

Development of a Multifunctional Rover System for Mars Exploration and Operations in the University Rover Challenge

Danishi Ai Sunami Sako Nagaoka Keita Okuda Kazuho Kataonami Teruhiro
Kato Shunsuke Saizaki Tomoki Matsuhashi Kota Karimata Sora Nakayama Akihiro
(Tohoku University)

Majima Sho Inoue Asahi ◦ Nagahara Ryoji(Keio University)
Miyoshi Shuji(Tokyo University of Agriculture and Technology)
Koizumi Karin(Tokyo University of Science)

In recent years, Mars exploration has seen significant advancements, with substantial efforts directed towards sample return missions and the search for life. Mars Desert Research Station hosts an annual competition that evaluates the performance of developed rovers. This paper details the design and development of rover ARES 7, created for participation in this competition. ARES 7 is equipped with high mobility for navigating rough terrain, a robotic arm for executing manipulation tasks, and a science module that facilitates life and geological exploration. Validation experiments were conducted in the competition field to assess its capabilities.

1. Introduction

1.1 Mars Rover and Competition

Recent Mars exploration advancements have focused on sample return missions and life detection, inspiring the University Rover Challenge (URC), a global college robotics competition at the Mars Desert Research Station. Student teams are evaluated on Delivery, Equipment Servicing, Autonomous Navigation, and Science Mission. ARES 7, shown in Fig. 1, has high mobility for rough terrain, a robotic arm for manipulation tasks, and a science module for life and geological exploration, validated through competition field experiments.

1.2 Rover Mechanism

The Mars Desert Research Station (MDRS) is a space analog facility simulating Martian conditions with its arid, rocky, and sandy terrain shaped by strong winds [1]. Rovers are required to keep enough durability for traversing in such a harsh environment. Since the rover is equipped with different modules, it needs to be scalable and rigid to ensure a stable move.

1.3 Robotic Arm Mechanism

Two missions out of four in URC require a robotic arm. The Extreme Delivery Mission involves carrying objects up to 5 kg. The Equipment Servicing Mission entails delicate maintenance tasks on mock-up spacecraft, such as opening drawers, tightening hex-head bolts, typing on a keyboard, and inserting or removing USB devices. Consequently, the robotic arm must possess a high degree of freedom (DOF), precise maneuverability, and significant payload capacity to perform these tasks effectively.

1.4 Science Mission Details

In the Science Mission, tasks include collecting soil samples and conducting life exploration based on geological observations and in-situ chemical analyses us-

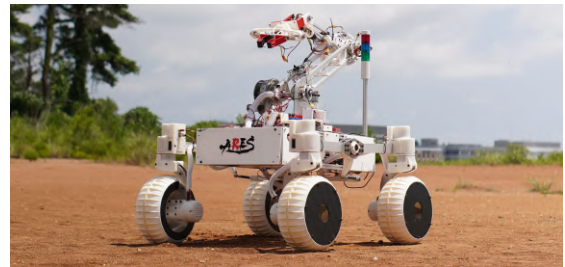


Fig. 1: Mars Rover ARES 7.

ing rover-mounted equipment. The rover must be driven to a suitable site for analysis and collect soil samples at a depth of at least 10 cm and a weight of at least 5 g. After the mission, a scientific discussion with judges, who are scientists, evaluates the data obtained by the rover, the validity of the chosen analysis methods, and the team's scientific knowledge.

1.5 Science Mechanism

The drill mechanism was developed to meet the depth and sample weight requirements. The Biuret reaction was selected for life detection due to its ease of use and rapid response time. An absorbance spectrophotometer confirmed reactions between the reagents, while centrifugation removed impurities from both reagents and reaction products. The system, including reagents and samples, was designed as a closed loop and transported by a tube pump to minimize contamination. A multispectral camera was integrated for stratigraphic analysis, with mechanisms specifically designed for each step.

2. Multifunctional Rover

2.1 Overall Development Policy

The test field features rugged terrain with undulations, ditches, and obstacles requiring navigation. Additionally, some missions demand precise maneuvering. Therefore, the development requirements for

ARES7 included stable traversal over rough terrain and flexible posture adjustments.

2.2 Rover Mechanism System

2.2.1 Rocker Mechanism

The rocker mechanism stabilizes the rover's posture by moving the front and rear tires oppositely from side to side within a $\pm 20^\circ$ range. It maintains stability over 40 cm obstacles while keeping the tires grounded. The center of gravity is lowered by passing the rotation axis through the enclosure's interior.

