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Article

A handling robot that mimics ant crawling in biomimicry

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Abstract: In order to improve the robot's motion stability and handling ability in complex terrain, a bionic handling robot imitating the crawling of ants is designed. The study is based on the ant's locomotion mechanism, and by analyzing its gait and handling behavior, an optimized design of the hexapod robot's mechanical structure and drive system is proposed. The control system adopts a layered architecture and integrates multi-sensor data fusion technology to achieve gait planning, balance control, and path planning functions. The prototype test shows that the robot can maintain stable operation in different terrain environments, with a gait error of less than 5%, and complete the handling task under a load of 800 g, with good terrain adaptability and load capacity. The performance evaluation shows that the energy consumption is well balanced with the task efficiency, and the design scheme is highly reliable in motion control and practical applications. The study provides a new technical path for intelligent handling tasks in complex environments and lays the foundation for subsequent optimization work.

Keywords: bionic robot; ant locomotion mechanism; gait planning

1. Introduction

Bionics, an interdisciplinary field inspired by natural organisms, has been extensively applied to robotic design in recent years. Among various biological models, ants have attracted significant research attention due to their complex locomotion mechanisms and exceptional handling capabilities. Their unique morphology and efficient three-point support gait enable them to navigate challenging terrains and lift objects far exceeding their body weight through collaborative efforts. These characteristics provide valuable insights for bio-inspired robotic design, particularly in improving environmental adaptability, load capacity, and energy efficiency.

Traditional handling robots often face limitations such as insufficient terrain adaptability, constrained payload capacity, and high energy consumption. The integration of bionic principles into robotic design offers a promising solution to these challenges, particularly in terms of gait planning, environment perception, and multi-degree-of-freedom motion control. Previous studies have explored various bio-inspired robotic systems. For instance, Meng [1] proposed an automatic navigation handling robot using advanced algorithmic approaches to enhance efficiency in handling tasks. Similarly, Alebooyeh et al. [2] investigated robotic automation for material handling, leveraging finite element modeling to optimize robotic manipulation. Additionally, Cheng [3] developed a path coordination scheduling method for intelligent warehouse handling robots, emphasizing the importance of optimizing spatial resource allocation. These studies highlight the growing interest in improving robotic motion efficiency, yet there remains a gap in developing a bionic handling robot that can seamlessly adapt to complex environments while maintaining high stability and load capacity. Recent research has also focused on specific technical advancements in handling robots. Cheng et al. [4] designed a logistics handling robot based on the STM32 microcontroller, demonstrating the benefits of embedded control in robotic motion precision. In another study, Chou et al. [5] explored vibration compensation techniques for silicon wafer handling robots, emphasizing the importance of motion stability in high-precision applications. Furthermore, Leib et al. [6] investigated quantum-hybrid scheduling for transportation robots, showcasing how computational advancements can further optimize robotic efficiency. These studies provide valuable technological frameworks, yet they primarily focus on industrial applications rather than terrain-adaptive, biologically inspired handling robots.

Building upon these foundations, this study presents a novel bionic handling robot inspired by the locomotion and handling behaviors of ants. The robot integrates bio-inspired gait mechanisms, a multi-joint hexapod structure, and a modular control system to enhance movement stability and load adaptability in various terrain conditions. Through systematic analysis of ant locomotion and grasping behavior, this study proposes an optimized robotic design capable of executing complex handling tasks in dynamic environments. The experimental validation of the prototype aims to bridge the gap between theoretical bionics research and practical robotic applications, ultimately contributing to the advancement of intelligent robotic systems in handling and transport scenarios.

2. Analysis of ant locomotion mechanism

2.1. Morphological and structural characteristics of ants

As a highly evolved insect, the morphological structure of ants embodies remarkable adaptive features, which provide a rich source of inspiration for bionic design. The body of ants is divided into three parts: Head, thorax, and abdomen, and the functions of each part are clearly divided [2]. The head is mainly responsible for perception and predation functions, and its antennae are important sensory organs that can sensitively detect the external environment, including chemical signals and mechanical vibrations. The strong mandibles (jaws) of the head are key tools for handling, with efficient gripping and cutting functions, allowing ants to carry objects several times their own weight. The thorax is the core of the locomotor system, connecting three pairs of legs that are responsible for the ant's walking and climbing. Each leg consists of multiple segments, including the basal, transverse, femoral, tibial, and tarsal segments, and relies on a highly flexible multi-joint structure to realize complex movement patterns, such as advancing, steering, and climbing. The legs end with tiny claws and sticky pads that enable the ants to easily attach to a variety of surfaces, including vertical walls and smooth blades, a property that provides important inspiration for the terrain-adaptive design of bionic robots [3]. The abdomen, on the other hand, contains digestive, reproductive and excretory organs with flexible mobility. The secretory organs at the end of the abdomen of some ants are capable of releasing chemical pheromones for communication and path marking. This function can be translated into a reference mechanism for path planning and collaboration patterns in bionic robots. By comprehensively analyzing the morphological structure of ants, theoretical support and technical direction can be provided for the realization of multifunctionality and adaptability in bionic robot design.

