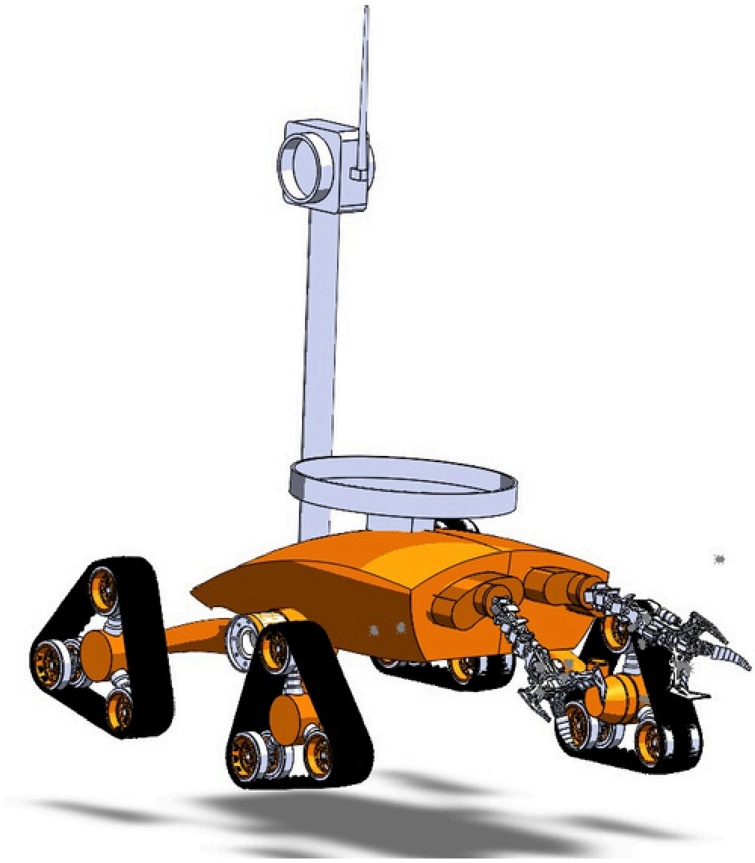
A REPORT ON MARTIAN ROVER

BY

TEAM - “ENDURANCE”



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Introduction

Team ENDURANCE is participating in the ADVANCED ROVER EXPLORATION & SIMULATION (A.R.E.S) event in NSSC 2025 by IIT Kharagpur.

Objective

In this event, our objective is to design, simulate and control an autonomous rover capable of operating in a Martian-like environment using CoppeliaSim Edu and Python.

Deliverables

- **[ARES_Endurance_Hardware]** contains the Solidworks file for our Rover Design
- **[ARES_Endurance_Software]** contains the terrains, Jupyter notebooks, Logs as csv files, Runthrough mp4 videos of the Rover simulation under every environment, and plots of those respective runs (2D + 3D).
- **[ARES_Endurance_Report]** describes our rationale of rover's mechanical design, control logic, sensor integration and mapping methodology along with challenges encountered by us and how we implemented most of their solutions.

This project also proves our effort in rover designing, control systems and computational simulation in realistic Martian environment.

Rover design

1. **Mission & Concept of Operations**
Purpose: a small exploration rover for remote scientific missions (fieldwork/planetary analogs) or an educational “maths exploration” platform that collects geometric/physical data for classroom analysis.
Primary tasks:

- Traverse uneven terrain.
- Inspect, drill or pick small samples with dual manipulators.
- Collect sensor data (IMU, lidar, stereo cameras, force/torque) for mapping and mathematical experiments (kinematics, localisation, SLAM).
- Operate autonomously or via tele-op.

2. **High-level Architecture**

- Chassis: central body with mast (camera/antenna) and two front manipulators.
- Locomotion: 4 leg modules, each ending in tri-roller wheel assemblies for compliant contact and obstacle negotiation.
- Manipulators: compact multi-DOF arms on the front for sampling and instrumentation.
- Payload: sensor suite (stereo cameras, lidar/ToF, environmental sensors), sample container, compute node.
- Power: battery pack + optional solar assist.

