Academic Journal of Engineering and Technology Science
ISSN 2616-5767 Vol.7, Issue 5: 32-42, DOI: 10.25236/AJETS.2024.070506

Multi-environment Adaptive Terrain Detection and Navigation Robot

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Abstract: *This abstract summarizes a detailed exploration of the design, development, and functionality of a terrain detection robot intended for extraterrestrial exploration. The primary objective of this robot is to enhance the safety and efficiency of space probes by enabling them to navigate diverse terrains without damage. The document elaborates on the robot's design, incorporating innovative features like ground hardness detection through applied force and feedback mechanisms for adaptive movement. Significant research has been referenced to highlight the robot's capability to adapt to various ground types, from swamps to deserts, which typically pose substantial risks to mobility due to their complex surfaces. For instance, technologies like the Probabilistic Neural Network and Support Vector Machines are utilized for surface classification based on texture features extracted using methods such as Local Binary Patterns and Speeded Robust Features. The robot's architecture includes a robust mechanical structure with aluminum alloy components and high-torque motors adapted for different gravitational pulls of various celestial bodies. A pivotal feature of the robot is its ability to reposition itself rather than reverse when encountering impassable terrain, which is facilitated by a unique wheel design and sophisticated control systems. This document also discusses the practical challenges and theoretical implications of designing robotic systems for space exploration, including durability tests over simulated extraterrestrial surfaces and the integration of advanced sensors and AI to improve navigational decisions. The business model outlined in the document's conclusion suggests a strategic approach to commercializing this technology for space exploration applications.*

Keywords: *Extraterrestrial Navigation, Terrain Detection, Adaptive Mobility, Robotic Exploration*

1. Introduction

Terrain awareness is essential for outdoor independent research robots, and this function is crucial in helping the robot safely reach its destination. Since outdoor environments have different terrains, the robot's wheels might be able to navigate through every climate safely. Some complex surfaces, such as swamps and deserts, will make the robot's movement performance different, so the robot is in danger. The desert will sink the robot, and the swamp will make it unable to move. For example, NASA's "Spirit" and "Opportunity" Mars rovers have been unable to work, seriously affecting work efficiency and potential cost waste. The objective I am currently addressing is to ensure the discovery car's safe, efficient, and damage-free terrestrial locomotion.

In 2008, Eric Coyle developed the ATRV-Jr robot at Florida State University for terrain classification. Equipped with an IMU, it collected velocity and acceleration data to identify six pavement types using a PNN classifier. The method showed 85% accuracy at 1m/s and 90% at 0.5m/s, offering a promising solution for terrain-based navigation but requiring further validation for varying speeds，as shown in Figure 1.[1]

Figure 1: ATRV-Jr

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Figure 2: BOVW

In addition, Filitchkin of the University of California used the SURF algorithm to extract the characteristics of the ground surface. K-means clustering algorithm (K-Means) was used to carry out feature clustering to generate a Bag of Visual Words (BOVW) model, and a support vector machine (SVM) was used as a classifier to complete the classification of 6 types of pavements. The robot uses the camera to gain the confidence of the land and then feeds its analysis back to the robot, which uses the feedback from the land to adjust its stride to suit the environment. However, some land environment robots need help correctly identify and make perfect adjustments, which may seriously damage the robot, as shown in Figure 2.[2]

In a 2006 study, researchers from the University of Michigan developed methods for mobile robot terrain classification and characterization. Using a Pioneer 2-AT robot, they tested various sensors to classify terrains like gravel, sand, and asphalt in real time. The X-axis gyroscope excelled in distinguishing certain terrains, while other sensors were effective for specific classifications, such as motor current sensors for sand. The study also proposed "motor currents versus rate of turn" (MCR) curves for assessing terrain trafficability, offering insights into power needs and safe driving parameters. The findings suggest that combining multiple sensors could improve mobile robot performance on diverse terrains,as shown in Figure 3.[3]