2.2. Gait analysis of ants

Gait analysis of ants is an important foundation for bionic robot design, mainly in its efficient and stable three-point support movement pattern. The six legs of the ant are divided into front, middle and back legs, which are arranged symmetrically in pairs. The gait follows the "three-point support principle", meaning that three legs are always in contact with the ground while the other three move alternately, forming a "crossed three-point support" pattern. This gait improves stability while ensuring efficient continuous movement and is particularly suitable for irregular terrain. Ant leg movements involve three main degrees of freedom, including swinging of the basal segment, elevation of the femoral segment, and grasping of the tarsus. Its gait cycle usually consists of leg lifting, leg swinging and leg releasing as the main phases, and the intervals between each phase are strictly coordinated to ensure smooth movement. Studies have shown that an ant's gait cycle is about 0.1 to 0.2 s, and the specific frequency depends on its body size and speed requirements. Through high-speed photography experiments, it was found that ants would adjust their gait when carrying objects, with the front legs used more for grasping and support, and the middle and hind legs mainly providing propulsion.

Gait motion can be modeled by the kinematic equations, and its position vector can be described by the following Equation (1):

$$r(t) = r_0 + v_t + \frac{1}{2}at^2 \tag{1}$$

where r_0 is the initial position, v is the velocity vector, and a is the acceleration vector. The low center of gravity and dynamic balance characteristics of the ant's motion also provide important references for the optimization of the robot's control algorithm. These characteristics enable it to efficiently adapt to the complex terrain and maintain the stability and reliability of the motion, which provides a detailed theoretical basis for the gait planning of the bionic robot.

2.3. Analysis of ant handling behavior

The carrying behavior of ants is a key aspect of their ecological adaptability, and their exceptional carrying capacity is mainly due to their unique mechanical structure and collaborative approach. A single ant is capable of carrying objects weighing much more than itself, and its carrying capacity is usually 10 to 50 times its body weight, with some species even reaching more than 100 times [5]. Experimental data show that worker ants with an average body weight of 5 mg can reach a maximum lifting force of 0.5 g, demonstrating their remarkable strength and stability (**Table 1**). This carrying capacity mainly relies on its powerful jaw muscles and coordinated multi-legged force generation method.

The carrying behavior of ants consists of two forms: Single-unit carrying and group collaboration. In single-unit handling, ants coordinate their gait to balance the object by holding it in their jaws while adjusting the posture of their head and thorax.

In the case of group collaboration, the ants communicate with their antennae through pheromone marking, quickly organize multiple ants to exert force together, and dynamically allocate the standing position and pushing/pulling direction according to the weight and volume of the object to ensure that the overall force is uniform and the action is synchronized.

Mechanical modeling shows that the force equilibrium is satisfied by the ants during handling:

$$F_{total} = \sum_{i=1}^{n} F_i \quad (2)$$

where F_{total} is the total handling force, F_i is the handling force provided by a single ant, and n is the number of ants involved in handling. The handling efficiency of the colony is affected by the number of ants and the degree of coordination, and the efficiency will be saturated or decreased when the number exceeds a certain threshold.

Table 1. Statistics of parameters related to ant handling behavior.

norm	Data range	note
Weight of a single ant	4–6 mg	Measured against different ant species
Maximum handling weight	40–200 mg	Usually 10 to 50 times body weight
Increased efficiency of group handling	2–5 times	Compared to monolithic handling
Pheromone diffusion rate	2–5 mm/s	Influencing the efficiency of group collaboration

An in-depth analysis of ants' handling behavior can provide inspiration for bionic robot design, especially in the optimization of load distribution and group collaboration.

3. Bionic robot mechanism design

3.1. Overall program design

The overall scheme design of the bionic handling robot in this study is based on the morphological structure and locomotion mechanism of ants and combines with practical application requirements to propose a modular and multifunctional robot design architecture [6]. The design is centered on handling and complex terrain adaptation and is divided into three parts: The mechanical structure module, the drive system module and the control system module to ensure the flexibility and reliability of the system. The details are shown in **Figure 1**.