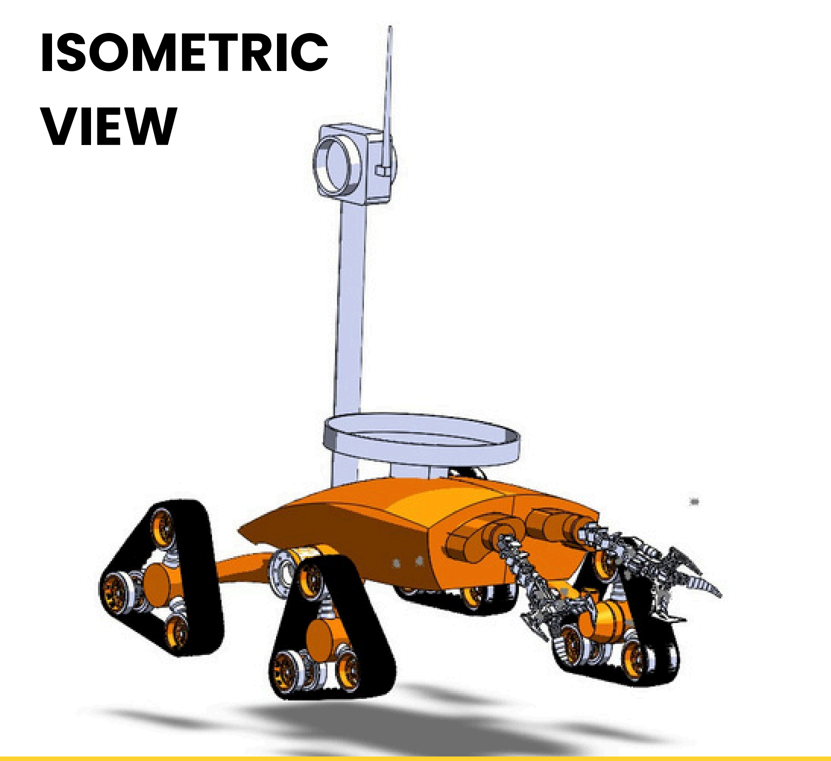
3. **Mechanical Design — Key Elements**

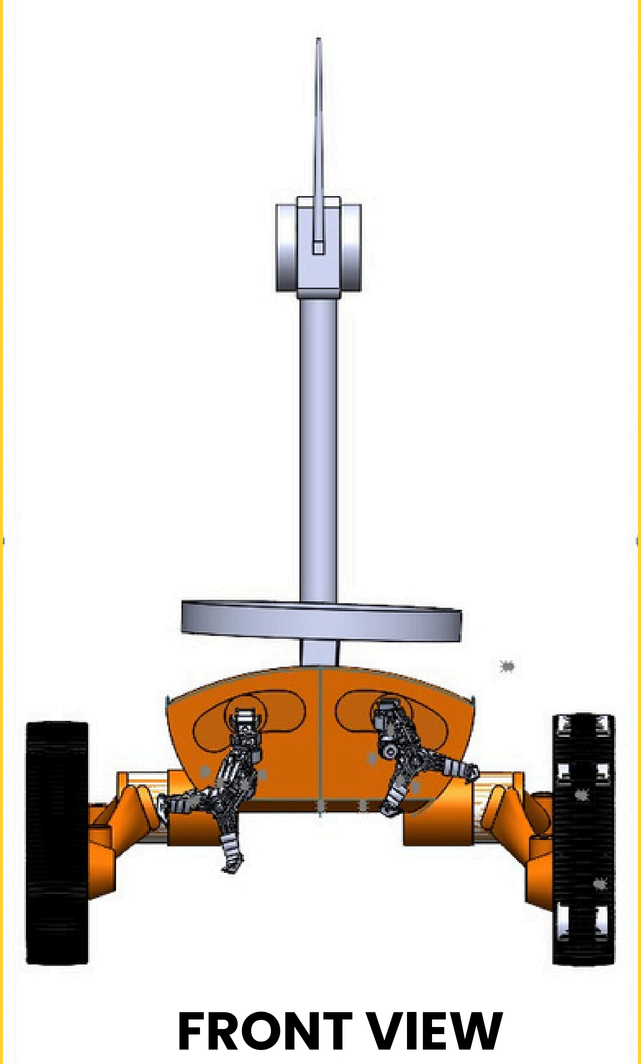
- Leg/Module Geometry: curved boom arms with rotary joints at the body; tri-roller end gives a combination of wheel and track behaviour — good for climbing and conforming to ground.
- Suspension: passive compliance in each leg (spring or elastomer) + limited pitch/yaw joints to keep contact over uneven surfaces.
- Manipulator: 4–5 DOF feet/arms with small brushless motors, harmonic or planetary gears, and a modular end-effector (gripper + drill adapter).
- Materials: aluminium 6061/Ti for structural parts; carbon-fibre panels for enclosure; UHMW/PU for rollers.

