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An autonomous robotic arm for efficient rock collection in uncharted territories

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ABSTRACT

The autonomous rock collector using robotic arm for exploration of unknown territories (ARCAxUT) is introduced as an innovative solution for the efficient retrieval of rock samples in unexplored space regions. Traditional, human-reliant methods are costly and hazardous, prompting the development of ARCAxUT. Equipped with a smart robotic arm, an RGB-D camera, and NUC computer, the system autonomously detects and estimates the mass of various rock samples. Validated in simulated and real-world environments, the algorithm ensures precise gripper control, achieving an impressive 95.4% accuracy in rock size estimation. This breakthrough offers transformative capabilities for space missions, revolutionizing celestial body sample collection and advancing broader societal implications in space exploration technologies.

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1. INTRODUCTION

The field of autonomous robotics has seen significant advancements in recent years, with robots being deployed in various domains, such as planetary exploration [1]. One of the critical tasks in planetary exploration is the collection of rock samples [2]. Historically, this task has been hazardous and costly, often requiring human intervention. The autonomous rock collector using robotic arm for exploration of unknown territories (ARCAxUT) aims to address this challenge by automating the process of rock collection [3].

The problem at hand is the efficient retrieval of rock samples from space [4]. This task is traditionally hazardous and costly, often requiring human intervention [5]. ARCAxUT aims to automate this process, thereby enhancing safety and mission efficiency [6].

Previous work in the field has focused on various aspects of autonomous robotics and planetary exploration [7]. Notable contributors include Schenker *et al.* [8], who tailored concepts for Martian landers and rovers, considering design constraints like mass and ambient conditions; Kennedy and Desai [9], who focused on a low-impedance robotic arm for human-like interaction with unknown objects; Beetz [10], who explored plan-based control for multi-robot coordination with minimal communication; and Martinson and Schultz [11], who presented an autonomous system for locating ambient noise sources using an evidence grid algorithm. Aparnathi and Dwivedi [12] aim to address labor shortages, production speed, and product quality by implementing automation technologies in industries, thereby enhancing overall efficiency and effectiveness. Kumar *et al.* [13] have developed an optimal control approach for movement and trajectory planning of a multi-degree-of-freedom robot arm using soft computing techniques, evaluated various degrees of freedom in robotic arm movement, and optimized the arm's movement using genetic algorithms and model joints to compensate for uncertainties like movement, friction, and settling time, achieving optimal results at all possible input values and reaching the target position within simulation time [14]. Dutta *et al.* [15] have proposed a novel trajectory and path generation approach for an industrial manipulator using optimal path planning (OPP) and Pontryagin's minimum principle, achieving effective joint angle, velocity, and torque control for a two degree of freedom (DOF) manipulator [16].

While previous work has made significant contributions to the field, several unresolved problems remain [17]. These include issues with existing methods, limitations of current technology, and challenges in the field of space exploration [18]. ARCAxUT aims to address some of these problems by automating the process of rock collection [19]. The unique contribution of ARCAxUT lies in its ability to automate the process of rock collection in extraterrestrial environments [20]. While previous work has focused on various aspects of autonomous robotics and planetary exploration, ARCAxUT combines advanced hardware and software components to create a robust and reliable system for rock collection [21].

The subsequent sections of this paper will detail the components, algorithm, and performance of ARCAxUT in simulated and real-world scenarios. This will include a discussion of the hardware and software components. The algorithm used for rock detection and estimation, and the performance of the system in various environments.

2. METHOD

The hardware configuration of the ARCAxUT is meticulously designed to ensure optimal functionality in extraterrestrial environments. The system is composed of three core components: a 6-degree-of-freedom robotic arm, a suite of sensors, and a central next unit of computing (NUC) acting as the computational hub. The robotic arm is engineered for precise rock manipulation, featuring resilient actuators and advanced control systems to withstand harsh conditions beyond Earth. The sensors, including an infrared (IR) camera, GPS, and Intel RealSense D 435i stereo camera, are chosen for their sensitivity, accuracy, and suitability to thrive in the unique target environment. These sensors contribute to data collection for tasks such as rock classification and environmental awareness, providing crucial information for the system's operations.

The central NUC, equipped with a Ryzen 5 processor and 8 GB of memory, processes data from the sensors, executes complex control algorithms, and orchestrates the robotic arm's movements through a Teensy 4.1 microcontroller. The NUC provides ample computational power to meet the system's demands efficiently. The robotic arm's precision movements are ensured by NEMA17 stepper motors regulated by the A4988 motor driver circuit, which controls the motors' speed and direction. Figure 1 illustrates the proposed system diagram for the ARCAxUT.

