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Design and Implementation of an Active Self-Leveling Chassis for a Mobile Exploration Rover

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Abstract: This paper presents the design specification and the initial proof-of-concept implementation of an active self-leveling chassis intended for a mobile rover operating on uneven planetary terrain. The project is motivated by the stringent requirements of in-situ operations, specifically subsurface sample collection using a drilling mechanism. Standard mobility systems often result in a tilted chassis when traversing slopes, which poses significant risks to drilling tools, including shear stress, borehole misalignment, and potential fracture. To validate the feasibility of mitigating these risks, a simplified experimental testbed was constructed. The prototype utilizes four independently controlled linear DC actuators to actively adjust the suspension geometry, ensuring the main platform remains horizontal relative to the gravity vector. The paper details the mechanical concept, the electronic control architecture based on high-current motor drivers, and the preliminary testing of the fundamental leveling logic required for safe drilling operations.

Keywords: self-leveling chassis, mobile rover, active suspension, linear actuators, proof of concept, mechatronic design

1. INTRODUCTION

The exploration of extraterrestrial bodies, such as Mars or the Moon, has evolved from simple imaging missions to complex scientific operations requiring physical interaction with the environment. Modern mission profiles often require rovers not only to traverse rugged terrain but also to perform delicate tasks such as robotic manipulation and deep-soil drilling [1].

A significant engineering challenge arises when these operations must be conducted on inclined surfaces. Planetary terrain is rarely flat; craters, dunes, and rocky outcrops present constant navigational challenges, often limiting the efficacy of traditional passive suspension systems [4, 2]. For a drilling mechanism rigidly mounted to a rover's chassis, the angle of the rover directly dictates the angle of penetration. Drilling into the regolith at an oblique angle introduces detrimental lateral forces. These forces can lead to drill bit jamming, increased power consumption, excessive heat generation due to friction against the borehole wall, or catastrophic tool failure. Consequently, the ability to decouple the chassis orientation from the terrain gradient is a critical operational requirement, a challenge shared by planetary landers which require similar stabilization for safe touchdown and operation [7].

This paper describes the development of the MPER (Multi-Purpose Exploration Rover) chassis concept (Fig. 1). The study focuses on the validation of an active suspension system designed to stabilize the rover's payload. A functional prototype (proof-of-concept) has been built to test the electromechanical integration and the fundamental control strategies required to achieve a stable, level platform using accessible, off-the-shelf components [10, 11].

Figure 1: *Conceptual design of the MPER system. The active chassis is designed to stabilize the central platform for the manipulator and drill.*

2. KINEMATIC ANALYSIS AND MECHANICAL DESIGN

The mechanical architecture of the MPER chassis was driven by two conflicting requirements: sufficient ground clearance for obstacle traversal and a rigid, stable base for drilling operations. The design process was divided into the theoretical kinematic specification and the practical implementation of the testbed.

2.1. Suspension Kinematics Concept

The target design utilizes an independent control arm configuration. In this topology, each wheel unit is attached to a pivoted suspension arm located beneath the main chassis (Fig. 2). The linear actuator connects the central frame to a specific hardpoint on the control arm. This active approach contrasts with passive rocker-bogie mechanisms, which average the terrain irregularities but cannot alter the chassis inclination [3]. While hydraulic systems offer high force capabilities for off-road leveling [8], they are often too heavy and complex for small-scale planetary rovers, making electromechanical actuators a more suitable choice for this application.

Mathematically, the system can be modeled as a closed kinematic chain where the actuator acts as a variable-length link (L_{act}). By extending or retracting the actuator, the system changes the angle of the control arm (θ_{arm}), which results in a change in the vertical position (z_{wheel}) of the wheel contact point relative to the chassis frame. This arrangement allows for the independent control of three degrees of freedom (DOF) of the chassis:

1. **Heave:** Uniform vertical lifting of the entire platform.
2. **Pitch:** Rotation around the lateral axis (nose up/down).
3. **Roll:** Rotation around the longitudinal axis (tilt left/right).

This design decouples the lateral structural loads—handled by the robust control arms—from the vertical height adjustment mechanism [6].