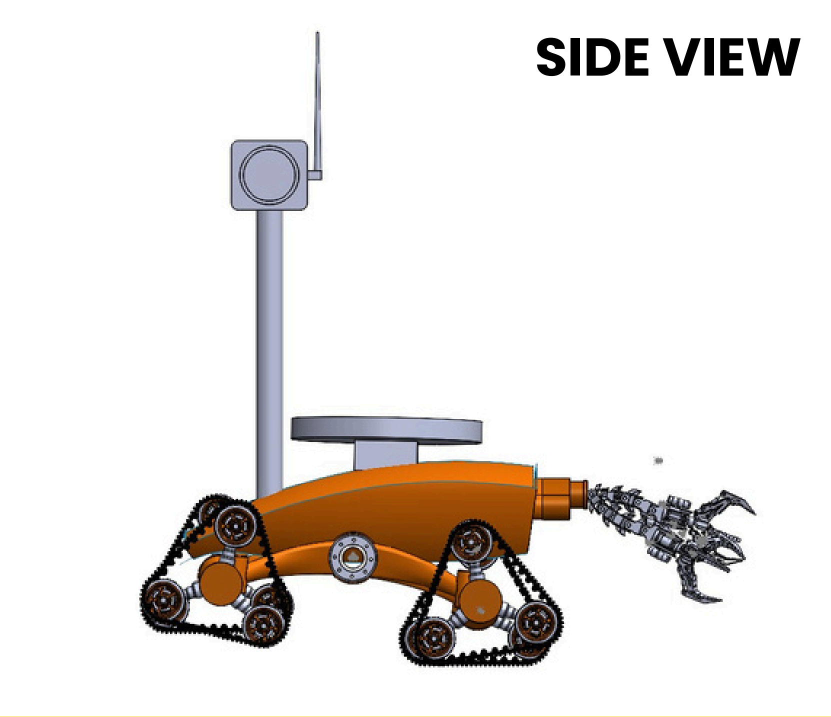
4. **Navigation Approach:**

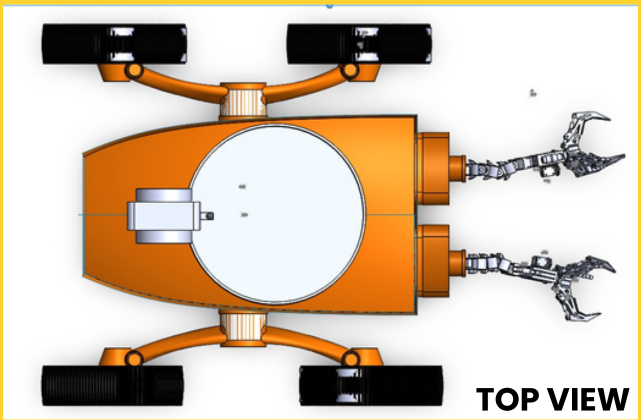
- Reactive Obstacle Avoidance: Dynamically adjusts linear and angular velocities using weighted proximity sensor data, giving higher importance to frontal sensors for safer maneuvering.
- Dynamic Goal Pursuit: Computes heading errors relative to the target, adjusting based on distance and orientation. It ensures precise convergence to the goal using real-time feedback from base position and yaw, maintaining responsiveness to environmental conditions.
- Intelligent Recovery Handling: When progress stalls, a multi-phase recovery routine is activated with reversing oscillations, reorienting toward the goal, and performing escape rotations.
- Integrated Logging and Feedback: Time-stamped positional data is captures, the system enables detailed analysis of navigation efficiency, path deviations, and obstacle encounters.

Rover design (Projected Views)









Wheel design

Introduction

The tri-star wheel mechanism is an innovative mobility system combining multiple independently rotating wheels arranged in a triangular configuration. These three wheels are mounted on a central rotating hub, which itself can rotate to allow dynamic repositioning. When fitted with a rubber track, this forms a hybrid wheel–track system that enhances traction, obstacle climbing, and stability.

This design is particularly beneficial for rovers and mobile robots that must traverse uneven surfaces, climb obstacles, or operate in off-road conditions (e.g., Mars rovers, exploration robots, or agricultural bots).