Figure 3: 2-AT robot

Figure 4: TORTOISE

In the paper "Self-Supervised Terrain Classification for Planetary Surface Exploration Rovers," authors Christopher A. Brooks and Karl Iagnemma from MIT propose a self-supervised learning framework for robotic systems to predict the mechanical properties of distant terrains based on prior interactions with similar terrains. The framework utilizes a proprioceptive terrain classifier to identify terrain classes from rover-terrain interaction and trains an exteroceptive (vision-based) classifier using these labels. The system's high accuracy is demonstrated with experimental data from a four-wheeled robot in an outdoor Mars-analogue environment,as shown in Figure 4.[4]

In the study presented by Xiaofeng Guo et al., a soft foot sensor pad integrated with an array of sensors, including tactile, acoustic, capacitive, temperature, and an accelerometer, is developed for dynamic legged locomotion robots. A terrain classification algorithm leveraging these sensors and employing Random Forests with a memory function achieves an accuracy of approximately 96.5%. This advancement is crucial for enabling bipedal robots to navigate diverse and complex terrains, enhancing their capabilities for field robotics and beyond,as shown in Figure 5.[5]

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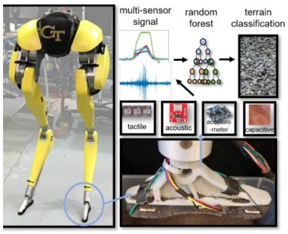

Figure 5: Multi-sensor terrain classification

Figure 6: Experimental platform

This research introduces a terrain classification system for autonomous ground vehicles using a 2D laser stripe-based structured light sensor. It employs spatial frequency and texture features analyzed by a probabilistic neural network, achieving over 97% accuracy. The method is robust to lighting and color variations, and an update rule is proposed to minimize misclassifications in control mode implementation, as shown in Figure 6.[6]

This paper introduces a novel graph embedding technique for classifying 3D deformable protein shapes. The method decomposes protein structures into triangle-stars, matches them using the Hungarian algorithm, and approximates the Graph Edit Distance. It employs supervised machine learning for classification, achieving superior results compared to existing algorithms. Future work includes integration with deep learning techniques.[7]

It introduces the Terrain Input Classification (TIC) method for autonomous ground vehicle (AGV) terrain identification, addressing speed dependency and the capability to traverse multiple terrains. TIC utilizes the AGV's vibration transfer function and surface profile inputs to classify terrains independently of speed, verified through simulations with various terrains, demonstrating improved accuracy over traditional vibration-based methods.[8]

In 2013, researchers presented an online visual terrain classification system for a hexapod robot, AMOS II, using a monocular camera and feature-based algorithms like SIFT and SURF. As is shown in Figure 7. The system achieved up to 90% accuracy, enabling the robot to select energy-efficient gaits for different terrains in real-time.[9]

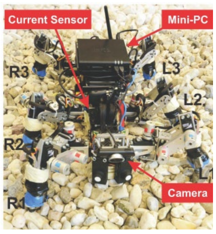

Figure 7: AMOS II

Figure 8: Sensor adhered to the foot of NAO

In the paper, a high-resolution plantar tactile sensor is developed for the NAO humanoid robot to

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classify surfaces in real-time. As is shown in Figure 8. The k-Nearest Neighbor (kNN) algorithm is utilized for classification, achieving over 95% accuracy after more than four walking steps, enhancing the robot's ability to adjust its walking pattern according to the surface type.[10]

This paper introduces a tactile probe for mobile robots that identifies surfaces using a single-axis accelerometer. The probe is dragged along surfaces, and an artificial neural network classifies the surface based on acceleration patterns with an 89.9% success rate for 1-second data windows. The system also supports unsupervised learning and real-time classification for a blind mobile robot.[11]

2. Mechanical Structure Design

The primary working method of this design is described as follows: If the robot only uses the ground acquisition and judgment method, some problems will cause the robot to be damaged, eventually leading to the mission's failure. Long-term considerations, for example, include encountering some unseen ground forms, such as the robot's inability to walk normally and explore. Therefore, to ensure the hardness of the ground, I will apply a force to the ground and judge whether the ground can walk by the depth of the ground collapse. In order to achieve this, a relatively simple and efficient way is to add a two-dimensional code to the part that touches the ground so that the camera above the robot can recognize the position of the two-dimensional code, and the program will make different judgments in different values. For example, when the overall drop of the QR code exceeds 50 percent, the robot will determine that the ground cannot walk. Then, it moves in parallel to another area and repeats the process. The purpose of parallel movement is to save energy consumption so that the robot can move farther and longer. The robot has the following advantages:

1) It can detect the ground more efficiently and accurately.