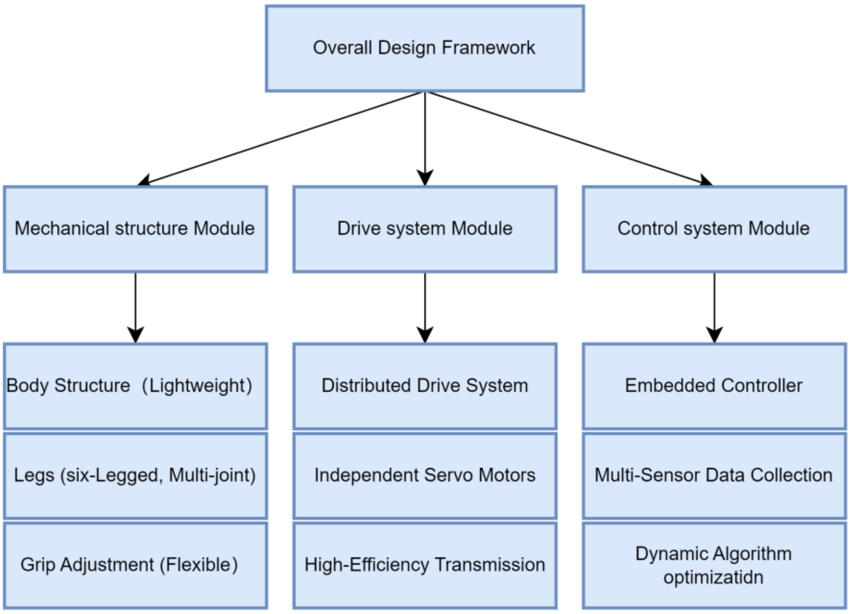

Figure 1. Flowchart of overall program design.

The mechanical structure module mainly simulates the body structure of ants, including the body, legs and grasping device. The body part adopts lightweight and high-strength materials to improve the carrying capacity and maneuverability of the robot in handling tasks; the leg design is based on a hexapod multi-joint model, which simulates the ant's three-point support gait to improve terrain adaptability; the grasping device is designed to be flexible, with adjustable gripping force to adapt to different sizes and shapes of objects to ensure the stability of grasping [7]. The drive system module provides power support for the robot, adopting a distributed drive scheme with independent servo motors for each leg to realize complex gait and coordinated handling functions. The power transfer is accomplished through a high-efficiency transmission mechanism to ensure the stability of the robot's motion under load. The control system module is the core part, adopting an embedded controller combined with multi-sensor data acquisition, responsible for gait planning, balance control and path planning. The system realizes dynamic adjustment through algorithm optimization to ensure efficient operation of the robot in multi-task and multi-terrain environments. The overall design emphasizes the coordinated work between modules to ensure that the robot has high adaptability, stability and handling efficiency, which provides a technical basis for practical applications.

3.2. Design of mechanical structures

The mechanical structure is the core part of the bionic handling robot, and its design directly determines the robot's motion performance and handling ability in complex terrain. The whole structure is divided into three parts: The body, the leg mechanism and the grasping device, and the coordinated operation of each part ensures that the robot has high efficiency and stability [8].

3.2.1. Fuselage structural design

As the core frame of the bionic handling robot, the fuselage is mainly responsible for supporting the leg mechanism, gripping device and the built-in control and drive system to ensure the overall rigidity and lightweight characteristics of the robot. The design adopts the combination of aluminum alloy frame and carbon fiber plate to ensure the balance of high strength and light weight. The body has an oval shape with dimensions of 300 mm × 200 mm × 100 mm and an overall weight of about 500 g. The internal layout of the body is designed as a three-layer structure with modularity as the core. The top layer mounts the gripping device and battery module, the middle layer arranges the controller and sensors, and the bottom layer serves as a fixed base for the drive system. The aluminum alloy wall thickness of the fuselage frame is 2 mm to provide the necessary resistance to deformation, while carbon fiber sheet encapsulation is used to further enhance the overall strength. The fuselage design considers the center of gravity distribution to enhance the stability of the robot during motion. The design is validated by calculating the center of gravity position, which is located near the geometric center of the fuselage at (150 mm, 100 mm, 50 mm).

3.2.2. Leg mechanism design

The leg mechanism is a key component of a bionic handling robot, and its design directly affects the motion flexibility and terrain adaptation ability. In this study, based on the ant hexapod model, six independent multi-degree-of-freedom legs are designed for the robot; each leg consists of a basal, femoral, tibial and tarsal segment with four degrees of freedom [9]. The legs are 100 mm long and have a range of motion that can span obstacles up to 20 mm high. Each leg is driven by a servomotor, and the leg lifting, swinging and grasping attachment functions are realized by a linkage mechanism. The servomotors are mounted at the base joint and provide high-precision joint motion control through gearing. The leg ends are designed with a combination of bionic dual hook claws and adhesive pads to ensure stable traction on smooth surfaces and irregular terrain.