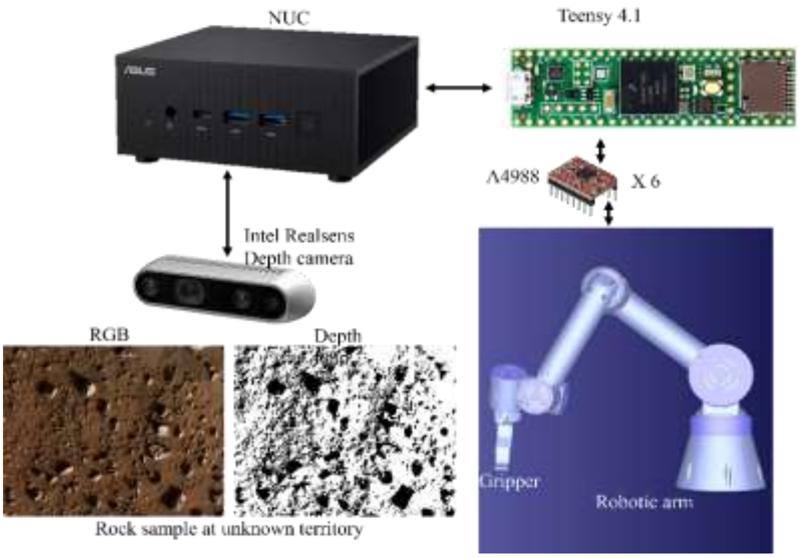
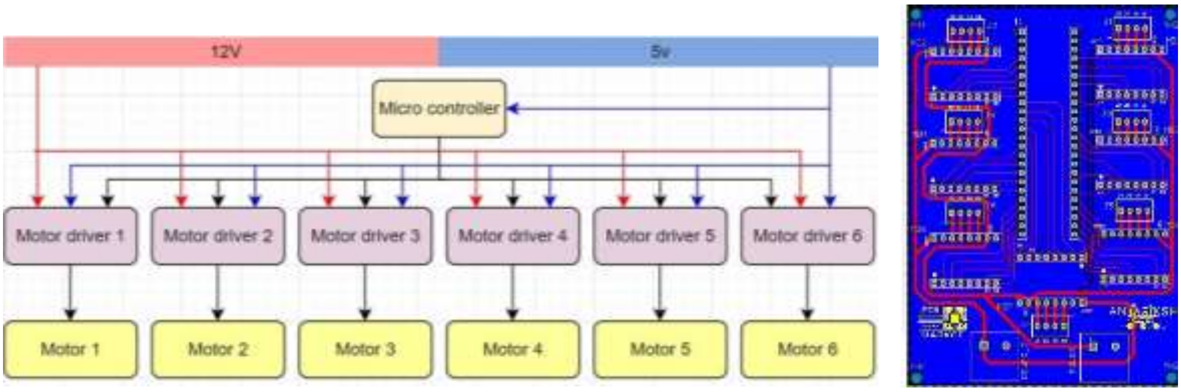


Figure 1. Proposed system diagram for the ARCAxUT

The software architecture of ARCAxUT consists of three main modules: the robot operating system (ROS) with MoveIt and Gazebo, the RC-Net neural network for rock classification, and TensorFlow for processing RGB-D data. Extensive testing in simulated and real-world scenarios included precision calibration of the robotic arm, sensor fusion for accurate data interpretation, and fine-tuning of the RC-Net. Figure 2 shows circuit details for driving the motors using microcontrollers with Figure 2(a) illustrates the block diagram depicting the Motor Interfacing with Teensy 4.1 (motor controller) and A4988 (motor driver) and Figure 2(b) showcases the PCB Design specifically tailored for the Integration of Teensy 4.1 with NEMA 17 stepper motors.



(a) (b)

Figure 2. Circuit details for driving the motors using microcontrollers (a) block diagram showing motor interfacing with Teensy 4.1 (motor controller) and A4988 (motor driver) and (b) PCB design for Teensy 4.1 integration with NEMA 17 stepper motors

Figure 3 presents the schematic diagram, elucidating the intricate wiring configuration of Teensy 4.1 Integration with six NEMA 17 Motors utilizing A4988 drivers. Figure 4 illustrates the 3D-printed robotic arm assembly, where Figure 4(a) shows a photograph of the printed assembly and Figure 4(b) depicts an image of the internal gear mechanism. Figure 5 shows the circuit details and gripper assembly where Figure 5(a) shows a screenshot of the PCB after soldering, and Figure 5(b) depicts a picture of the gripper lifting an object. The planetary gearbox, shown in Figure 5(b), enhances motor torque, essential for the system's efficiency and reliability.