2) To a certain extent, it can reduce electricity consumption.

The overall structure of this machine car is just as shown in Figure 9. There are four wheels at the bottom, which are controlled by the steering engine and can be rotated forward and backward. Above is a cuboid made of aluminum alloy, the upper and lower aluminum alloy are parallel structures, this cuboid is the body, the connection of the middle protector circuit, the upper and lower board is used to shield. On the upper part of the body there is a mechanical arm with a screw shaped lever (by turning to move the mechanical arm back and forth), the mechanical arm has three connection points, which can be moved. On the top of the robot arm is installed a QR code image and a force controller. Next, I will introduce the structure of the parts in detail, Physical as in Figure 10.

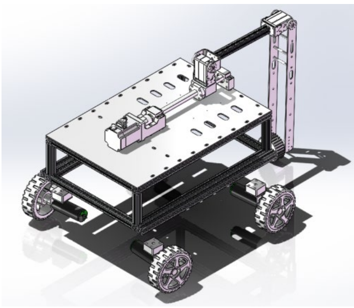

Figure 9: Structural design drawings

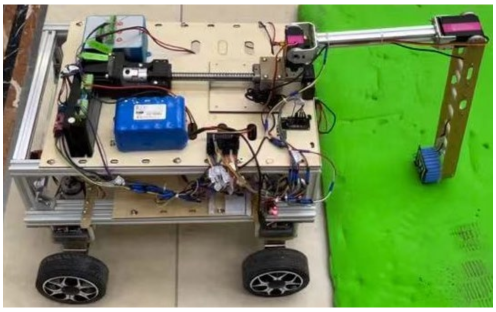

Figure 10: Complete Physical Picture

Aluminum light material, to ensure quality, durability, material cost performance, practicality is very high at the same time, but also has a relatively light weight, which can make the car in the planet faster, more portable movement. I put these pieces together to form a simple cuboid. The advantages of aluminum light material are hard, not easy to rust, and firm, which means that it can be used in different environments. I had a total of 12 aluminum weights, and to connect them together, I used Angle aluminum, as shown in Figure 11.

The aluminum light material is used for the frame, which is assembled with screws in a cuboid shape. High-quality robot driving wheels are selected for their performance within budget constraints. A super torque motor is chosen to handle varying gravitational forces on different planets, which is controlled by a board and connected to the wheels.

Initially, the vehicle was designed with front wheels steered by a gear for movement and turning capabilities. However, considering the potential need for reversing and re-detection during space exploration, the idea of using Mecanum wheels was considered. These wheels offer omnidirectional movement without the need for a steering mechanism, but they have drawbacks such as increased friction and high cost, which could affect the vehicle's efficiency and lifespan.

Ultimately, the decision was made to stick with the original design, enhancing it with steering gears on all four wheels for better maneuverability. This allows for efficient lateral movement and adaptability to various planetary terrains, ensuring the vehicle can navigate obstacles effectively during space missions that can span from weeks to decades.