The kinematic model of the leg uses the following Equations (3) and (4) to describe the end position:

$$x = l_1 \cos(\theta_1) + l_2 \cos(\theta_1 + \theta_2) \tag{3}$$

$$y = l_1\, sin(\theta_1) + l_2\, sin(\theta_1 + \theta_2) \tag{4}$$

where l_1 and l_2 are the lengths of the basal and femoral joints, respectively, and θ_1 and θ_2 are the corresponding joint angles.

3.2.3. Gripping device design

The gripping device is the core functional component of the bionic handling robot, responsible for grasping, handling, and releasing target objects. The design is based on the ant jaw as a bionic prototype and adopts a dual-claw gripping structure, with each claw 50 mm long and a maximum opening angle of 45°, and the gripping action is driven by micro DC motors [10]. Gripping forces of up to 10 N are available for handling tasks. The gripper body is made of high-strength engineering plastics to ensure low weight (50 g per gripper) and sufficient rigidity. The claw surface is designed with a non-slip texture and a soft rubber coating to increase friction and prevent slipping when gripping objects of different shapes and materials. The gripping device also incorporates a torque sensor to monitor the gripping force in real time and adjust the motor output via closed-loop control to avoid object damage.

The grasping action can be described as the following mechanical model:

$$F_g = \mu N \tag{5}$$

where F_g is the gripping force, μ is the coefficient of friction of the claw surface (about 0.8), and N is the normal force. The design adjusts the gripping force to accommodate objects of different weights by controlling the magnitude of N.

3.3. Drive system design

The drive system is the power source of the bionic handling robot, which directly affects its motion accuracy, stability and load capacity. This design adopts a distributed drive system; each leg is equipped with independent servo motors, and the motors' actions are coordinated through an electronic control unit (ECU) to ensure gait synchronization and flexibility. The servo motors are selected as high-torque models with a maximum output torque of 5 Nm for a single unit to meet the demand for adaptation to complex terrain. The drive system consists of a servomotor, a gear reducer and a linkage drive mechanism. The servomotor is mounted on the leg base section, and the gear reducer outputs power to drive the connecting rod to realize the joint movement. The gear reduction ratio is 1:15, which ensures the power output and reduces energy consumption at the same time. The overall drive efficiency is about 85%, with high energy utilization [11]. The system is designed with redundant drive channels to ensure that the robot can still maintain basic motion functions in case of individual drive failures. The drive motors are connected to the master module via CAN bus for efficient communication and real-time control. Each servo motor is equipped with a built-in encoder for real-time feedback of position and speed information to ensure high-precision control of the drive system. Details are shown in **Table 2**.

Table 2. Key parameters of the drive system.

character radical	**parameters**
servo motor	Maximum torque 5 Nm
Gear reduction ratio	1:15
drive efficiency	85%
Encoder Resolution	1024 pulses/revolution
energy supply	Lithium battery 24 V, 5000 mAh

4. Control system design

4.1. Overall control system architecture

The control system is the core part of the bionic handling robot, which is responsible for coordinating the operation of each module to realize efficient movement, balance adjustment and task execution. The overall architecture adopts a layered distributed design, which is divided into perception layer, decision-making layer and execution layer. Details are shown in **Figure 2**.

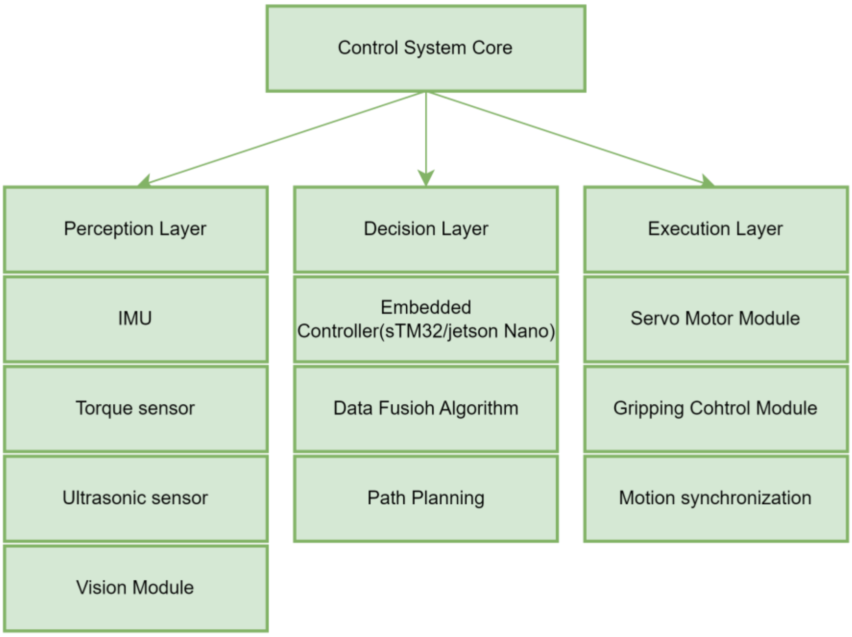

Figure 2. Overall architecture of the control system.

