = 2 mm, number of teeth: *z* = 56, profile angle: *a* = 20°, the coefficient of addendum: *h* = 1, helical angle: *B* = 0°, the spur gear is in the spiral direction, radial modification coefficient: *xn* = 0, common normal length: *W* = 38.31, spanning measurement tooth number: *k* = 6.72, accuracy level: 5-H-A GB, shaft angle: Σ = 90, matching gear tooth number: *z* = 15, accumulated pitch tolerance: *Fp* = 0.028, pitch deviation: *Fpt* = 0.006.
Component ②	Bevel gear wheel: 15 × 2, modulus: *mn* = 2 mm, number of teeth: *z* = 15, profile angle: *a* = 20°, the coefficient of addendum: *h* = 1, helical angle: *B* = 0°, the spur gear is in the spiral direction, radial modification coefficient: *xn* = 0, common normal length: *W* = 10.26, spanning measurement tooth number: *k* = 2.17, accuracy level: 5-H-A GB, shaft angle: Σ = 90, matching gear tooth number: *z* = 56, accumulated pitch tolerance: *Fp* = 0.014, pitch deviation: *Fpt* = 0.006.
Component ③	Ripplet handwheel, for the advancement of snake robots, the ripple shape is employed to increase the stability of the center of gravity.
Component ④ and ⑤	Bevel gear wheel: 20×2, modulus: *mn* = 2 mm, number of teeth: *z* = 20, profile angle: *a* = 20°, the coefficient of addendum: *h* = 1, helical angle: *B* = 0°, the spur gear is in the spiral direction, radial modification coefficient: *xn* = 0, common normal length: *W* = 13.68, spanning measurement tooth number: *k* = 2.72, accuracy level: 5-H-A GB, shaft angle: Σ = 90, matching gear tooth number: *z* = 20, accumulated pitch tolerance: *Fp* = 0.016, pitch deviation: *Fpt* = 0.006.

The work-in parameters between Component ① and Component ② are as follows (**Figures 17–21**):

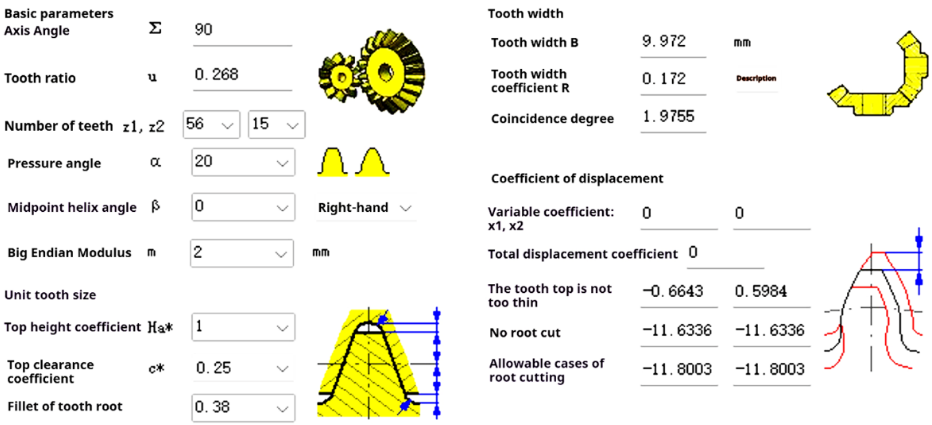


Figure 17. Design parameters for both.

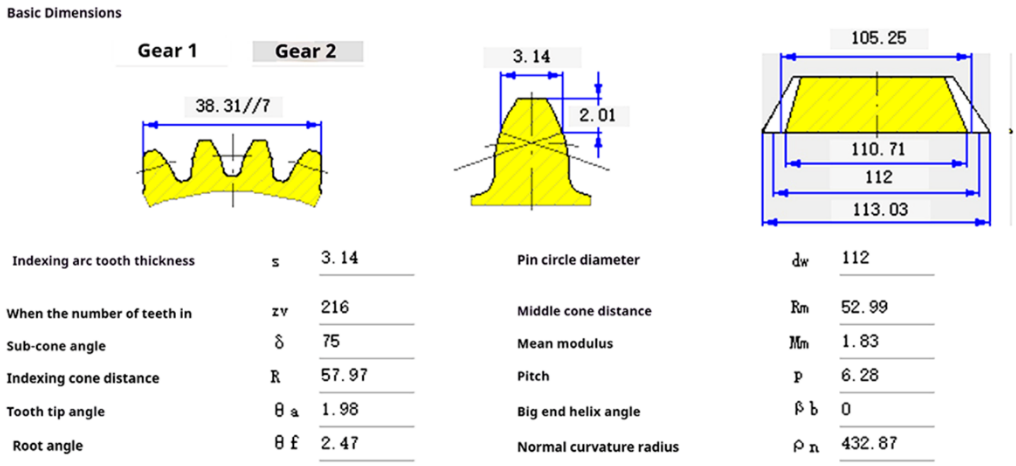


Figure 18. Basic dimensions of Component ①.