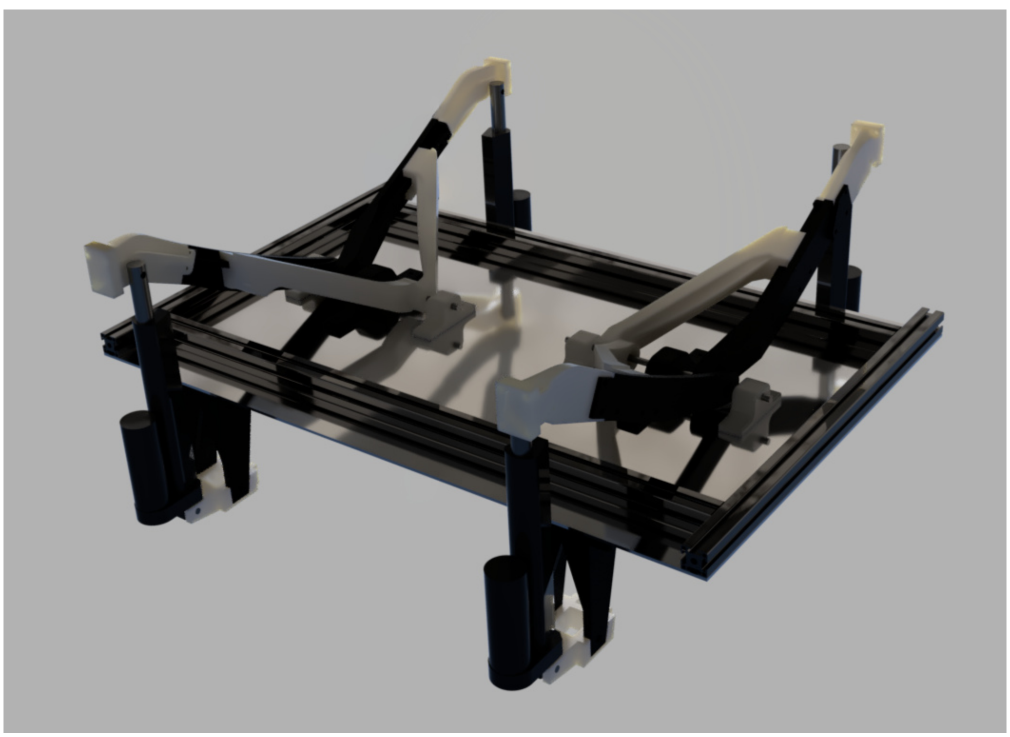

Figure 2: *Undercarriage view of the design illustrating the independent suspension arm configuration.*

2.2. Prototype Construction Details

To validate this kinematic concept without incurring the cost and machining time of a full aerospace-grade chassis, an experimental testbed was assembled.

Actuation: The prototype employs 12V DC linear actuators with a stroke length of 150 mm. These actuators were selected specifically for their lead-screw mechanism, which provides a high self-locking force. Unlike servo-driven systems that require continuous power to hold a position against gravity, the lead-screw allows the actuators to be powered down once the target level is achieved. This is a crucial feature for energy efficiency during the drilling phase.

Structural Integration: The wheels are attached to the actuators and control arms via custom-designed brackets. Given the high shear loads generated during skid-steering maneuvers and the reaction forces during lifting, standard 3D printing materials were deemed insufficient. Therefore, these key structural components were manufactured using FDM technology with PCTG filament reinforced with 10% carbon fiber (PCTG-CF10). This material choice offers a superior stiffness-to-weight ratio compared to standard PET-G or ABS.

Chassis Base: To facilitate rapid reconfiguration of the electronic layout during the testing phase, the prototype chassis utilizes a composite baseplate structure (combining aluminum profiles with a rigid mounting plate) rather than the final fully welded frame. This allows for easy access to the motor drivers and wiring harness during troubleshooting (Fig. 3).

