A Prototype Locomotion Concept for a Lunar Robotic Explorer

Yasutaka Fuke[1], Dimitrios Apostolopoulos[2], Eric Rollins[3], Jack Silberman[4], William Whittaker[5]

The Robotics Institute, Carnegie Mellon University, Pittsburgh, PA 15213, USA

Phone 412 268-8130, Fax 412 268-5895, fuke@cs.cmu.edu

Abstract

Carnegie Mellon University is pursuing research of robotic vehicles for lunar exploration. In our mission scenario two rovers will traverse one thousand kilometers on the Moon over a period of two years, starting in 1998. Throughout the mission the rovers will transmit to Earth rich video telemetry to be used by theme parks ventures and scientist worldwide. Critical to achieving the goals of the two-year mission is the rover's locomotion capability. The requirements of survivability in the harsh lunar environment, substantial terrainability and long term reliability drive the configuration of the locomotion system. These performance requirements have led to the consideration of a wheeled configuration as the preferred locomotion scheme for the intended lunar traverse. To achieve substantial climbing capability and mitigate body excursions we selected a six-wheeled configuration that utilizes pivot arm linkages for body suspension. In this paper we discuss the configuration of robotic locomotion for the moon, and describe analysis and experimental results obtained through testing of a physical prototype.

1. Introduction

Over the past two years the Lunar Rover Demonstration program at Carnegie Mellon University has configured lunar robots and addressed some of the key aspects of robotic operations on the moon, including issues related to mobility, control architecture, telemetry and imagery. Of key importance to the success of the mission is the capability of the rover's locomotion system to reliably traverse one thousand kilometers of unknown terrain over two years.

Our intended mission involves soft landing two rovers near the Apollo 11 site. From there, the rovers will navigate under human teleoperation and autonomous safeguarding to regions that have been visited by previous exploratory missions, such as the landing sites of Apollo 17 and Lunakhod 2 (Figure 1). During the traverse the rovers will provide real-time, high-resolution panoramic imagery of the lunar terrain and unique views of each other traversing the lunar surface. Throughout the traverse, commercial sponsors and scientists will share command of the rovers, while the public will participate through interactive theme parks and tele-networks. It is therefore required that the rovers must safely allow teleoperation by semi-skilled operators on Earth.

In this paper first we address the issues related to locomotion requirements. Next we discuss the configuration approach and propose a six-wheeled rover with individual wheel drives, explicit steering of its corner wheels and pivoting arm linkage suspension. Then we describe the drive torque / power analysis to investigate the performance of the proposed configuration. Finally we evaluate its mobility performance through testing of a physical prototype.

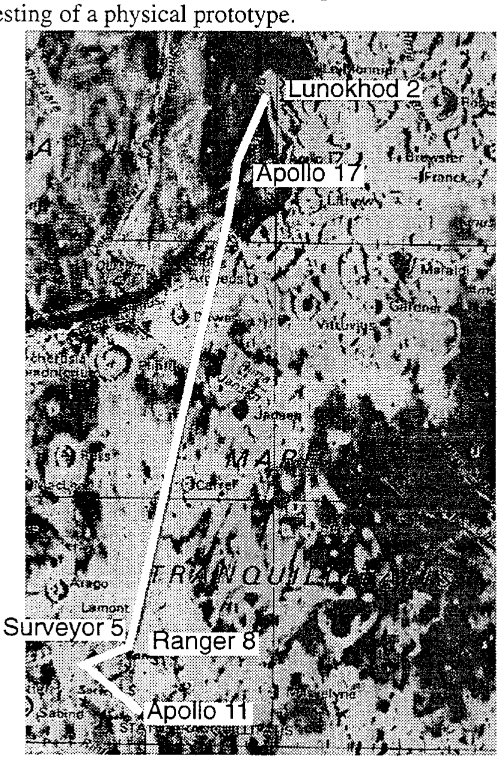


Figure 1: Mission traverse route

2. Locomotion Requirements

Robotic locomotion for lunar exploration is driven by the following requirements:

- Environmental survivability

The rovers should survive the harsh lunar environmental conditions summarized in Table 1 ([1], pp. 27-56). Table 1 also describes some of the effects on rover due to these conditions. Key design issues therefore include thermal control, component sealing and lubrication confinement.