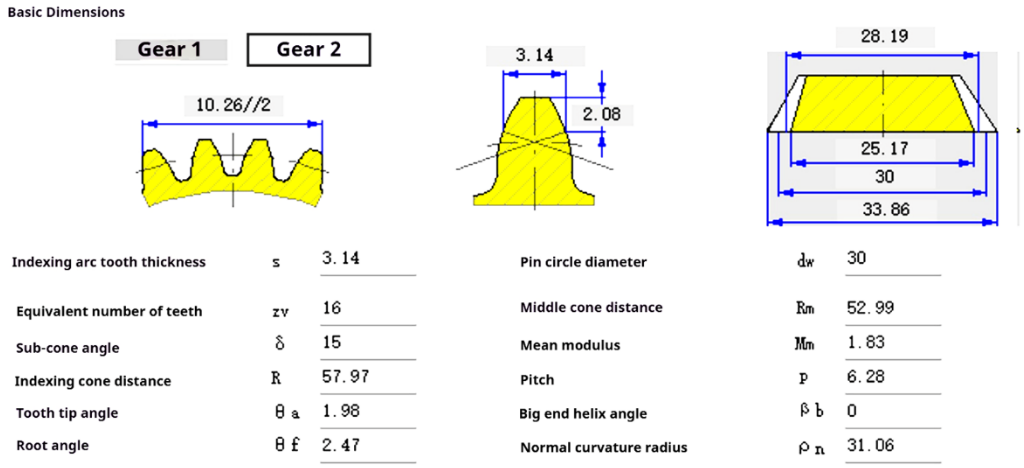


Figure 19. Basic dimensions of Component ②.

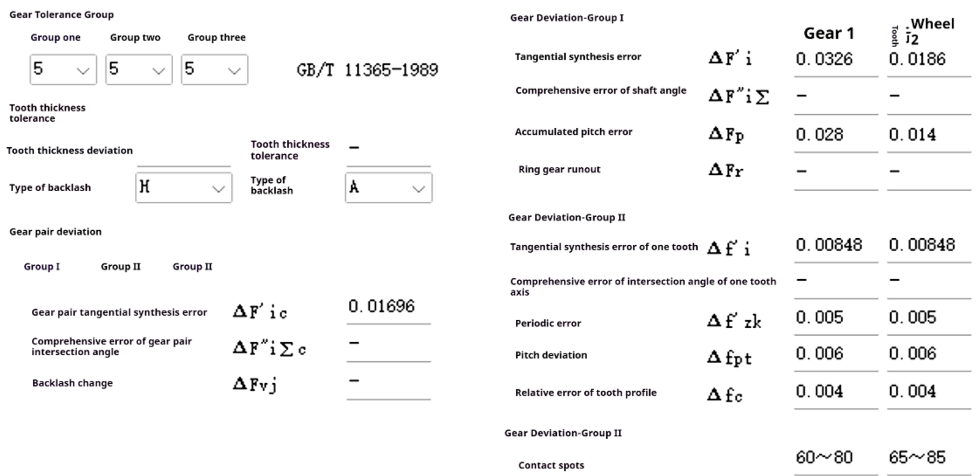


Figure 20. Gear accuracy.

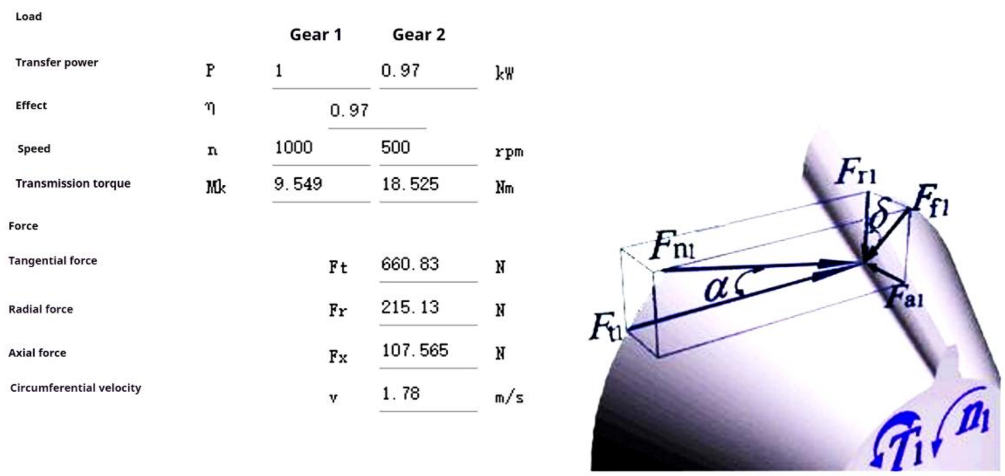


Figure 21. The Loads.