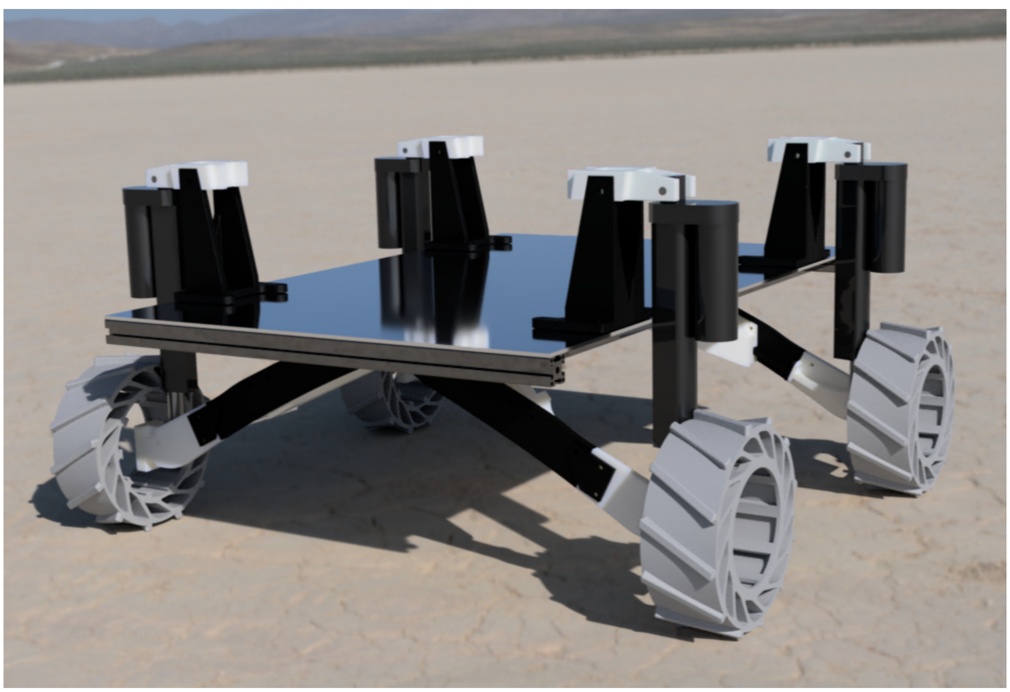

Figure 3: *Mechanical configuration of the chassis. The linear actuators adjust the angle of the suspension control arms.*

3. PHYSICS OF DRILLING ON INCLINED TERRAIN

The primary driver for the active leveling capability is the physics of the onboard drilling subsystem. Drilling into consolidated soil or rock dictates strict alignment tolerances to ensure sample quality and tool longevity.

Consider a scenario where the rover is positioned on a slope with an inclination angle α. If the chassis is parallel to the slope, the drill bit enters the ground at an angle α relative to the gravity vector $\vec{g}$. When a thrust force F_{thrust} is applied along the drill axis, it decomposes into two orthogonal components relative to the vertical plane:

$$F_{vertical} = F_{thrust} \cdot \cos(\alpha) \tag{1}$$

$$F_{lateral} = F_{thrust} \cdot \sin(\alpha) \tag{2}$$

The component $F_{lateral}$ (shear force) is particularly problematic. Research on mobile manipulator stability indicates that lateral forces on inclined terrain significantly increase the risk of tip-over and mechanical stress [9]. Specifically, this leads to:

1. **Bending Moment:** It creates a bending moment on the drill shaft, which can exceed the elastic limit of the tool steel, leading to permanent deformation.
2. **Borehole Ellipticity:** The lateral force causes the bit to "walk" or scrape against the side of the borehole, increasing friction and potentially jamming the bit.
3. **Rover Stability:** The reaction force tends to push the rover down the slope. If $F_{lateral}$ exceeds the static friction force of the wheels (μF_{normal}), the rover will slip, shearing the drill bit inside the ground.

By utilizing the active chassis to drive $\alpha \to 0$, the term $\sin(\alpha)$ vanishes, and $F_{lateral}$ is minimized. This ensures that the entire thrust force is directed into penetration, optimizing energy use and safety.