2.2.2 Driving System

The rover is equipped with 775 DC motors and planetary gearboxes, enabling a maximum speed of 150 rpm and 78 Nm of torque, allowing travel at 140 m/s. It features a steering mechanism for easy turning and precise positioning. The grouser design of the tires, optimized for Martian terrain, provides excellent grip [2]. Additionally, generative design techniques were used for parts of both the rover and the robotic arm. This AI-driven approach optimizes strength and reduces weight by proposing designs based on specified loads, constraints, and materials. [2]

2.2.3 Rover Electrical System

Rover's electrical system is divided into four main parts: the Power Supply Unit, Motor Control Unit, Communication Unit, and Main Control Unit. The Power Supply Unit uses five 18V 6Ah lithium-ion batteries for extended operation. The Motor Control Unit includes a high-power DC motor driver and a microcomputer, employing PID control for smooth tire and steering operation. CAN communication is utilized between units for noise immunity and efficiency.

2.2.4 Rover Control System

The Main Control Unit is a Jetson Orin NX running Ubuntu 20.04 with ROS Noetic. It handles advanced tasks like image processing and mapping. A customized package generates routes for autonomous navigation using data from LiDAR, IMU, and GPS. During remote operation, the Main Control Unit is bypassed, and the Motor Control Unit directly drives each motor based on received commands.

2.2.5 Rover Communication System

The rover uses the 915 MHz frequency band for communications, which has excellent diffraction characteristics, enabling communication with the base station. A 3-meter antenna at the base station allows data communications up to 45 km at 20 Kbps using XBee S3B modules. CAN IDs and data are transmitted in packets. The base station sends operation commands, while the rover sends GNSS, IMU, and operating status data. During autonomous control, only data downlink occurs.

For video transmission, the rover employs a 5.8 GHz analog VTX and a 5.8 GHz digital VTX, supporting up to five modular cameras. These cameras can be positioned differently for each mission. The analog

VTX transmits images from multiple cameras simultaneously with low latency, enhancing precise arm and rover maneuvering.

2.3 UAV System

In URC competitions, drones are allowed as auxiliary tools for rovers in specific missions. Our drone is equipped with a gripper designed to grasp and transport rocks and other objects. Precise landing above the target is crucial for the gripper's effectiveness. To achieve accurate hovering, the drone uses an Extended Kalman Filter (EKF) that integrates data from dual GPS units, a compass, a barometer, and an accelerometer to estimate its position. Additionally, the drone has a camera mounted on servo gimbals, transmitting real-time images to the base station, enabling the operator to control the drone and monitor the rover. The drone is also capable of autonomous navigation using GPS.

3. Robotic Arm

3.1 Overall Development Policy

The ARES Arm7.0 shown in Fig. 3, which has undergone numerous improvements tailored for missions, was implemented as the final robotic arm model. The robotic arm performs the "Extreme Delivery Mission" (carrying objects up to 5 kg) and the "Equipment Servicing Mission" (delicate maintenance tasks on a spacecraft-simulated device). These tasks require high torque output and precision control, which the ARES Arm7.0 is designed to achieve.

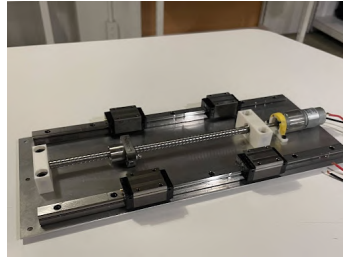
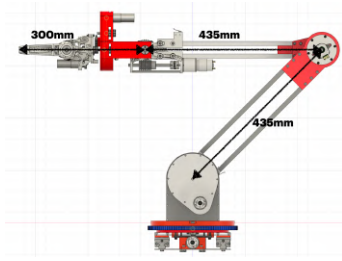
3.2 Arm Mechanism System

The developed robotic arm features a horizontal parallel drive system and five degrees of freedom Fig. 2(b). The first and second joints are 870 mm each, giving a total arm length of 1170 mm and a weight of 14 kg. The first joint is equipped with a custom-made cycloid reducer with a reduction ratio of 1:38, driven by a geared motor that produces a maximum torque of 98 Nm and can lift to 7 kg Fig. 2(c) [3]. The second joint uses a cycloid reducer for high precision and high torque output. The horizontal parallel drive system, designed for tasks in equipment service missions such as keyboard input or bolt operation, consists of two linear guides and one ball screw, allowing 400 mm of travel perpendicular to the direction of movement [4].