Component	**Description**
Central Hub	The main rotating body that holds the three wheel arms at 120° apart. It allows rotation around the central axis for obstacle negotiation and balance during uneven terrain movement.
Wheel Arms (Spokes)	Connect each wheel to the central hub, generally using a fixed or spring-damped joint. They help distribute the rover’s weight and provide stability during motion.
Wheels	Function as individual rollers that provide movement and traction. Each wheel may have its own motor or be driven collectively via the central hub mechanism.
Track Belt	A continuous rubber or polymer belt looped around the three wheels, combining the benefits of both wheels and tracks for smooth operation, increased grip, and efficient obstacle climbing.
Bearings & Axles	Reduce friction between rotating components, ensuring smooth motion while supporting mechanical loads and maintaining stability.

Working Principle

The tri-star wheel works in two primary modes:

1.Normal Motion:

The three wheels rotate together, driving the rover smoothly along flat surfaces.

The track provides continuous contact with the ground, improving traction and weight distribution.

2.Obstacle-Climbing Mode:

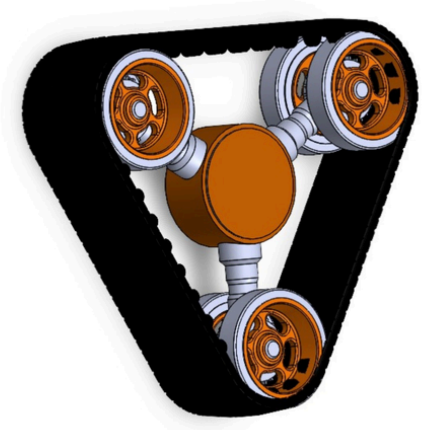
When the assembly encounters an obstacle (rock, ledge, or step), the central hub rotates, bringing another wheel into contact with the ground.

This rotation allows the system to “walk” over the obstacle, maintaining traction without losing balance.

The continuous track prevents slippage and distributes weight evenly during the transition.

This dual mechanism allows the rover to handle terrain discontinuities that traditional wheels or tracks alone cannot manage.

Feature	Advantage
Obstacle Negotiation	The triangular wheel arrangement enables climbing over obstacles up to 1.5× the wheel radius.
Continuous Traction	The track ensures constant contact with the ground, minimizing slippage.
Shock Absorption	The geometry and track material absorb shocks during movement over rough terrain.
Compact Design	Efficient use of space, ideal for small rover bodies.
Hybrid Efficiency	Combines advantages of both **tracked** and **wheeled** locomotion systems.



Arm Design

Introduction

A robotic manipulator arm on a rover is a versatile mechanism used for performing tasks such as sample collection, drilling, object manipulation, surface analysis, and maintenance.

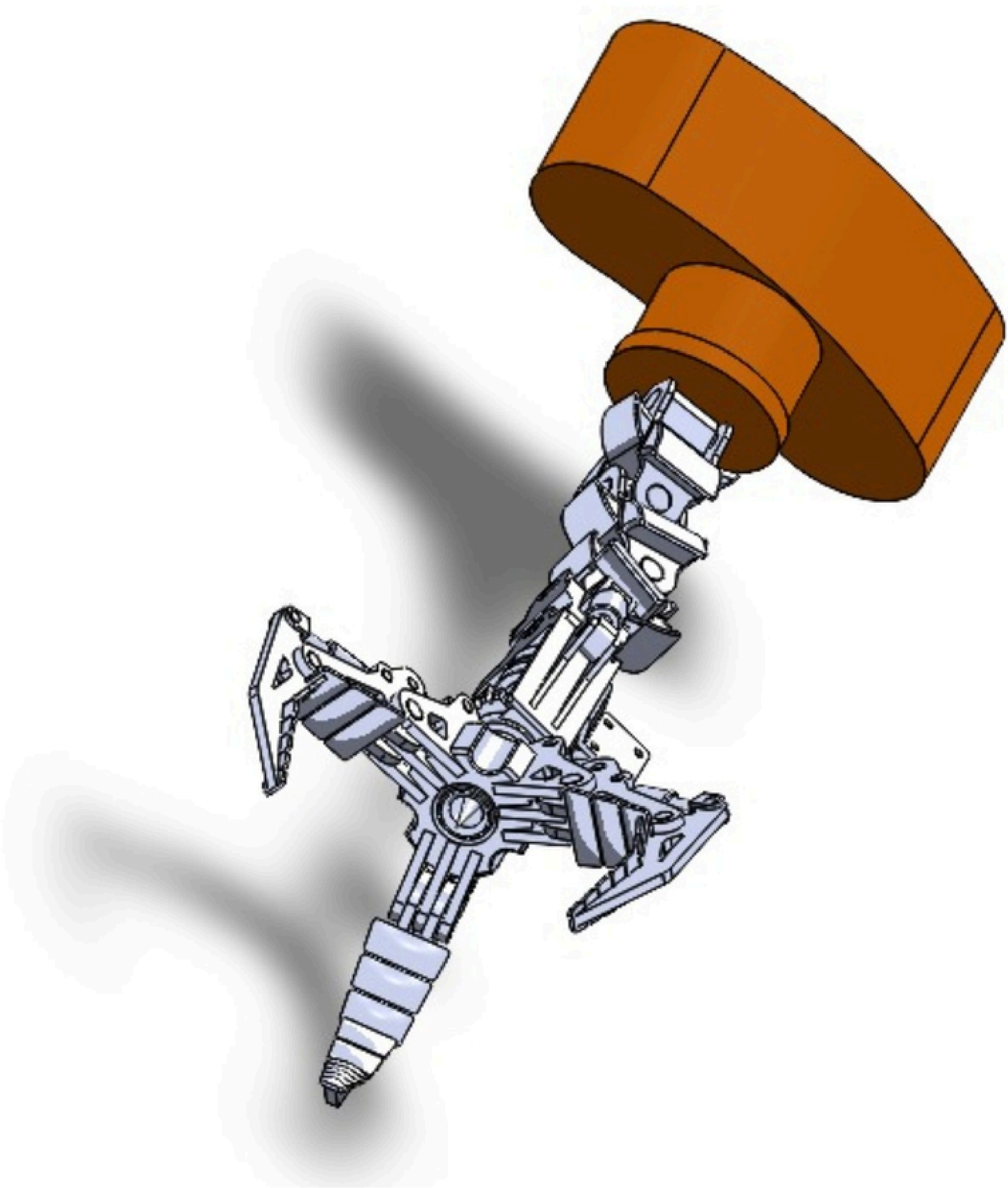
The arm is typically multi-degree-of-freedom (DOF), allowing precise movement and adaptability to varied terrains and target orientations.