The sensing layer mainly includes a variety of sensor modules for collecting environmental information and robot state data. The sensors include an inertial measurement unit (IMU), a moment sensor, an ultrasonic sensor and a vision module, etc. The IMU monitors the robot's attitude and motion status in real time; the moment sensor is used to monitor the force of the gripping device, and the ultrasonic sensor and vision module collaborate to complete the environment sensing and obstacle detection. The decision layer consists of an embedded master control unit (e.g., STM32 or Jetson Nano) responsible for data processing and algorithm execution. The master control unit communicates with the distributed control nodes via a CAN bus to plan the robot's gait, path, and handling maneuvers in real time. The system uses data fusion algorithms to achieve accurate perception of the robot's state by integrating sensor data to further optimize decision-making. The execution layer includes a servo motor drive module and a gripping device control module, which complete specific actions by receiving commands from the decision-making layer [12]. The servo drive system works closely with the control node to ensure the precise synchronization of leg movement and grasping action.

4.2. Hardware system design

The hardware system is the physical foundation of the control system, which is responsible for realizing the functions of data acquisition, processing and execution of actions. The design is based on embedded architecture and is divided into three main parts: The sensor module, the main control module and the execution module.

The sensor module is mainly used to collect information about the environment and robot status, including the inertial measurement unit (IMU), torque sensor, ultrasonic sensor, and camera.The MPU-6050 module is used for the IMU to provide three-axis acceleration and angular velocity data; the torque sensor is used to monitor the force of the gripping device, with the range of 0–10 N and the accuracy of 0.1 N. The ultrasonic sensor (HC-SR04) is used to detect the obstacles in front of the robot; the ultrasonic sensor (HC-SR04) is used to detect the obstacles in front, with a measuring range of 2–400 cm; the camera adopts a wide-angle RGB camera to realize real-time environmental image acquisition with a resolution of 1280 × 720. The main control module is the core of the system, and the STM32F407 microcontroller is responsible for real-time processing of sensor data and execution of control algorithms. The module is equipped with a Cortex-M4 core with a main frequency of 168 MHz, which has strong computational and multitasking capabilities, and communicates with the actuator modules via a CAN bus [13]. The actuator module includes a servo motor driver and a gripper controller. The servo motor driver, model MG995, supports PWM control and has an output torque of 5 Nm; the gripper controller realizes precise opening and closing actions through the DC motor driver.

4.3. Motion control algorithms

Motion control algorithms are the core of bionic handling robots to achieve efficient motion and task execution, including gait planning, balance control and path planning [14].

4.3.1. Gait planning

Gait planning is the basis for bionic handling robots to achieve smooth motion, which mainly simulates the three-point support gait of ants, and ensures the stability and efficiency of the robot on complex terrains through reasonable support and swing allocation. The robot gait cycle is divided into a support phase and a swing phase, and the gait cycle and time allocation are different under different speed conditions. The details are shown in **Table 3**.

Table 3. Gait parameters of the robot at different motion speeds.

Velocity (cm/s)	Gait cycle (s)	Support Phase Duration (s)	Oscillation phase duration (s)
5	1	0.7	0.3
10	0.8	0.56	0.24
15	0.6	0.42	0.18

From the table, it can be seen that as the robot speed increases, the gait period decreases from 1.0 s to 0.6 s. The duration of the support phase also decreases, but it always accounts for about 70% of the total gait period. This design ensures that a stable three-point support state can still be maintained at high speeds. Meanwhile, the duration of the swing phase decreases gradually with the increase of speed, which ensures that the leg has enough time to return to the support state when the swinging action is completed. Through the reasonable allocation of gait parameters, the robot is able to realize efficient and stable movement under different motion conditions.The details are shown in **Figure 3**.