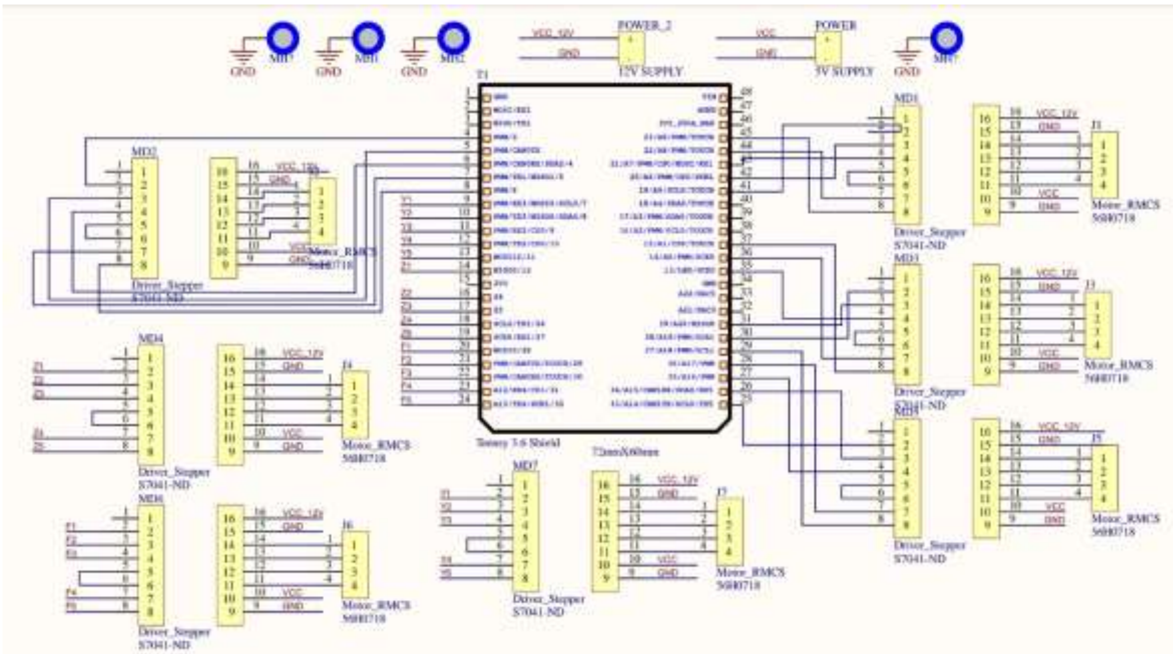


Figure 3. Schematic diagram of proposed system

(a) (b)

Figure 4. 3D-printed robotic arm assembly (a) picture of the 3D-printed assembly and (b) picture of internal gear mechanism

(a) (b)

Figure 5. The circuit details and gripper assembly (a) screenshot PCB of the project after soldering and (b) image of gripper lifting the object

The hardware configuration of ARCAxUT is a sophisticated ensemble. Harmonizing cutting-edge technology to enable precise and reliable extraterrestrial exploration and experimentation. The system's robust design, advanced sensors, and powerful computational capabilities make it a transformative tool for autonomous rock collection in unknown environments.

3. RESULTS AND DISCUSSION

The ARCAxUT system demonstrated exceptional accuracy in estimating the size of various rock samples, achieving a remarkable accuracy rate of up to 95.4%. This high accuracy was rigorously evaluated through testing in both simulated and real-world environments, employing a sophisticated algorithm. The rock classification network (RC-Net) played a crucial role in achieving this accuracy, exhibiting robust and reliable performance across various metrics. Figure 6 displays a Screenshot of MOVIT.rviz program running on ROS in Ubuntu loaded on NUC.

Precision, recall, and the F1 score were the key metrics used to assess the RC-Net's performance. Precision, which measures the accuracy of positive predictions, showed a commendable rate, indicating the system's ability to accurately identify rocks with minimal false positives. The high precision score underscored the reliability of the RC-Net in classifying rocks accurately. The F1 score, which balances precision and recall, was notably high at 94.1%, indicating a good balance between accurately identifying positive instances and capturing the total number of actual positive instances. The RC-Net's high F1 score suggests its effectiveness in making accurate predictions across various rock classifications. The system's ability to accurately estimate rock sizes and classify them positions it as a promising tool for scientific exploration, particularly in extraterrestrial environments. The RC-Net's proficiency in minimizing false positives and false negatives, along with its consistent high performance, makes it a valuable asset for scientific missions that require precise rock classification and size estimation.