The work-in parameters between Component ④ and Component ⑤ are as follows (**Figures 22–25**):

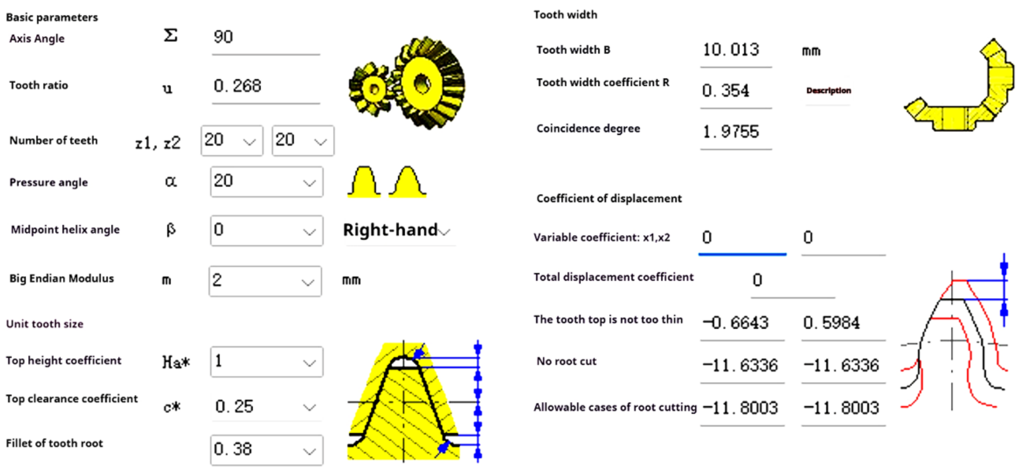


Figure 22. Design parameters for both.

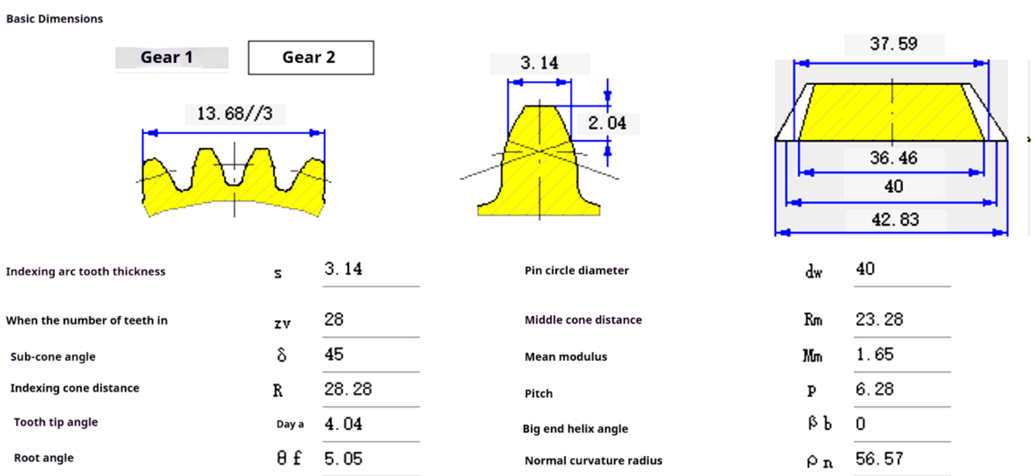


Figure 23. Basic dimensions of Components ④ and ⑤.

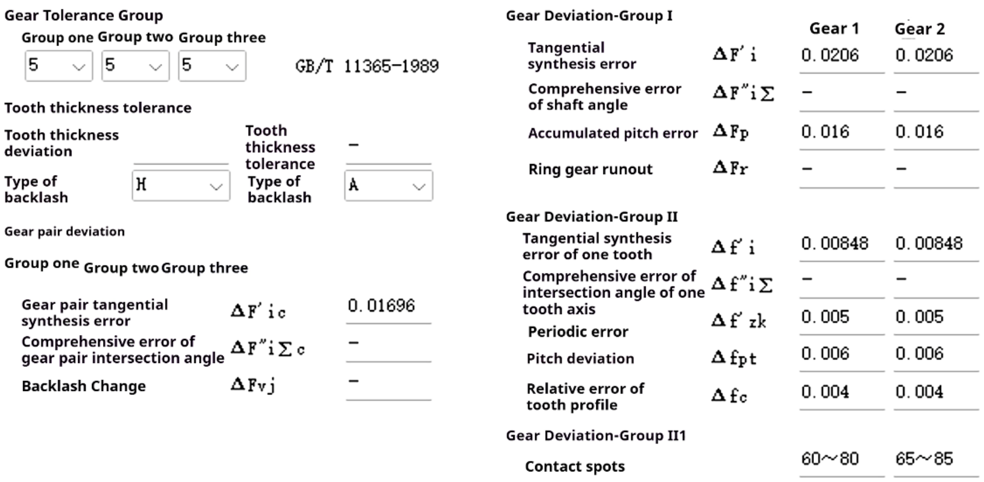


Figure 24. Gear accuracy.