The model in the image shows a multi-jointed mechanical arm ending in a drilling or sampling mechanism, with an upper actuated rotary base — suggesting a system designed for planetary exploration or geological surveying.

Component	Function / Description
Base Motor Assembly (Orange Unit)	Houses the **rotary actuator** for azimuthal rotation of the arm about the rover's main body. Provides yaw motion (0–360°).
Main Arm Segment	Primary load-bearing member with **telescopic** or **articulated joints** for reach extension. Usually made of aluminum or
Intermediate Links	Allow flexibility and orientation adjustment. Contain pivot joints actuated by servo or brushless DC motors.
End Effector / Drill Unit	Designed for drilling, coring, or gripping. Includes high-torque motor and possibly a percussive drill bit.
Joint Actuators	Provide movement in multiple axes—pitch, roll, yaw. Controlled via encoders for feedback precision.
Sensors	Actuated upon the command of the Vision Sensor for pick and place operation
Cable Routing System	Channels power and data cables through protective conduits to prevent entanglement.

Working Principle

The base motor rotates the entire arm assembly horizontally to align with the target zone.
Arm segments extend or articulate to reach the surface or object.
The end effector (drill or gripper) performs the required task: drilling, sampling, or manipulation.
Integrated sensors provide feedback to the rover’s control system for precise motion and error correction.
After operation, the arm retracts and locks in its stowed configuration for safe mobility.



Electronics Subsystem

The Electronics Subsystem is the core sensory apparatus of the rover, enabling autonomous navigation, obstacle avoidance, and mission-critical data logging for mapping. This section details the selection, placement, and functional role of the vision and proximity sensors chosen for the A.R.E.S. mission.

Sensor Selection and Rationale

The rover employs a combination of passive and active sensors to achieve robust spatial awareness and accurate odometry, satisfying the requirement to navigate through hazards and generate path maps.

Sensor Type	Specific Component	Function	Rationale for Selection
Vision	Monocular Camera (Vision Sensor)	High-level visual input sample identification, and distant feature recognition.	Required for **Sample Collection** and providing a visual log for the **2D/3D Map generation**.
Proximity	Cone-Type Proximity Sensor (3x)	Short-range, real-time detection of nearby hazards for immediate collision prevention.	Essential for meeting the requirement to **avoid all crashes** with rocks and craters in hazardous environments.

Localization and Odometry Sensors

These sensors ensure the rover can accurately track its position, orientation, and movement for precise navigation and mapping.