The robot arm has a two-finger gripper driven by a single motor and can open and close up to 105 mm. It can be fitted with a hexagonal wrench-type component for certain missions: a spiked finger for Extreme Delivery Mission [5] and a two-finger gripper for Equipment Servicing Mission. Fig. 4 shows the operation of the robotic arm mounted on the rover.

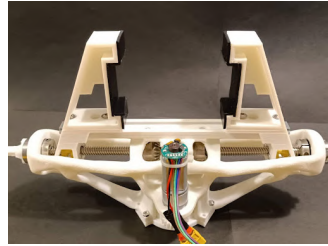
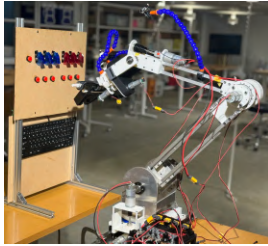
3.3 Arm Control System

The robotic arm uses the same communication system as the rover, sending commands to the joy controller from the base station. The software system is built on Robot Operating System 2 (ROS 2), a



(a) Details of the Arm7.0 link lengths. (b) Lateral movement mechanism. (c) Developed cycloidal reducer.

Fig. 2: Design specifications and main drive mechanisms of the robotic arm.



(a) Robotic arm overview (b) Gripper module

Fig. 3: Arm7.0 and gripper module

middleware for robot software development. In this system, the operator sends the target position of the end-effector from the base station based on the received camera video. The microcomputer on the rover receives these values, calculates the target angles for each joint using inverse kinematics based on the arm's estimated posture from incremental encoder values on each joint, and outputs these values. Additionally, the system can control the speed of each joint as a backup in case an encoder value fails.

4. Science System

4.1 Theoretical Explanation

4.1.1 Geological Analysis

The area around the mission site is known to be covered by the Mesozoic Morrison and Dakota Formations, composed of volcanic ash and fluvial deposits [6]. Past geological investigations have shown that these two formations differ in color and surface appearance due to differences in their constituent particles. Therefore, it is possible to determine different layers' formation mechanisms by comparing the image of the formation obtained using a wide-angle camera with the features of the respective formation.

4.1.2 Mineral Analysis

Mineral analysis was carried out using a multispectral camera mounted on the actual Mars rover Curiosity and other rovers [7]. The multispectral camera is equipped with six different wavelength filters, including 1050 nm, to identify minerals such as haematite and gypsum, which are assumed to be identified at the site [8]. These minerals would imply the presence of liquid water at the site, which would be very important in the search for life.



(a) Equipment Servicing (b) Extreme Delivery

Fig. 4: Missions involving the use of robotic arm.

4.1.3 Life detection analysis

Among various potential life detection methods, our rover focuses on detecting membrane proteins in soil samples as biomarkers. The current rover uses the Biuret reaction for protein detection due to its rapid response and easily distinguishable color change. This reaction involves the formation of a complex between peptide bonds and divalent copper, changing the color from blue (430-490 nm) to purple (380-430 nm).

4.2 Overall Development Policy

The sample collection mechanism uses a drill capable of three operations: rotation, descent, and lid control via an iris mechanism shown in Fig. 5. A single DC motor manages both rotation and descent, while a servo motor controls the iris mechanism. During operation, the drill rotates and descends to collect the sample, then ascends to allow a sliding mechanism to transport the sample to the analysis apparatus. The drill then reverses rotation to release the sample, and the iris mechanism closes. Post-collection, the sample is agitated in a phosphate buffer to stabilize proteins adsorbed on the soil surface [9]. It is then transported by a pump to a centrifuge and subsequently moved to another tester for reaction with Biuret reagents. The absorbance of the green reagent is measured by a light intensity sensor, enabling analysis of protein concentration in the soil based on absorbance differences. Detailed system is shown in Fig. 6.

5. Verification Experiment

5.1 Rover

The rover has conducted driving tests in desert and dune terrains to simulate the Martian environment.