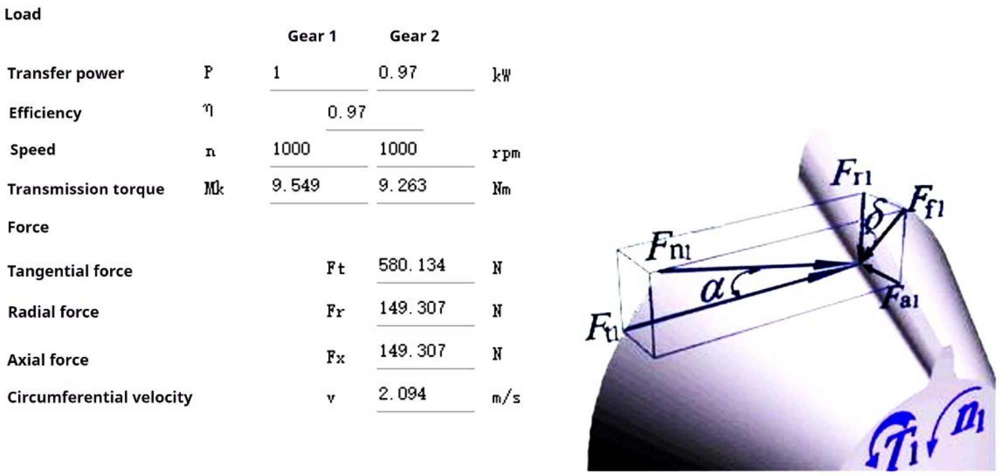


Figure 25. The loads.

3.2. Bevel gear transmission formula

Transmission ratio $i = \dfrac{Z_1}{Z_2}$, where Z_1 and Z_2 are the tooth numbers of driving and driven gears, respectively. Center distance $a = \frac{m \times (Z_1 + Z_2)}{2} \times cos(\beta/2)$, where β is the angle between the axes of two gears.

The torque T can be approximately obtained from the following formula: $T = \dfrac{9500 \times P}{n}$, where P represents the power in kilowatts, and n denotes the speed in revolutions per minute. Power P is the product of torque and angular velocity: $P = T \times \omega$, where ω stands for the angular velocity.

3.3. Analysis of bevel gears

Bevel gear transmission is broadly applied in mechanical transmission systems. It is composed of two bevel gears and transmits power and motion through meshing. The schematic diagram is shown in **Figure 26**. Due to the advantages of a large transmission ratio, compact structure, strong load-bearing capacity, and smooth transmission, bevel gear transmission has been extensively used in fields such as automobiles, aviation, ships, and engineering machinery 15.

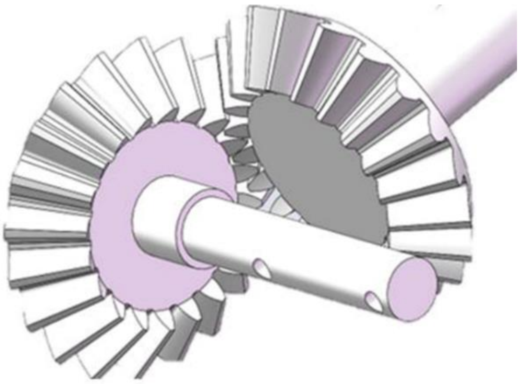


Figure 26. A simple structure of bevel gear transmission.

The principle of bevel gear transmission is that when one bevel gear wheels, its tooth surface meshes with that of another one, causing the other bevel gear to whirl. The tooth surface of bevel gears is a part of a conical surface. Therefore, the tooth trace of bevel gears is a curve 16. Bevel gear transmission usually employs an equal angular velocity ratio: the ratio of the angular velocities of the input shaft to the output shaft is identical to that of the tooth numbers of the input gear to the output gear 17. Therefore, the snake robot incorporated into the bevel gear transmission system possesses the following characteristics:

(1) Large transmission ratio and compact structure: Bevel gear transmission can achieve a large transmission ratio, thereby achieving greater torque and speed conversion in a smaller space. In addition, the tooth surface of the bevel gear is a part of a conical surface. Therefore, the bevel gear transmission has a high space utilization rate, making the entire transmission system compact with small occupations. It can significantly diminish the friction of snake robots in confined spaces, thereby protecting the robot's body.

(2) Strong bearing capacity and stable transmission: Bevel gear transmission has a solid bearing capacity and can withstand large torque and impact loads 18. This makes it suitable for various high-load working environments. Moreover, during the bevel gear transmission process, the meshing of the tooth surface smooths the transmission, abates vibration and noise, and promotes transmission efficiency. It evidently ameliorates the snake robot's capacity to smooth operation. Furthermore, the low noise of this transmission system endows this type of snake robot with a specific degree of invisibility.

As an efficient, compact, and reliable method, bevel gear transmission prominently favors the development and adaptability of snake robots, further optimizing their performance and providing high-quality transmission solutions.