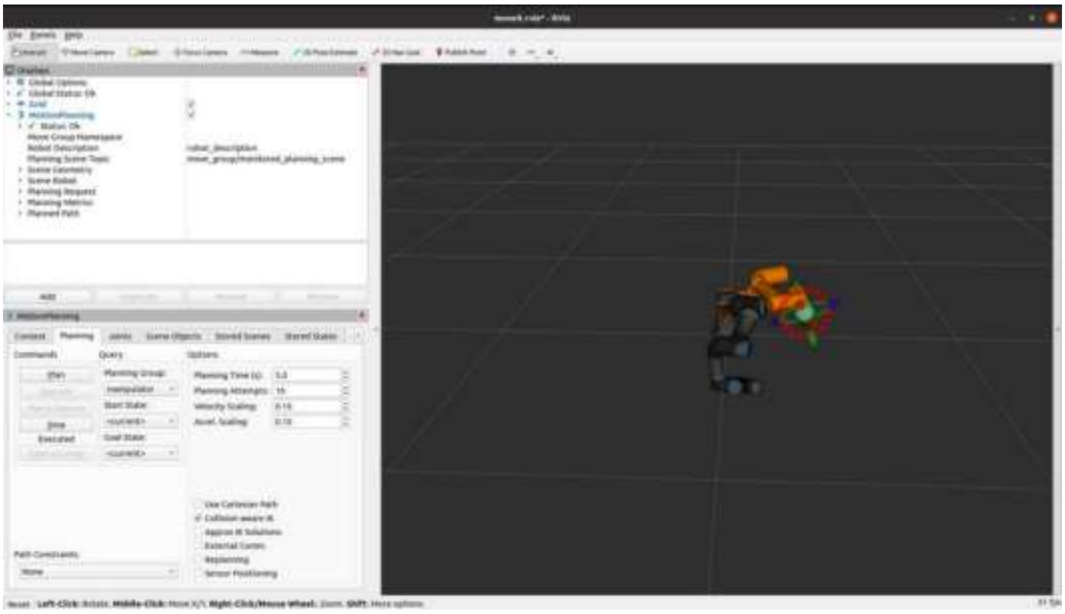
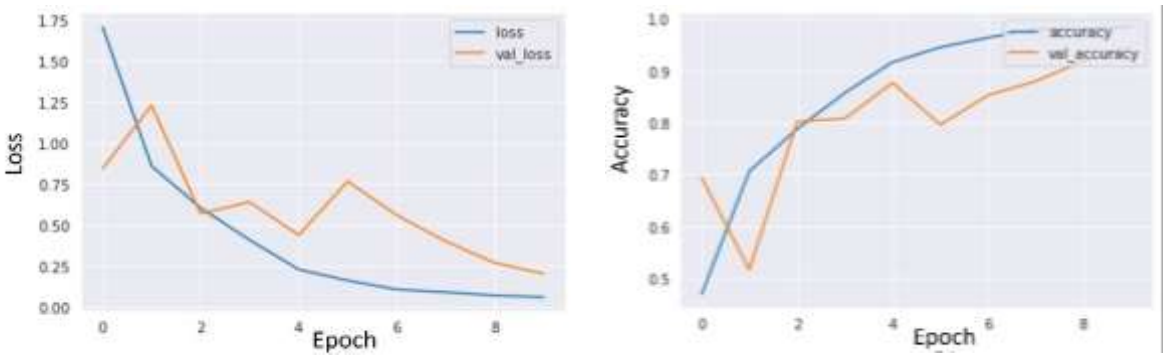


Figure 6. Screenshot of MOVIT.rviz program running on ROS in Ubuntu loaded on NUC

Figure 7 shows the intermediate results achived during training, where Figure 7(a) displays the Loss curve, and Figure 7(b) exhibits the Accuracy curve. The training outcomes for a 7-class classification task are depicted in Figure 7, which includes a performance-assessing confusion matrix and a screenshot from the ROS. The loss function graph (Figure 7(a)) shows a significant reduction in loss over the course of training, indicating an improvement in the model's discriminatory abilities. The accuracy plot shows a consistent increase in accuracy throughout training, reaching an impressive 94.1%.