Sensor Type	Specific Component	Function	Rationale for Selection
Localization	Inertial Measurement Unit (IMU)	Measures angular velocity and linear acceleration (pitch, roll, yaw).	Critical for tracking the rover's attitude and providing correction data, improving **mapping of the rover path**.
Odometry	Wheel Encoders (6x)	Measures the rotation and speed of the drive wheels.	Provides basic distance travelled and velocity data, crucial input for the rover's localization algorithms.

Vision System (Monocular Camera)

A single Monocular Camera, simulated as a Vision Sensor in CoppeliaSim, is mounted on a mechanical mast equipped with a Pan-Tilt Mechanism.

- Placement: Elevated on the mast for maximum line-of-sight clearance over terrain features facing front at a depression angle of 20°
- Role in Navigation: Provides image frames for processing. In the software layer, these images are used to identify the designated samples (objects).
- Role in Mapping: The camera's field of view is used in conjunction with the IMU and Encoders to correlate visual landmarks with logged coordinates, refining the accuracy of the final 2D and 3D plots.

Proximity Sensor Array for Collision Avoidance

To ensure reliable and immediate obstacle avoidance, three cone-type proximity sensors (simulated range/ultrasonic sensors) are strategically positioned at the front, front-left (45°), and front-right(45°).

Configuration: The sensors are arranged in a triangular configuration with overlapping fields of detection to eliminate blind spots directly ahead of the chassis:

- Center Sensor (front): Directed purely forward (Range = 1.5m, Angle=25°. Provides the primary trigger for obstacles dead ahead. Upon sensing, slows the rover down to avoid head-on collison
- Left Sensor (S2): Directed forward and slightly outward (45° left, Range=1m).
- Right Sensor (S3): Directed forward and slightly outward (45° right, Range=1m).

Functionality: Each sensor continuously outputs a normalized distance value to the nearest object within its conical detection field minimizing blind zones, enabling early detection of terrain irregularities or obstructions within a fixed detection cone.

Threshold Trigger: If any sensor reading drops below the critical collision avoidance threshold (e.g., 0.5 meters), the drive motors are immediately halted or slowed, and the software initiates a local avoidance maneuver (turn, then re-engage).

Safe Distance Compliance: This three-sensor array is specifically designed to enforce the mission requirement of maintaining a safe distance from rocks and craters at all times.

Role in Mapping: Each detected obstacle point is correlated with the rover's current position from odometry data and projected onto the occupancy grid, incrementally refining the local map. This integration ensures that both static and dynamic obstacles are accounted for during path planning and D* re-planning cycles, enhancing environmental awareness and route reliability.

Rationale for Avoiding LiDAR with Potential Field or D Lite Approaches:

While LiDAR-based mapping combined with potential field or D* Lite algorithms is highly effective in structured & well-defined environments, it presents several drawbacks in uneven, unstructured terrains encountered by the rover. LiDAR excels in generating precise obstacle contours and walls but struggles with irregular natural features, often producing noisy or incomplete point clouds that complicate local navigation. Potential field methods, are prone to local minima traps and require extensive parameter tuning for each terrain type

Challenges and Solutions

Importing issues of Solidworks URDF file to CopelliaSim

The issue of importing the SolidWorks-generated URDF file into CoppeliaSim
could not be resolved due to the **lack of sufficient support, tutorials, and resources** available for this process (Not even in the resources provided by the ARES team). Consequently, the hardware team's SolidWorks rover model (provided in the hardware folder) could not be imported into the simulation environment.
This, in turn, **prevented the software team from testing the rover in simulation** and from implementing the pick-and-place mechanism.

CAD Model Creation

Achieving a unique design in SolidWorks that was robust yet simplified enough for efficient simulation. Prioritizing **primitive shapes** for the main chassis components and utilizing the Weldment feature to ensure a unified, rigid base structure.

Joint and Kinematic Assembly

Perfectly assembling over 20 parts (wheels, bogies, links) with accurate mates to ensure the rocker-bogie joints moved realistically without slippage or excessive friction. Rigorously defining **coincident, concentric, and parallel mates** in SolidWorks to ensure high-quality, non-redundant joints, and checking the full range of motion

Conclusion

Our team report has successfully demonstrated the design, simulation and various autonomous operations of the rover in a simulated Martian environment using CoppeliSim Edu and python through ZMQ remote API. The rover engineered by us is capable in navigating in uneven terrain, avoid obstacles driven by sensor based-algorithm and object manipulation using robotics arms. The 2D and 3D maps validated accurate terrain traversal and path tracing. At the end, our simulation has successfully highlighted the efficiency of integrated mechanical design, control-logic systems, computational intelligence in planetary exploration in Martian environment.

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