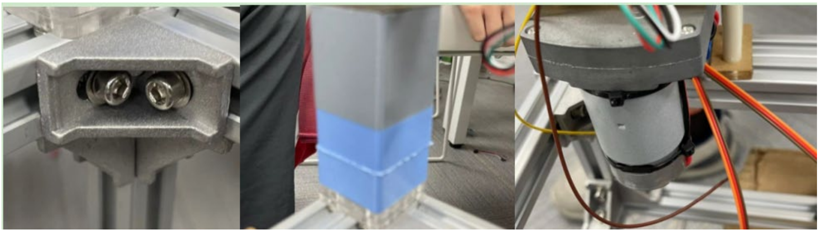

Figure 11: Mounting structure details

After my first assembly I found that the height of the wheels conflicted with the aluminum light material, so I used some pads (Figure 11) to increase the distance between them. After assembling the overall outline of the car, I need to consider the stability of the car. That means I need to reinforce the car. I need to carry out the design from multiple aspects. The first is the reinforcement between the two plates. Because the body is relatively heavy, there is great pressure on some structures at the bottom, which is easy to crush these structures, so I need to strengthen these parts. This is my first idea of reinforcement. In the lab, the most convenient and stable part is the nylon column. The size of the nylon column is m2, m3, m4, the choice of size depends on the size of the screw, the need to strengthen the space around the object, etc. And I need the exact size of the nylon column because it will fill the space between the reinforcement perfectly. Then I need to use Auto CAD technology sto make up and down shapes to fix the motor. The technique used here is relatively simple but requires the exact size of the hole and the exact size of the hole to be successful. As shown in the Figure 12, I used different screws for reinforcement, and then put nylon columns between the screws to help strengthen, so as to stabilize the object, not to let it move from side to side, and to add a supporting force.

Figure 12: Wheel mounting

Figure 13: Motor Installation

After assembling the overall outline of the car, I need to consider the stability of the car. That means I need to reinforce the car. I need to carry out the design from multiple aspects. The first is the reinforcement between the two plates. Because the body is relatively heavy, there is great pressure on some structures at the bottom, which is easy to crush these structures, so I need to strengthen these parts. This is my first idea of reinforcement. In the lab, the most convenient and stable part is the nylon column. The size of the nylon column is m2, m3, m4, the choice of size depends on the size of the screw, the need to strengthen the space around the object, etc. And I need the exact size of the nylon column because it will fill the space between the reinforcement perfectly. Then I need to use Auto CAD technology to make up and down shapes to fix the motor. The technique used here is relatively simple but requires the exact size of the hole and the exact size of the hole to be successful. As shown in the picture, I used different screws for reinforcement, and then put nylon columns between the screws to help strengthen, so as to stabilize the object, not to let it move from side to side, and to add a supporting force. The principle of this diagram (Figure 13) is the same, by increasing the support force in the two objects, the use of nylon columns, which can hold the two objects and increase the stability.

Figure 14: Connection bracket

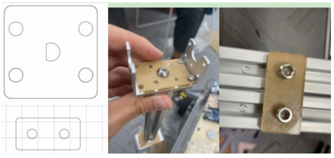

Figure 15: Mounting structure

These are two relatively simple graphics (Figure 14), very easy to make, and then I used a laser cutting machine to cut out the graphics, and then reinforced it with screws and nuts. The purpose of Figure 15 is to secure the two aluminum light materials, because the large weight can easily separate the aluminum light materials. The purpose of Figure 14 is to control the big arm of the robot arm and not let the big arm of the robot arm move easily. Because the robotic arm controls the probe, if the robotic arm is loose, the whole probe will be affected. In order to control the robot arm, I fixed the front and back of the robot arm, so that the robot arm can be easily fixed to prevent loose.

3. Hardware Design

3.1. Pressure Detection

In order to ensure the stability and durability of the robot, the choice of hardware is an indispensable link. After strengthening the parts, I decided to perfect the part of the robot arm and connect it to the whole car. First, I need an instrument to detect the force, because my idea is to output the force to the ground, and then detect the change of the ground through the camera, so as to judge whether the road can be walked. So, I first chose the force sensor, in order to ensure accuracy and quality, I spent a high price to buy a good quality sensor. Although it is small, it can be detected very efficiently and can withstand relatively large forces. However, the individual parts of this sensor are relatively fragile, so I need to give it a protection, as shown in Figure 16.