3.4. Finite element analysis of bevel gears

In order to verify the power gear transmission of the snake robot, this study conducted finite element simulation analysis on the robot using SolidWorks 3D software. Taking the conical gear driven by the torque provided by the intermediate motor as an example, ordinary carbon steel was used to simulate the material elastic modulus, Poisson's ratio, yield strength, and hardness of the conical gear. The material's elastic modulus was set to 2 GPa, Poisson's ratio to 0.3, and the gear and pinion only released the degrees of freedom to rotate around their axes. The torque applied to the bull gear was 13.6 N·m, and the two ends of the bevel pinion were constrained. The specific application is shown in **Figure 27**.

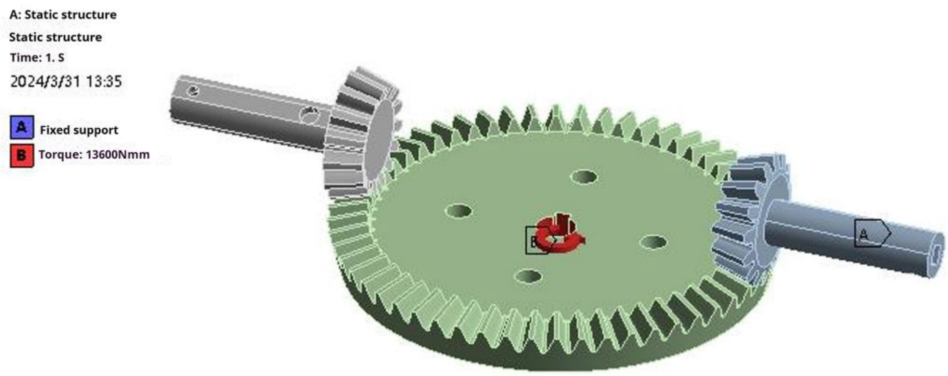


Figure 27. The application of boundary conditions and loads.

Moreover, strength verification and analysis were conducted on the corresponding parts of the gears based on the meshing frequency. The deformation, stress, and contact stress of the gears after meshing were obtained. The stress and deformation of the gears under external loads were first derived from the finite element analysis. The deformation solution is displayed in **Figure 28**, and the stress solution is depicted in **Figure 29**.

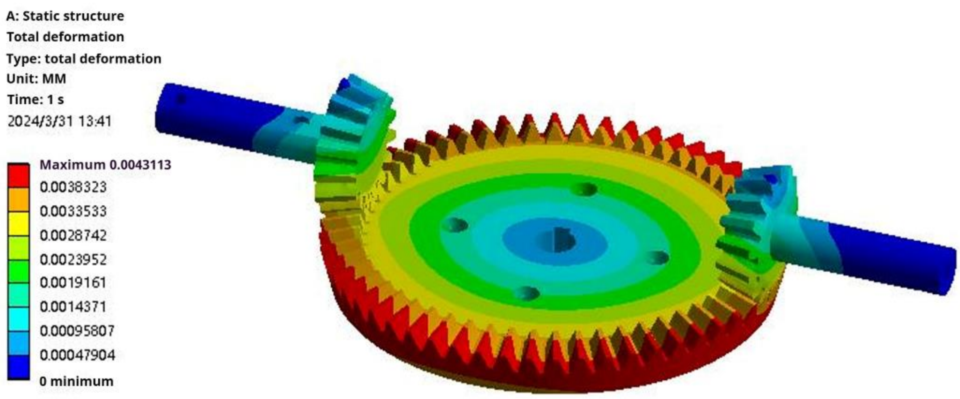


Figure 28. The deformation solution.

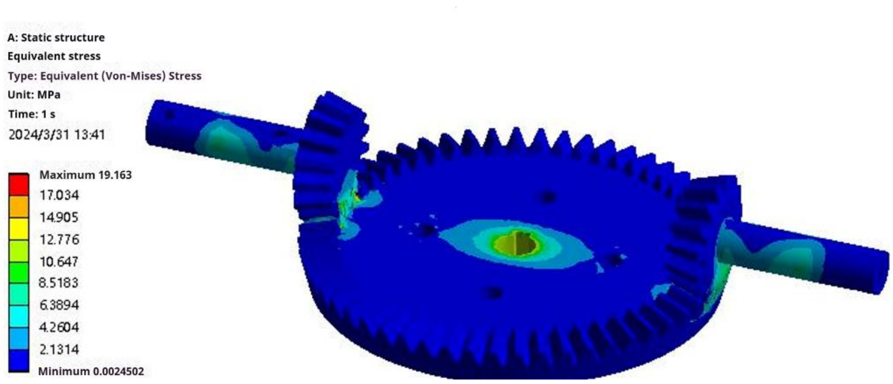


Figure 29. The stress solution.

The results of finite element analysis show that the maximum deformation is 0.004 mm on the bull gear. The highest stress point is located in the initial contact area of the tooth surface, with a maximum value of 19.163 MPa. When two separated surfaces come into contact and are tangent to each other, they are considered to be in contact, i.e., the lower meshing zone 19. Moreover, the contact analysis discloses the specific pattern of the distribution of contact stress on the tooth surface in the fully meshing area, indicating the nonuniformity of gear load. The peak position of gear contact stress will shift, further implying the influence of loading conditions on gear meshing performance. The contact stress solution is illustrated in **Figure 30**. The maximum contact stress is 13.328 MPa. The high nonlinearity of contact analysis makes finite element analysis more difficult, and this value can serve as a reference.