4. ELECTRONIC SYSTEM ARCHITECTURE

The electronic control system (Fig. 4) for the proof-of-concept is designed to be robust and capable of handling high current loads, while maintaining a simplified logic structure appropriate for an initial prototype using low-cost embedded systems [10].

4.1. Power Distribution and Actuation

The power system is supplied by a high-discharge Li-Ion source. A critical component selection was the motor driver units. The four leveling actuators, under load, can draw significant current, especially during the initial phase of lifting the chassis. Standard L298N drivers were deemed insufficient due to their voltage drop and thermal limitations.

Instead, the prototype utilizes two Cytron MDD10A dual-channel DC motor drivers. These drivers utilize NMOS H-Bridge technology, which allows for continuous currents up to 10A per channel without active cooling. This ensures that the system can handle the peak currents required to lift the rover's weight. The drivers are interfaced via PWM (Pulse Width Modulation) and DIR (Direction) signals, allowing for bidirectional control (extension and retraction) of the actuators.

4.2. Sensor Fusion and Signal Processing

To determine the rover's orientation in 3D space, a 6-axis Inertial Measurement Unit (IMU) is employed, consisting of a 3-axis accelerometer and a 3-axis gyroscope. The IMU is mounted at the geometric center of the chassis to minimize the influence of centrifugal accelerations during rover rotation.

Raw accelerometer data is susceptible to high-frequency noise and mechanical vibrations caused by the traction motors. To address this, a complementary filter is implemented in the microcontroller firmware [13]. The estimated pitch (θ_{est}) is calculated as:

$$\theta_{est} = \alpha \cdot (\theta_{gyro} + \omega \cdot dt) + (1 - \alpha) \cdot \theta_{accel} \quad (3)$$

Where α is a weighting factor (typically 0.98), ω is the angular velocity, and θ_{accel} is the angle derived from the gravity vector. This filtered data forms the feedback loop for the leveling controller.

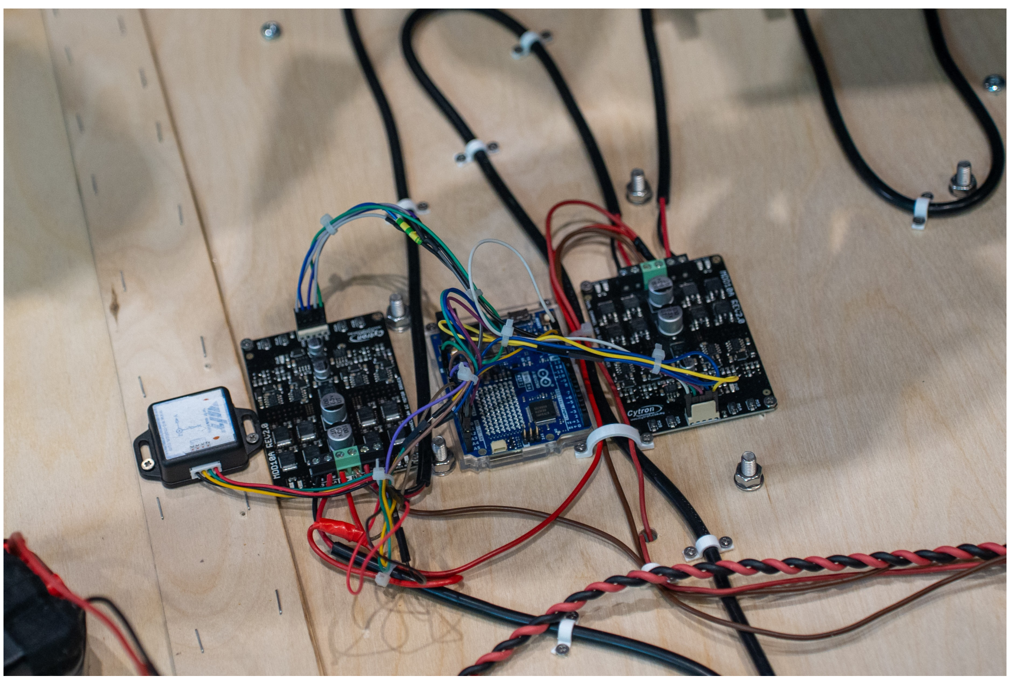

Figure 4: *View of the electronics, showing the microcontroller, Cytron MDD10A drivers, and wiring harness.*

5. CONTROL STRATEGY IMPLEMENTATION

For this stage of development, the focus was on validating the mechanical capability of the system to self-level. Therefore, a fundamental closed-loop control strategy was implemented.