Figure 16: Pressure sensors and transmitters

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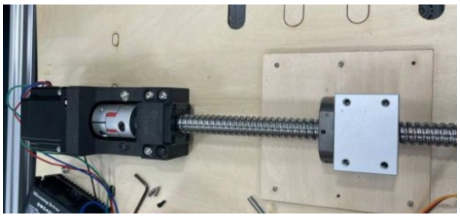

Figure 17: Linear drive platforms

3.2. Transmission

This part (Figure 17) does is it allows the arm to move back and forth, because I want to retract the arm and retract it at any time. The benefit is to be able to increase the possibility of movement and better adapt to moving in narrow Spaces. The arm can be moved back and forth by turning the screws in the middle. The arm needs to be assembled on top of the white cube and secured with screws. Finally, the two connecting points of the mechanical arm are respectively installed on the steering gear, the purpose of the steering gear is to adjust the Angle of the mechanical arm. And the length of the robot arm allows the robot to detect a wider range, which can reduce the movement of the robot.

3.3. Deep Recognition

My car needs to identify a pattern through the camera, and then by judging the position of the pattern, it can detect whether the land is ready to walk. Force is applied to the ground by a robotic arm so that the figure sinks with it. I printed out the image using a printer, and then glued it to the wheel of the robot arm using double-sided tape, as shown in Figure 18.

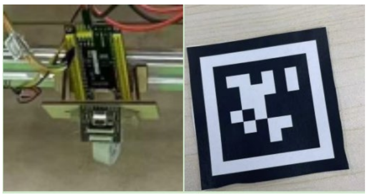

Figure 18: Visual identity and tag

4. Control System

4.1. Visual Judgment

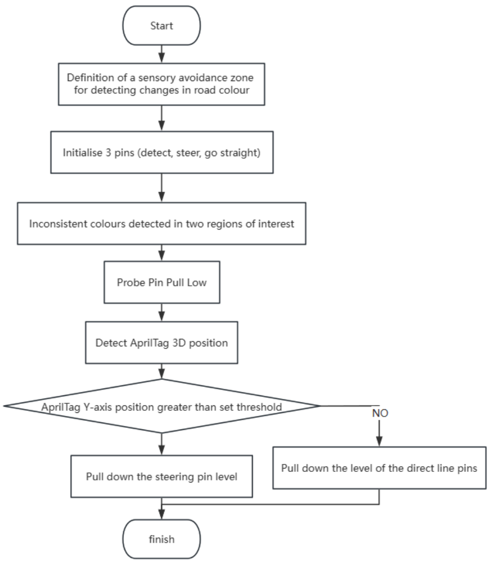

Figure 19: Visual Identity Flowchart

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The diagram outlines a decision-making process for a robotic system when detecting changes in road color, which is part of a sensory avoidance strategy, as shown in Figure 19.

1) Define Sensory Avoidance Zone: A specific area is designated for detecting changes in the road's color.

2) Initialize Pins: Three control pins are initialized:

Detect for color detection.

Steer for steering control.

Go straight for direct movement control.

3) Inconsistent Colors Detected: If inconsistent colors are detected in two regions of interest, it indicates a change in the road's color.

4) Probe Pin Pull Low: Upon detecting a color change, the probe pin is pulled low (set to a low electrical level).

5) Detect AprilTag 3D Position: The system detects the 3D position of an AprilTag, which is used for 3D positioning.

6) AprilTag Y-Axis Position Check: If the Y-axis position of the AprilTag is greater than a set threshold:

The steering pin is pulled down, signaling the robot to steer.

The go straight pin is also pulled down, indicating the robot to stop moving straight.

7) Steering Decision: If the Y-axis position of the AprilTag does not exceed the threshold, no steering action is taken.