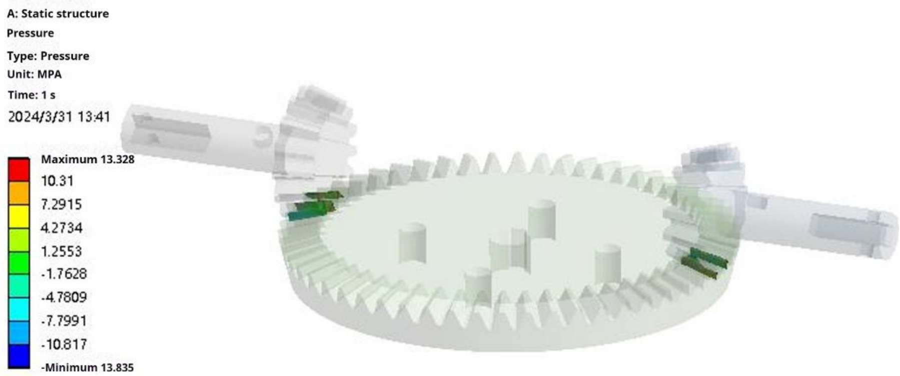


Figure 30. The contact stress solution.

The finite element analysis shows that the maximum deformation of the bevel gear during meshing is 0.004 mm on the bull gear. The highest stress point is located in the initial contact area of the tooth surface, with a maximum value of 19.163 MPa. The maximum contact stress is 13.328 MPa. It can be concluded that the maximum stress is under the allowable stress of the material, and the structure is safe 20. Meanwhile, in-depth research on contact analysis results can provide support for the selection of gear lubrication schemes, as the distribution of contact stress directly affects the formation and rupture of lubricating oil films. The findings of this study have guiding significance for understanding the changes in gear meshing performance under various load conditions.

4. Algorithm control

The control complexity of snake robot is mainly due to its high degree of flexibility and redundant freedom, which makes the design and implementation of its control algorithm very challenging. To solve this problem, the following control algorithm optimization and simplification strategies are designed in this paper 20.

4.1. Distributed control system

Architecture: Each module has its own control unit, while communicating with the central control unit to achieve coordinated control. This architecture distributes the control tasks to the control units of each module, avoiding a single control unit to deal with all complex tasks and reducing the complexity of the overall control. Some algorithms of the control system are shown in **Figure 31**.

Advantages:

(1) Increased flexibility. Each module can be controlled independently based on its own state and received instructions, and when the robot needs to change shape or perform different tasks, the module can quickly adjust its behavior without requiring a large-scale reconfiguration of the entire control system.

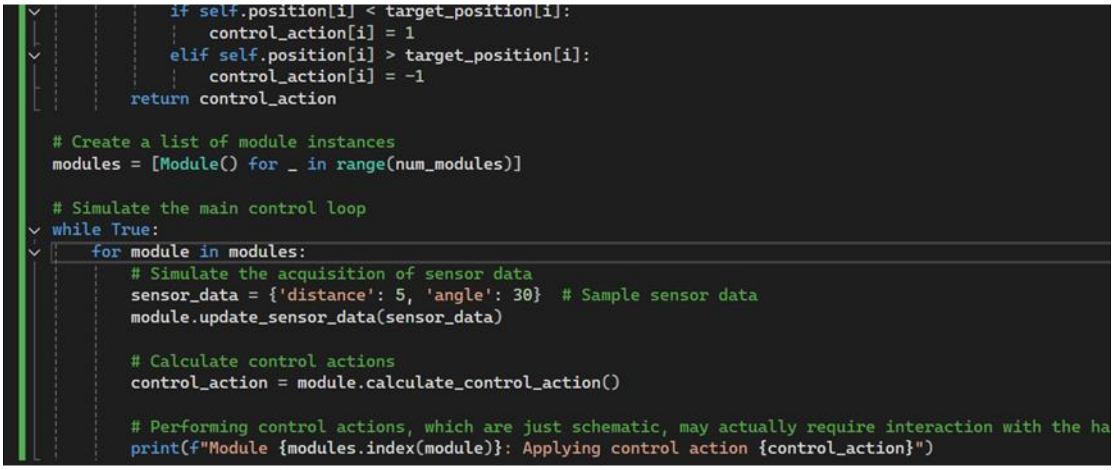
(2) Enhanced scalability. If the number of modules needs to be increased or decreased, the distributed control system can more easily adapt to this change. The newly added module can be integrated with the existing system through standard interfaces and communication protocols, and its own control unit can participate in the overall control independently.

```python
# Distributed control
class ModuleController:
    def __init__(self, module_id):
        self.module_id = module_id
        self.status = False

    def turn_on(self):
        self.status = True
        print(f"Module {self.module_id} is turned on.")

    def turn_off(self):
        self.status = False
        print(f"Module {self.module_id} is turned off.")


# Create multiple module controller instances to simulate distributed control
module1_controller = ModuleController(1)
module2_controller = ModuleController(2)
module3_controller = ModuleController(3)

# Control specific modules
module2_controller.turn_on()
```

Figure 31. Partial algorithm of distributed control system.