5.1. Control Logic

The control algorithm operates on a "Bang-Bang" principle with hysteresis. This approach was chosen for its simplicity and robustness in the absence of absolute position encoders on the linear actuators, a common practice in early-stage educational rover prototyping [11]. The control loop executes the following sequence:

1. **Data Acquisition:** The system reads the filtered pitch (ϕ) and roll (ψ) angles from the IMU.
2. **Error Calculation:** The system calculates the deviation from the horizontal plane ($0°$).
3. **Threshold Comparison:** The error is compared against a defined deadband (tolerance) of $\pm 0.5°$. This deadband is essential to prevent "hunting"—a phenomenon where the motors continuously oscillate back and forth trying to achieve an impossibly perfect zero angle.
4. **Actuation:**
   - If $Error_{pitch} > +0.5°$ (Nose Up): The rear actuators extend and/or the front actuators retract.
   - If $Error_{pitch} < -0.5°$ (Nose Down): The front actuators extend and/or the rear actuators retract.
   - Similar logic is applied simultaneously to the Roll axis using left/right pairs.
5. **Hold State:** Once the error falls within the $\pm 0.5°$ window, the motors are powered down. The mechanical self-locking of the lead screws holds the platform in position.

6. PRELIMINARY VALIDATION AND RESULTS

The assembled proof-of-concept device was subjected to initial functional testing to verify the integration of the mechanical structure, the PCTG-CF10 mounts, and the control logic.

6.1. Test Setup

The testing procedure involved placing the rover on a variable-angle ramp. The ramp angle was incrementally increased from $0°$ to $25°$. At each increment, the auto-leveling sequence was triggered, and the final platform angle was measured using an external digital inclinometer for verification.

6.2. Observations

The tests confirmed that the electromechanical system successfully interprets IMU data and drives the actuators in the correct direction to counteract the slope.

- **Load Capacity:** The Cytron MDD10A drivers and selected actuators demonstrated sufficient torque to lift the chassis under its own weight (approx. 10 kg for the prototype) without stalling.
- **Range of Motion:** The system successfully leveled the platform on slopes up to approximately $20°$. Beyond this angle, the stroke length of the linear actuators (150 mm) became the limiting factor, as the actuators reached their mechanical end-stops.

- **Stability:** The structural rigidity provided by the PCTG-CF10 brackets proved sufficient. No significant deflection or plastic deformation was observed in the mounts during the lifting cycles.

These results validate the fundamental design premise: that a simple, modular active suspension can effectively create a stable workspace for drilling operations, even with a simplified control architecture.

7. CONCLUSION AND FUTURE WORK

This paper presented the design specification and the initial prototyping of an active self-leveling chassis for the MPER project. The constructed testbed confirms that a relatively simple architecture using linear actuators and inertial feedback can effectively maintain a horizontal platform orientation, significantly mitigating the risks associated with drilling on inclined terrain.

Future development of the MPER chassis will focus on transitioning from this proof-of-concept to a fully autonomous field rover. Key planned improvements include:

- **Feedback Integration:** Installing linear potentiometers or optical encoders on the actuators to enable more sophisticated control strategies, such as adaptive control algorithms [14], allowing for proportional speed adjustment and smoother motion compared to the current bang-bang approach.
- **Structural Optimization:** Replacing the prototype baseplate with the final welded aluminum chassis frame to reduce weight and increase torsional stiffness.
- **Predictive Leveling:** Researching the integration of LiDAR or depth cameras to scan the terrain ahead. This would allow the rover to adjust its suspension preemptively (Feed-Forward control) rather than reacting to tilt after it occurs.

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