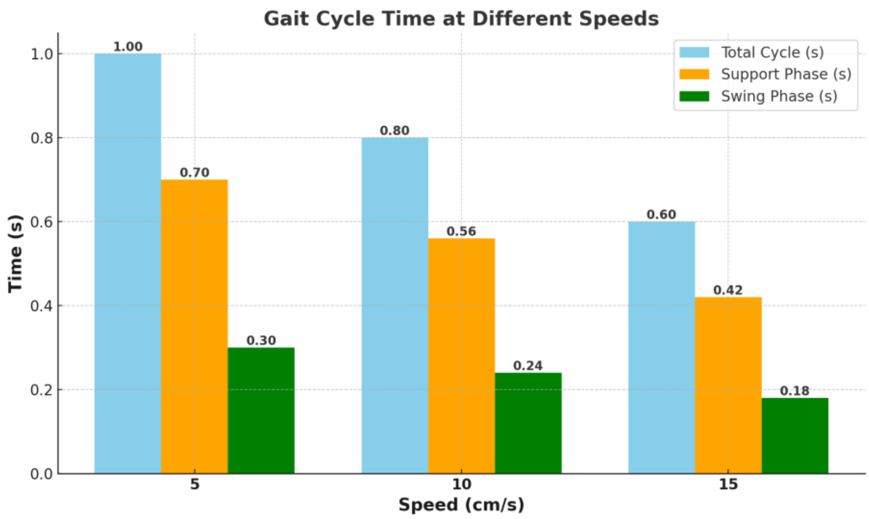

Figure 3. Gait cycle time at different speed.

4.3.2. Balance control

Balance control is the key to ensuring the stable operation of bionic handling robots on complex terrains, and the core of its design lies in the real-time adjustment of the position of the center of gravity and attitude angle to avoid tipping over and destabilization. The robot realizes balance control through multi-sensor fusion technology, including inertial measurement unit (IMU), torque sensor, position encoder, etc., to provide all-round state awareness.

The dynamic adjustment of the center of gravity is particularly important in balance control. The system calculates the position of the center of gravity in real time by collecting the leg joint position and body attitude data. The center of gravity offset is controlled within ±5 mm to ensure motion stability. Meanwhile, the attitude angle adjustment is driven by the real-time data provided by the IMU, including the pitch and roll angles, with the error range controlled within ±2°, and the attitude correction is realized by adjusting the angle of the leg joints and the support strength [15,16]. To further enhance stability, the system is designed with a prioritized response mechanism. When uneven terrain or load offset is detected, the attitude angle of the support leg is prioritized to restore the balance of the center of gravity. In addition, the gait cycle is combined with balance control to improve the stability of the robot on inclined terrain by extending the support phase time. This strategy provides the robot with a strong, dynamic, adaptive capability to maintain motion stability in high loads and complex environments, providing reliable support for mission execution.

4.3.3. Route planning

Path planning is the core technology of autonomous navigation for bionic handling robots, which is used to design optimal motion paths in dynamic environments. The planning process includes global path planning and local obstacle avoidance. Global path planning is based on the environment map to generate the shortest path for the robot from the starting point to the target point; local obstacle avoidance relies on real-time sensor data to dynamically adjust the path according to the current environment to ensure that obstacles are avoided. Global path planning usually uses the A* algorithm or Dijkstra's algorithm. These algorithms generate efficient initial paths by evaluating the cost function of the paths and integrating distance and terrain complexity. The map is represented in a rasterized form, and each cell contains information about obstacles, free space, or impassable areas to provide data support for path search. Localized obstacle avoidance uses the Dynamic Window Approach (DWA) or the Artificial Potential Field Approach, which dynamically generates safe next motion commands based on sensor feedback (e.g., obstacle distance from ultrasonic sensors and environment images from the vision module). The goal of local obstacle avoidance is to optimize the real-time adaptability of the robot in complex environments. To realize the effectiveness of path planning, the system integrates multi-sensor data fusion technology to ensure comprehensive perception of the environment. Meanwhile, the path planning module is tightly integrated with the motion control algorithm, which enables the robot to have efficient navigation capabilities in complex terrain and dynamic environments to accomplish the mission objectives by coordinating gait planning and balance control.

5. Sample machine test and analysis

5.1. Prototyping

Prototyping is a crucial stage in transforming the theoretical design of bionic handling robots into a functional entity, involving mechanical structure processing, drive system installation, control system integration, and overall debugging. Mechanical structure processing: According to the design drawings, the body frame is made of aluminum alloy, which is shaped by CNC machining to ensure high precision and good mechanical properties. The leg parts are made of engineering plastics and produced by 3D printing technology, which not only reduces the overall weight but also ensures the flexibility of each joint. The gripping device is injection molded from high-strength engineering plastics, and the surface of the gripping jaws is added with rubber coating to enhance the friction. Drive system installation: The drive system adopts high-torque servo motors, which are mounted at the base joint position of the legs and connected to the leg joints through a gear reducer and linkage mechanism. Each leg is mounted independently of the servo motor to ensure motion flexibility and gait controllability. Torque and speed tests were performed after the motors were installed to ensure that their performance met the design requirements.Control system integration: The STM32 microcontroller is selected for the main control module, which connects the sensor module and the drive system. The modules communicate via CAN bus in order to realize real-time data interaction and command transmission. The control system also integrates IMU, ultrasonic sensors and torque sensors for environment sensing and state feedback. Finally, after completing the integration of mechanical, electrical and control systems, the prototype is fully debugged, including a motion test, gripping ability test and communication test, to ensure that the prototype meets the design function requirements and lays the foundation for subsequent experiments.