4.2. Improved motion control method

Real-time monitoring and adjustment: Drive monitoring and torque transmission monitoring are carried out for each module. If the torque deviates from the set value or the transmission efficiency is reduced, the control algorithm is adjusted to ensure that the working state can be realized normally and the control accuracy can be improved. The algorithm design is shown in **Figure 32**.



```
            if self.position[i] < target_position[i]:
                control_action[i] = 1
            elif self.position[i] > target_position[i]:
                control_action[i] = -1
        return control_action

# Create a list of module instances
modules = [Module() for _ in range(num_modules)]

# Simulate the main control loop
while True:
    for module in modules:
        # Simulate the acquisition of sensor data
        sensor_data = {'distance': 5, 'angle': 30}  # Sample sensor data
        module.update_sensor_data(sensor_data)

        # Calculate control actions
        control_action = module.calculate_control_action()

        # Performing control actions, which are just schematic, may actually require interaction with the ha
        print(f"Module {modules.index(module)}: Applying control action {control_action}")
```

Figure 32. Real-time monitoring algorithm design.

Specific implementation:

(1) Use the sensors in the module to obtain motion status information, such as joint angle, speed, acceleration, etc. This information is fed back to the module's control unit as well as to the central control unit.

(2) The control unit adjusts the movement of the module according to preset algorithms and objectives. For example, if the movement of a module deviates from the expected trajectory, the control unit can correct the deviation by adjusting the output torque of the motor or changing the Angle of the joint.

Algorithm principle: PID (proportional-integral-differential) control algorithm is used to precisely control the position of the steering gear.

$$u(t) = K_P \cdot e(t) + K_i \cdot \int e(t)dt + K_d \cdot \frac{dt}{de(t)}$$

Proportional term (*Kp*): Based on the current error, direct control action is generated to make the steering gear position quickly close to the target position. The larger the proportional coefficient, the faster the response speed of the system, but the stability of the system may be reduced.

Integral term (*Ki*): The error is integrated to eliminate the steady-state error of the system. When there is a long-term deviation in the system, the integral term will gradually accumulate, resulting in a continuous control effect, so that the steering gear can finally accurately reach the target position.

Differential term (*Kd*): The system dynamic response is optimized according to the rate of change of the error. When the error changes quickly, the differential term can predict the trend of the system in advance to avoid overshoot or oscillation. By adjusting the PID parameters reasonably, the position of the steering gear can be precisely controlled, so as to improve the control precision of the joint connection module, and then optimize the motion control of the whole snake robot.

5. Energy management

The system uses intelligent algorithms such as genetic algorithm and fuzzy logic control to find the most suitable energy management strategy for the current task by constantly optimizing and adjusting the power distribution. Part of the program is shown in **Figure 33**. Designing efficient energy management algorithm is the core of optimizing energy distribution. This algorithm can calculate the best power distribution scheme according to the task goal, battery power, environmental conditions and other factors to achieve the maximum utilization of energy.

```
# Fuzzy logic membership functions
def battery_level_low(battery):
    return max(0, min(1, (30 - battery) / 30))

def battery_level_medium(battery):
    return max(0, min(1, (70 - battery) / 40))

def battery_level_high(battery):
    return max(0, min(1, (battery - 70) / 30))

def task_difficulty_low(task):
    # Assume task difficulty is a numerical value from 0 to 10
    return max(0, min(1, (3 - task) / 3))

def task_difficulty_medium(task):
    return max(0, min(1, (7 - task) / 4))

def task_difficulty_high(task):
    return max(0, min(1, (task - 7) / 3))

def environment_harshness_low(env):
    # Assume environment harshness is a numerical value from 0 to 10
    return max(0, min(1, (3 - env) / 3))

def environment_harshness_medium(env):
    return max(0, min(1, (7 - env) / 4))

def environment_harshness_high(env):
    return max(0, min(1, (env - 7) / 3))
```

Figure 33. System—partial program algorithm.

By concentrating power in the first few sections, limited energy can be used more efficiently. In actual operation, the snake robot may only need some modules to work fully to meet the specific task requirements, avoiding the energy waste caused by the simultaneous high power operation of all modules. The non-rotating joint in the standby state can greatly reduce the overall energy consumption and extend the working time and driving range of the robot. This way of energy management allows the snake robot to flexibly adjust to different task scenarios and environmental conditions. For example, you can increase the power output of the first few sections when you need to move forward quickly or overcome large obstacles, In the case of smooth operation or without high power, more modules can be put into standby to save energy. For complex terrain and tasks, serpentine robots can dynamically adjust power distribution to improve their adaptability and survivability in different environments. In addition, reducing unnecessary energy consumption can reduce the depth of discharge and the number of cycles of the battery, thereby extending the service life of the battery. This is especially important for serpentine robots that run for a long time or require frequent charging.