(a) (b)

Figure 7. The intermediate results achieved during training (a) loss curve and (b) accuracy curve of ARCAxUT

Figure 8 displays the Confusion matrix after 10 training epochs, offering a comprehensive overview of the rock classification algorithm's performance. The integration of NEMA17 stepper motors, controlled by the Teensy 4.1 microcontroller via the A4988 motor driver, ensured precise rock manipulation, optimizing both power efficiency and control accuracy. While the RC-Net model excels in rock classification and gripper control, future iterations could explore alternative configurations like Arduino and servo motors for enhanced simplicity and efficiency. Our findings demonstrate that ARCAxUT represents a significant breakthrough in autonomous robotics, particularly in planetary exploration, by automating rock collection and enhancing mission efficiency and safety. Beyond planetary exploration, the technology developed for ARCAxUT has broader applications in environmental monitoring, disaster response, and industrial automation, offering potential innovations and advancements across various industries.

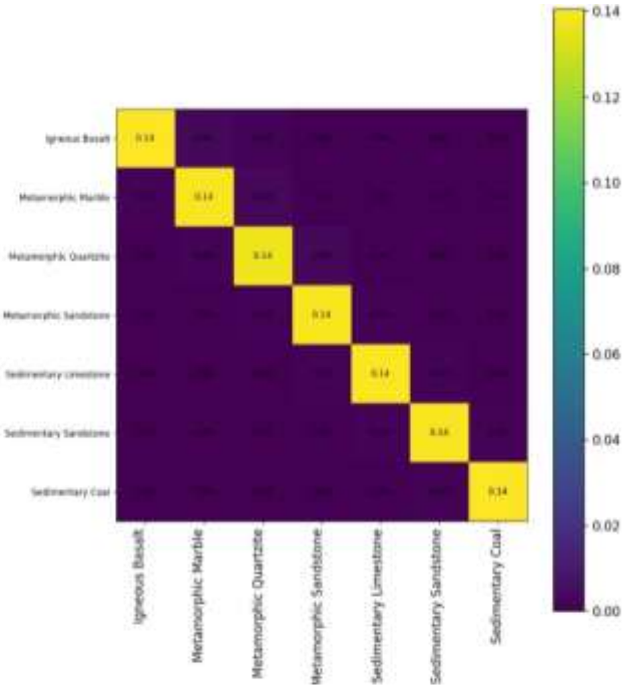


Figure 8. Confusion matrix for a rock classification algorithm trained on 10 epochs

Table 1 shows the proposed Autonomous Rock Collector using ARCAxUT method exhibits a competitive accuracy of 95.4% across seven rock classes, surpassing the performance of existing methods in terms of the number of classes covered. For instance, the feature localization comparison network (FPCN) by Ma *et al.* [22] achieved an accuracy of 93.3% across four classes using a camera as the hardware. Similarly, Lampinen *et al.* [23] neural network (NN) achieved 93.3% accuracy across two classes using a camera. Wei *et al.* [24] deep convolutional neural network achieved an accuracy of 95.6% across six classes, again using a camera.

Table 1. The comparison of proposed method with different rock classification methods

Method	Accuracy (%)	Classes	Hardware
Feature localization comparison network (FPCN) [22]	93.3	4	Camera
Neural Network (NN) [23]	93.3	2	Camera
Deep Convolutional Neural Network (DCNN) [24]	95.6	6	Camera
Variable Permeability System (VPS) [25]	53.8	2	3D depth camera
ARCAxUT	95.4	7	Camera

ARCAxUT's utilization of seven rock classes surpasses other methods in class diversity, with notable accuracy rates. Despite the variable permeability system (VPS) by Ran *et al.* [25] achieving 53.8% accuracy across two classes, ARCAxUT's performance stands out, especially in handling diverse rock classes effectively. Our research holds significant implications for autonomous robotics and space exploration, offering a foundation for future advancements in this field.

4. CONCLUSION

The ARCAxUT autonomous rock collector represents a groundbreaking leap in autonomous robotics, achieving an impressive 95.4% accuracy in estimating rock size. Its proficiency in rock classification, environmental awareness, and gripper control positions it as a transformative tool for autonomous rock collection, particularly in unpredictable extraterrestrial environments. Future endeavors could enhance adaptability through adaptive learning and explore cost-effective alternative setups, reflecting our dedication to advancing exploration technologies for scientific discoveries.

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