5.2. Gait movement test

The gait locomotion test is verifying the feasibility of gait planning and locomotion performance of the bionic handling robot, focusing on its stability and flexibility under different terrain conditions. The test mainly includes flat ground tests, slope test and irregular terrain tests. Flat ground test: The robot performs linear motion on flat ground at preset speeds (5 cm/s, 10 cm/s, 15 cm/s). The test results show that the robot can accurately execute gait planning, the error between the gait cycle and the theoretical value is less than 5%, and the switching between the support phase and swing phase is smooth without obvious sliding or destabilization.Slope test: Gait movement tests were conducted on 15° and 30° slopes to observe the stability of the robot's gait. The results show that the robot performs well on a 15° slope, with a smooth center of gravity and a stable gait; on a 30° slope, the support phase time is automatically extended by 20% and remains stable by adjusting the center of gravity position in real time. Irregular terrain test: The robot's leaping ability was tested on a small obstacle terrain covered with sand and stones. The robot successfully crosses a 20 mm high obstacle with rapid gait adjustment, showing good terrain adaptation. The experimental results verify the reasonableness of the robot's gait planning and the effectiveness of the motion control algorithm, provide data support for subsequent optimization, and also show that the robot is able to satisfy the motion requirements in a variety of complex environments.

5.3. Handling capacity tests

The objective of the handling ability test was to evaluate the stability, grasping ability and gait coordination of the bionic handling robot under different load conditions. The tests were conducted on flat ground and irregular terrain to simulate the actual application environment. The robot completed linear handling tasks under different load conditions (200 g, 400 g, 600 g, and 800 g), and the distance of each task was set to 2 m. The completion time, gait stability, and performance of the grasping device were recorded. The gripping objects were cubes of uniform size but different weights to ensure the consistency of the test. Details are shown in **Table 4**.

Table 4. Test data under different loads.

Load weight (g)	Completion time (s)	Gait Error (%)	Grip Stability
200	15.2	2.5	No slipping or loosening
400	16.8	3	No slipping or loosening
600	18.3	4.2	Slightly sliding
800	21	5.6	The grip is slightly unstable.

5.4. Performance analysis and evaluation

The performance analysis and evaluation aim to compare the proposed bionic handling robot with other bio-inspired robotic designs, highlighting its advantages in stability, adaptability, and handling efficiency.

Motion stability and terrain adaptability: Compared with insect-inspired robots, such as stick insect or cockroach-based designs, this ant-inspired hexapod exhibits superior terrain adaptability due to its three-point support gait. Unlike quadrupedal or mammalian-inspired robots, which often require sophisticated balance control mechanisms, this robot maintains stability with minimal computational adjustments. In slope tests (15° and 30°), the robot successfully adjusted its support phase timing and center of gravity, enabling smooth operation. Additionally, the robot demonstrated improved climbing performance compared to previous insect-based robots by crossing 20 mm obstacles with a lower energy cost.

Handling capability comparison: In handling tasks, the robot achieved a load capacity of 800 g, surpassing many bio-inspired designs of similar scale. For example, many cockroach-inspired robots struggle to lift and transport objects due to their lightweight and limited leg strength. In contrast, this design benefits from the integration of a gripping mechanism inspired by ant mandibles, which provides a more stable grip. However, under maximum load conditions, slight slippage was observed, suggesting that future iterations should incorporate force-controlled gripping enhancements.

Adaptability and real-time control: Sensor fusion enables rapid posture correction and precise path planning, which is comparable to or better than certain mammalian-inspired designs that rely heavily on complex AI-driven motion strategies. The integration of the A* algorithm and Dynamic Window Approach (DWA) provides robust navigation and obstacle avoidance, while insect-inspired robots often rely on simpler reactive behaviors with less predictive planning capability.

Energy efficiency and operational endurance: The proposed robot exhibits a power consumption of approximately 15 W, ensuring continuous operation for 2.5 h. Compared to many quadrupedal robots, which require high-power actuation systems, this design achieves efficient energy utilization through its hexapod kinematics. The efficient leg mechanism and optimized gait planning reduce unnecessary power expenditure, giving it an advantage in long-duration missions.

Conclusion on comparative performance: The proposed design outperforms many insect-based and quadrupedal robots in terrain adaptability, handling strength, and power efficiency. However, its high-load handling stability still requires improvement, particularly in enhancing gripping precision and reducing gait error under maximum load conditions. Future optimizations will focus on improving the gripping mechanism, refining the motion control algorithms, and incorporating AI-based terrain adaptation strategies to further enhance performance.