6. Durability test

Observe and record the performance of each component during the test through durability testing. It is found that the joint connection parts may be worn due to frequent bending and twisting, the gear of the power transmission system may be damaged due to large torque, and the shell may be broken due to friction or impact, so through experimental tests, consider the use of high-strength alloy materials or engineering plastics with good wear resistance and self-lubrication, For the gear, the selection of high-quality alloy steel, and appropriate surface treatment to improve its hardness and wear resistance. The durability test data pairs are shown in **Table 7**.

Table 7. Durability test data comparison.

test environment	test time	Joint-related data	Shell-related data	Data related to power transmission system	Data related to motion performance
rugged terrain	100 hours	The wear amount of the connecting piece is about 0.1–0.2 millimeters. The joint activity angle error of some biaxial steering gears increases from ±0.5° to ±1.5°.	Slight scratches and bump marks appear on the shell of the snake body trunk module, accounting for 10%–15% of the surface area.	The tooth surface of the transmission gear is worn by about 0.05–0.1 millimeter, and the transmission efficiency drops from about 85% to 80%–82%.	/
narrow space	100 hours	The joint bending range is reduced from −180° to +180° to −170° to +175°, and the activity resistance increases by about 10%–15%.	Obvious scratches appear at the contact part between the shell and the pipe wall. The average thickness of the shell at the contact part is reduced by about 0.05–0.1 millimeter.	/	The overall movement speed drops from the initial average speed v to 0.8v–0.9v. The joint activity angle error increases from ±0.5° to ±1°–±1.5°.
Dusty environment (about 5–10 grams per cubic meter)	100 hours	The average resistance of joint activity increases by about 20%–30%.	The dust coverage rate on the shell surface reaches 60%–70%, and the appearance is rough.	There is a small amount of dust accumulation on the tooth surface of the transmission gear.	Affect the movement flexibility of the robot.

7. Conclusions

With the booming of intelligent robot technologies, snake robots, as a highly flexible and adaptable robot system, have performed their distinctive application potential in multiple fields. This article proposes an innovative transmission system design method, structural optimization strategy, and advanced control algorithm through probing into reconfigurable modular snake robots with bevel gear transmission, providing new solutions and a theoretical basis for the technological progress and application expansion of snake robots.

However, research on snake robots encounters a series of challenges. Addressing these issues is of great significance for promoting the development of snake robot technologies. Firstly, the autonomous obstacle avoidance and path planning capabilities of snake robots should be further strengthened in complex environments. Precise environmental perception technologies, efficient data processing algorithms, and intelligent decision-making mechanisms are essential to achieve autonomous navigation of robots in unknown or dynamic environments.

Secondly, the dynamic stability and the control accuracy of snake robots during high-speed motion significantly constrain their performance improvement. This requires in-depth research on the dynamic model of snake robots, establishing highly accurate mathematical models, and developing efficient control algorithms to realize precise control and stability optimization of robot motion.

In addition, the modular design and reconstruction ability of snake robots are also primary research directions. Modular design optimization can ameliorate the scalability and adaptability of snake robots, enabling them to promptly reconstruct and expand their functions according to diverse task requirements. Meanwhile, modular design can strengthen the maintainability and reliability of robots, abating operating costs.

Finally, the risks that may exist when the robot is working are analyzed, including mechanical injury to the human body, adverse environmental impact and electromagnetic interference. In view of these risks, corresponding measures have been taken. For example, the assembly of bioelectric sensors to avoid mechanical damage to the human body, the use of GPS and position sensors with sealing, heat dissipation, anti-corrosion design to cope with the adverse environmental impact, the selection of anti-interference ability of strong wireless communication frequency bands and the use of error-correcting coding technology to solve electromagnetic interference problems. The implementation of these measures is of great significance to improve the safety and reliability of robots.

Nevertheless, these issues can be great opportunities for the development of snake robots. Solving these problems not only can profoundly enhance the performance and application range of snake robots but also boost innovation and progress in related technologies, such as sensor technology, information processing technology, and intelligent control technology. Furthermore, the research and application of snake robots can impel the development of related disciplines, including bionics, robotics, and artificial intelligence, possessing critical scientific significance and practical value.

With the constant progress and innovation of intelligent technologies, there are reasons to believe that snake robots will have increasingly extensive applications in enormous fields, such as search and rescue, medical surgery, deep-sea exploration, and space exploration. The development prospects of snake robots are broad. They will bring more convenience to our production and life and promote the development and progress of intelligent robot technologies. Meanwhile, it should be realized that the research and development of snake robots is a long-term and complex process that needs the joint efforts and support of researchers, engineers, decision-makers, and various sectors of society. Through persistent exploration and innovation, the difficulties and challenges can be conquered, thus achieving breakthroughs and development in snake robot technologies.

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