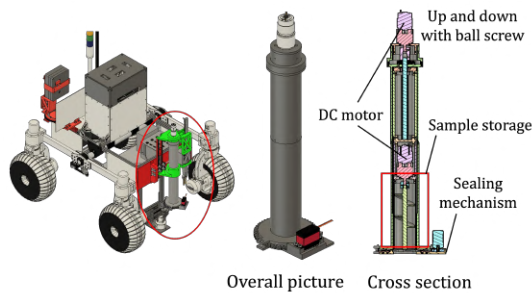


Fig. 5: Drill mechanism

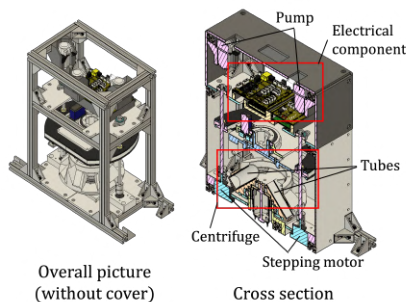


Fig. 6: Centrifuge system

These tests verified tire grip, drive torque, and vehicle stability using the rocker mechanism. Results confirmed the adequate performance of both the tires and the rocker mechanism, with and without the onboard module. However, improving steering responsiveness to reduce running time remains a key challenge.

5.2 Robotic Arm

Performance evaluation test of the robot arm was conducted for each mission because the technical requirements of each mission were different (Fig. 4).

5.2.1 Extreme delivery mission

In this mission, development focused on two main tasks: picking up objects from the floor and operating the robot arm up to 1 km away.

Performance tests included lifting a 5 kg weight, with the arm fixed to a desk and mounted on the rover. Two objects, a stone and a box with handrails, were used. In both tests, the end-effector successfully grasped the objects, and the arm lifted them without damage, confirming the structural integrity and reliability of the robotic arm.

Communication tests were divided into remote camera communication and remote control of the robotic arm. Clear camera transmission was achieved from approximately 300 m, even with obstacles present. The robotic arm operated without delay up to 300 m, and effective communication was verified up to 500 m.

5.2.2 Equipment servicing mission

In this mission, development focused on the following tasks: keyboard operation, opening drawers, pushing buttons, tightening screws, and lifting objects. Consequently, a field was created to simulate the actual mission environment, as shown in Fig. 4 and performance evaluation tests were conducted.

5.3 Science equipment

5.3.1 Laboratory experiments

Experimental methods for the rover are initially verified through laboratory experiments. High reactivity conditions are selected using commercially available protein powder. Comparison experiments are then conducted with soil samples assumed to contain life-derived proteins and blank samples, which are baked at 500°C for 6 hours to remove organics. To detect color changes, standards of different concentrations are purified and their absorbance data are recorded to create a standard curve. Using our custom spectrophotometer, we confirm the color change and that a protein measurement of 1 mg/g in the soil is achievable.

5.3.2 On board experiments

The drill mechanism and temperature/humidity sensor were mounted on the rover for demonstration tests, confirming their ability to collect samples and obtain accurate readings. Collected samples were transported to an agitator for mixing and then transferred to the rover's interior via a tube pump for centrifugal separation. Although the centrifuge was successfully tested in the laboratory, further testing is needed to ensure its functionality when integrated with the rover. The multispectral camera was tested using geological formations and mineral samples, and its effectiveness in identifying minerals was verified by comparing its data with existing mineral databases.

References

- [1] Z. Martins *et al.*, "Extraction of amino acids from soils close to the mars desert research station (mdrs), utah," in *International Journal of Astrobiology*, 2011.
- [2] Skonieczny *et al.*, "A grouser spacing equation for determining appropriate geometry of planetary rover wheels," in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2012, pp. 5065–5070.
- [3] 三浦研人 and 湯川俊浩, "サイクロ減速機を応用した連続変速機," in *ロボティクス・メカトロニクス講演会講演概要集 2016*. 一般社団法人日本機械学会, 2016, pp. 2A1-05a3.
- [4] 吉川恒夫, "ロボットアームの可操作度," *日本ロボット学会誌*, vol. 2, no. 1, pp. 63–67, 1984.
- [5] 加藤匠哉 *et al.*, "ビン配列型凹凸地形把持機構," *日本ロボット学会誌*, vol. 42, no. 2, pp. 177–180, 2024.
- [6] Kirkland *et al.*, "The lower cretaceous in east-central utah the cedar mountain formation and its bounding strata," in *Geology of the Intermountain West*, 2016, pp. 3, 101–228.
- [7] J. F. B. III *et al.*, "The mars science laboratory curiosity rover mastcam instruments: Preflight and in-flight calibration, validation, and data archiving," in *Earth and Space Science*, 2017, pp. 4, 7, 395–452.
- [8] A. M. Eng *et al.*, "Mastcam multispectral investigation of rock variability in gale crater, mars: Implications for alteration in the clay-sulfate transition of mount sharp," in *JGR Planets*, 2024.
- [9] A. P. Golovanov *et al.*, "A simple method for improving protein solubility and long-term stability," in *J. Am. Chem. Soc.*, 2004.