6. Conclusion

This study presents the design and implementation of a bionic handling robot inspired by ant locomotion, demonstrating its effectiveness in stable movement, terrain adaptability, and medium-load handling tasks. The integration of gait planning and balance control algorithms ensures smooth operation in dynamic environments, while the modular mechanical design enhances the robot’s flexibility. Beyond planetary exploration, this robot has potential applications in disaster response, search-and-rescue missions, and hazardous material handling, where its ability to traverse complex terrain and manipulate objects autonomously can be highly beneficial.

However, certain limitations remain. The robot's gripping stability decreases under high loads, and its motion coordination may need further refinement for extreme environments. Additionally, energy efficiency constraints limit long-duration operations, which could be improved through advanced power management systems and lightweight materials. Future work will focus on optimizing the gripping mechanism, enhancing autonomous navigation with AI-driven decision-making, and integrating improved sensor fusion techniques for real-time adaptability. These advancements will further expand the robot's capabilities, making it a valuable tool in both industrial automation and extreme environmental operations.

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References

1. Meng T. Algorithm realization of automatic navigation handling robot. Journal of Physics: Conference Series. 2024; 2926(1): 012009. doi: 10.1088/1742-6596/2926/1/012009
2. Alebooyeh M, Urbanic J. Development of robotic automation solutions for limp flexible material handling leveraging a finite element modelling technique. The International Journal of Advanced Manufacturing Technology. 2024; 132(1–2): 781–800. doi: 10.1007/s00170-024-13229-z
3. Cheng W. Path coordination scheduling method of handling robot considering three-dimensional cargo space of intelligent warehouse. International Journal of Manufacturing Technology and Management. 2024; 38(1): 14–26. doi: 10.1504/ijmtm.2024.137383
4. Cheng X, Jiang J, Fu W, et al. Design of a new type of logistics handling robot based on STM32. International Journal of Information and Communication Technology. 2024; 24(3): 245–261. doi: 10.1504/ijict.2024.137928
5. Chou CH, Qian C, Lin YC, et al. Feedforward compensation of the pose-dependent vibration of a silicon wafer handling robot. CIRP Annals. 2024; 73(1): 321–324. doi: 10.1016/j.cirp.2024.04.081
6. Leib D, Seidel T, Jäger S, et al. An optimization case study for solving a transport robot scheduling problem on quantum-hybrid and quantum-inspired hardware. Scientific Reports. 2023; 13(1). doi: 10.1038/s41598-023-45668-1
7. Vijayakumar V, Sobhani A. Performance optimisation of pick and transport robot in a picker to parts order picking system: A human-centric approach. International Journal of Production Research. 2023; 61(22): 7791–7808. doi: 10.1080/00207543.2023.2232469
8. Jiang Y, Yu Y, Zhang H, et al. Research on application of compliant control of smart meter box handling robot. Energy Reports. 2023; 9(10): 1494–1501.
9. Lotter W, Kreiman G, Cox D. A neural network trained for prediction mimics diverse features of biological neurons and perception. Nature Machine Intelligence. 2020; 2(4): 210–219. doi: 10.1038/s42256-020-0170-9
10. Wang L, Liu J, Yang C, Wu D. A novel interval dynamic reliability computation approach for the risk evaluation of vibration active control systems based on PID controllers. Applied Mathematical Modelling. 2021; 92: 422–446. doi: 10.1016/j.apm.2020.11.007

11. Eisa SA, Stechlinski P. Sensitivity analysis of nonsmooth power control systems with an example of wind turbines. Communications in Nonlinear Science and Numerical Simulation. 2021; 95: 105633. doi: 10.1016/j.cnsns.2020.105633
12. Han H, Zhang C, Jiang J. Dynamic models and control system design for heated channels in a Canadian SCWR. Annals of Nuclear Energy. 2021; 151.
13. Liu KZ, Sun XM, Teel AR, Liu J. Stability analysis for networked control systems with sampling, transmission protocols and input delays. Nonlinear Analysis: Hybrid Systems. 2021; 39: 100974. doi: 10.1016/j.nahs.2020.100974
14. Ni TW, Yang ZG. Failure analysis on unexpected leakage of electro-hydraulic servo valve in digital electric hydraulic control system of 300 MW thermal power plant. Engineering Failure Analysis. 2021; 119: 104992. doi: 10.1016/j.engfailanal.2020.104992
15. Pakonen A, Buzhinsky I, Björkman K. Model checking reveals design issues leading to spurious actuation of nuclear instrumentation and control systems. Reliability Engineering & System Safety. 2021; 205: 107237. doi: 10.1016/j.ress.2020.107237
16. Dontsova TV, Kozulin KG, Piskazhova TV, Danykina GB. Simulation of the Control System of the Coke Calcination in Tubular Rotary Kilns. Russian Metallurgy (Metally). 2020; 2020(13): 1600–1606. doi: 10.1134/s0036029520130091