4.2. Pressure Judgment

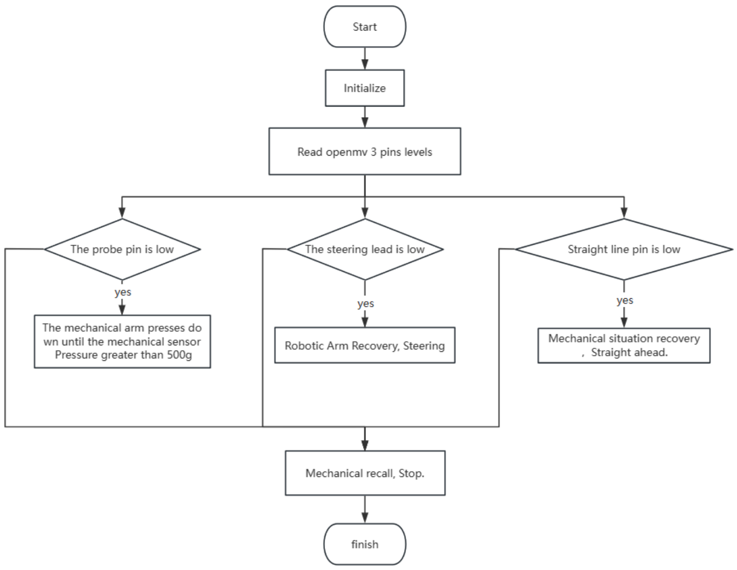

Figure 20: 3D Force Sensor Recognition Flowchart

As shown in Figure 20 above, the flow of 3D force sensor recognition is demonstrated.

1) Initialize (Suart): The process begins with the initialization of the system.

2) Read OpenMV 3 Pins Levels: The system reads the electrical levels of three OpenMV control pins, which are likely associated with the actions of the mechanical arm.

3) The Probe Pin is Low: If the probe pin reads a low level, it may signal that the robot needs to respond.

4) Rearing Lead is Low: If the rearing lead pin is also low, it could be another signal for the robot to

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perform a specific action.

5) Straight Line Pin is Low: If the straight line pin is low, it might indicate that the robot needs to cease moving straight.

6) Pressure Greater than 500g: If the pressure detected exceeds 500 grams, this could be the threshold that triggers the action of the mechanical arm.

7) Until the Mechanical Arm Recovery: The system waits for the mechanical arm to complete its recovery movement.

8) Steering, Straight Ahead: After the mechanical arm has recovered, the robot may need to steer or move straight ahead.

9) Mechanical Recall: If necessary, the system can initiate the recall action of the mechanical arm.

10) Stop: After all required actions have been performed, the robot comes to a stop.

5. Experimental Measurement

5.1. Experiment 1: Robotic arm motion test

Objective: To verify whether the movement of the robotic arm is continuous enough to complete the pressure measurement and complete the process of extension, measurement and contraction of the robotic arm.

Movement process record: The following Figure 21 shows the complete movement process of the robotic arm.

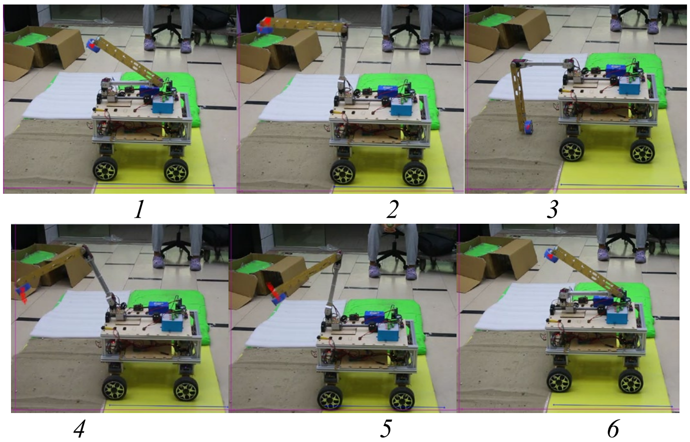

Figure 21: Mechanical arm movement process

Analysis of the exercise results, as in Figure 22:

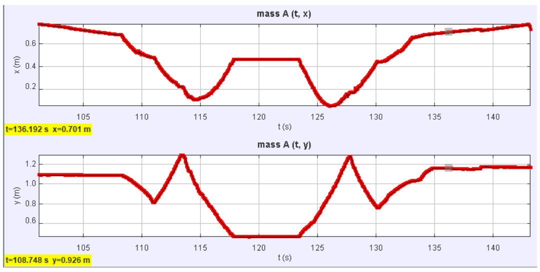

Figure 22: End position change

Changes in movement trajectory, as in Figure 23:

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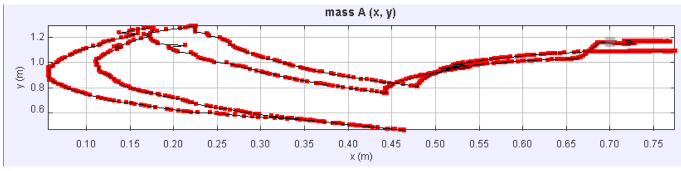

Figure 23: Trajectory change curve

As can be seen from the figure above above, the robotic arm can realize continuous movement during the process of movement, and can normally realize the extension, expansion, measurement, contraction, retreat and other movements of the robotic arm, ensuring that the terrain can be judged normally.

5.2. Experiment 2: Topographic measurement of walking experiment

After completing the construction of the mechanical car, I simulated four kinds of terrain according to the possible environment of the alien planet and encounter. The first terrain is made of soft plasticine, which simulates some soft ground. The second type of ground is the ground made of sand, which simulates some of the ground mainly composed of sand and soil. The third type of floor is the floor made of marble. The fourth is a surface made of foam panels, which mimics the softer surface of a planet. The final result of the experiment is that the robot can accurately judge the softness with the ground and can make correct changes, as in Figure 24.

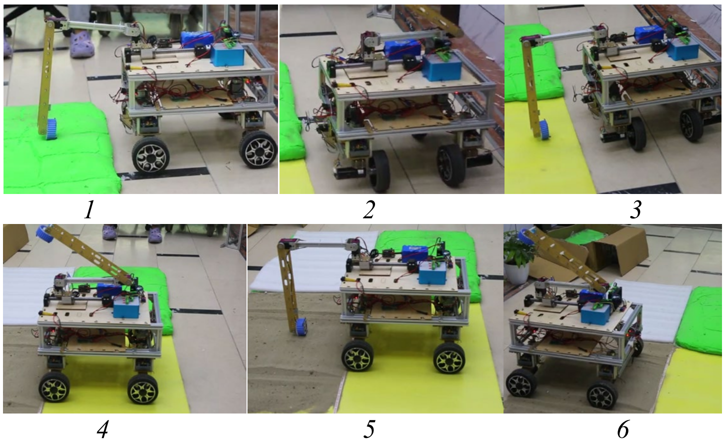

Figure 24: Dynamic terrain recognition process

Different materials are used throughout the diagram to simulate different types of terrain, including sand, soft terrain, hard terrain, and foam terrain.

As shown in the figure above, a judgment of four kinds of terrain is shown. The robot can accurately judge the terrain category and make corresponding movements according to different judgment results.

6. Conclusions

The terrain detection robot project has demonstrated significant progress in advancing the capabilities of robotic systems for extraterrestrial exploration. The integration of innovative technologies and methodologies has resulted in a robot prototype that can effectively navigate and adapt to diverse terrains, enhancing the safety and efficiency of space missions.

Key achievements of this project include:

Innovative Design: The robot's design, featuring a robust mechanical structure and specialized wheel systems, has proven to be adaptable to various gravitational forces and terrain types.

Advanced Sensing and Feedback Mechanisms: The implementation of advanced sensors and feedback systems allows the robot to make real-time adjustments to its movement strategy based on ground conditions, significantly improving its ability to traverse challenging landscapes.

High-Torque Motors: The use of high-torque motors has been crucial for overcoming the varying gravitational pulls of different celestial bodies, ensuring the robot's mobility and functionality. AI and Machine Learning Algorithms: The incorporation of AI, such as the Bag of Visual Words model and other machine learning algorithms, has enabled the robot to classify terrain types and make informed navigational decisions.

Durability and Cost-Effectiveness: The project has successfully developed a robot that balances high-quality performance with cost-effectiveness, a critical factor for space exploration applications.

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