- Long term reliability:

The rovers are required to operate for two years without failure. It is expected that some components will undergo a million loading cycles or more. Key issues

1. Visiting Researcher from Mitsubishi Heavy Industries, Takasago Research Laboratory, Takasago, Japan 676
2. Robotics Graduate Student
3. Mechanical Engineering Graduate Student
4. Civil Engineering Graduate Student
5. Principal Research Scientist

are therefore component lifetime in the harsh lunar environment and recovery from operational contingencies such as having a wheel entrapped in soft soil.

• Terrainability

A variety of studies such as [1], [2], have quantified lunar surface geometry and physical properties. In some areas, distribution data of craters and boulders has been obtained [2]. During the recent Clementine project, an imaging sensor took comprehensive high resolution (~20 m) images of the moon. These images will be useful for rover navigation.

However, the rover will encounter small craters and boulders without a priori knowledge of their location, roughness and physical properties. Overall the rover is required to have as much terrainability as possible in order to achieve robust teleoperation. Table 2 summarizes representative terrain types on the lunar surface and their effect on locomotion. The actual terrain along the intended traversed path will likely be a combination of these conditions.

• Reduction of body oscillation:

The communication antenna should be continuously directed to the Earth within 0.5° pointing accuracy while the rover is moving. To help the antenna pointing problem, a chassis type that will reduce body oscillations is deemed necessary.

3. Locomotion Configuration

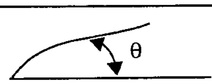
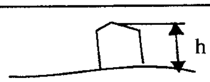
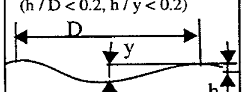
3.1 Selection of locomotor type

The principal terrestrial locomotion types are wheels, legs and crawlers. Crawlers exhibit high terrainability on various ground geometries and soft soils due to low contact pressure, but the track mechanisms would suffer from much invasion of lunar soil particles which are very abrasive and could cause critical failures [1], [3]. Two years of reliable operation is therefore very doubtful. On the other hand, legged locomotion has been intensively researched as a mobility option for the rough surface of Mars [4], [5]. However, for this mission, wheel type locomotion is optimal for the fol-

Table 1: Environmental conditions on the moon

Condition	Characteristics	Effects on Rover
Atmosphere	Hard vacuum (8×10^{-9} Torr during daytime)	Evaporation of lubricants; no oxidation of metal surfaces which typically prevents metal-to-metal contact
Temperature	Daytime: +130°C, Nighttime: -180°C Rapid change from day to night	Thermal stress on structural materials
Radiation	10^7rad/m^2/yr. solar radiation High energy cosmic radiation	Damage on structure, electronics etc. by sputtering, ionization and polymerization
Dust	Electrostatic, highly abrasive	Abrasion of bearing surfaces Adhesion on optical surfaces

Table 2: Lunar terrain and locomotion requirements

Type	Geometry	Attributes	Effect on locomotion	Requirements
Normal		Mostly negotiable Compaction resistance < 0.1	Moderate slip and sinkage Moderate mobility resistance	Contact pressure: 7 ~ 10kPa ([1], p. 512)
soft regolith		Exists in limited regions Low bearing capacity	Large slip and sinkage High mobility resistance	Contact pressure: 2 ~ 3kPa
Slope		θ < ϕ (soil friction angle)	Tipover Decreased tractive force	(nominal) 20° (max) 30° (static stability) 40°
Boulder / step		Distribution in 100 m^2: h > 6cm: 100, h > 25cm: 3~4, h > 50cm: 0.6 (based on Surveyor 3 site)	Hang-up Tipover	h < 25cm climability Body clearance > 25cm
Crater	(h / D < 0.2, h / y < 0.2) 	Distribution in 100m^2: D>1m: 10, D>3m: 0.4, D>5m: 0.1 (based on Apollo 11 site)	Hang-up, nose-in failure Tipover	D < 2~3 m (Assuming ~2 m size rover, a $D \approx 1m$ crater is hard to avoid. A $D \approx 5m$ crater is hard to cross, but easy to detour around)

lowing reasons:

- Easier to attain required maximum speed (1m/s). Though usually speed limited due to mechanism, walkers may increase maximum speed through the use of multi-ratio gear trains [6]. However, such designs entail more mechanical and operational complexity.
- Requires less autonomy for safeguarding. Legged mechanism may need autonomy for foot placement selection, control and verification.
- Proved locomotion on the moon. (Apollo Lunar Roving Vehicle (LRV) and Russian Rover (Lunakhod)) ([1], pp. 522-527)

3.2 Body articulation and suspension

Single body with wheel suspension

A single body with wheel suspension, common to automotive vehicles, was used for the Apollo LRV and the Lunakhod. However, for the proposed mission, there are two areas of concern. Taking the lander scale into account, possible step climability with a 2m length rover (limited by lander volume) is less than 25cm (Table 3). In order to increase step climability and stability, softer and larger wheel suspension is needed. However as wheel suspension stroke increases, stability on cross-slopes is degraded due to body deflection on the downhill side.

Multi-body articulation

One solution to address the above mentioned problems is a multi-body articulated configuration with flexible joints [7]. Though such a configuration achieves high terrainability (see Table 3), it tends to be sensitive to local terrain roughness due to its flexible joints. This results in oscillatory body motion which may be problematic for real-time precise antenna pointing to Earth while the rover is in motion.

Single body with pose averaging linkage

An alternative configuration approach is to incorporate pose averaging linkages [8]. As a result of trading off step climbing capability for less body excursions, we selected a six-wheeled configuration as shown in Figure 2. The chassis is linked with two pivot arms, two side arms and an averaging linkage which provides higher terrain adaptability and lower body oscillations (Figure 3).

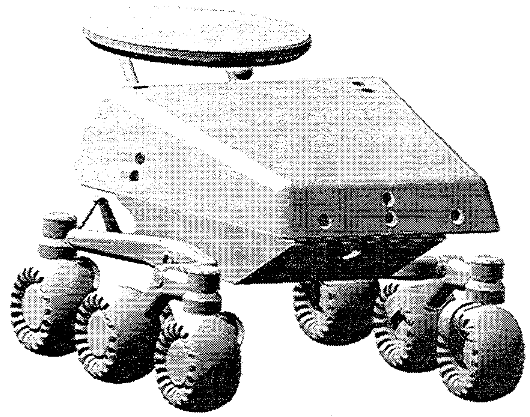


Figure 2: Lunar rover configuration design

Table 4: Rover specification

Characteristics	Specification
Wheel diameter	53 cm
Wheelbase	1.47 m
Wheel width	30 cm
Overall width	2 m
Height	1.5 m
Ground clearance	55 cm (C.G. 75 cm from ground)
Drive scheme	Individual wheel drive
Steering scheme	Explicit (corner wheels)
Speed	1 m/s (maximum)
Longitudinal stability	44°
Lateral stability	48.6°
Contact pressure	3.9 kPa
Maximum step	25cm
Power	100 W (maximum)

3.3 Locomotion configuration

The proposed rover configuration is shown in Figures 2 and 3. It is dimensioned to fit inside the anticipated lunar lander. The front and rear wheels are explicitly steered using independent actuators. All wheels have independent propulsion actuators. The overall vehicle specification is given in Table 4.

Table 3: Step climability of various wheeled locomotors

Configuration	Single body with wheel suspension		Multi-body articulation	Single body with pose averaging linkage
	Apollo LRV	Lunakhod	Marsokhod	Suggested configuration
Wheel diameter D [cm]	80	51	35	53
Vehicle length L [cm]	310	220	105	200
Step climability h [cm]	25	25	75	< ~58
Theoretical h for L = 2m	16.1	22.7	143	~58

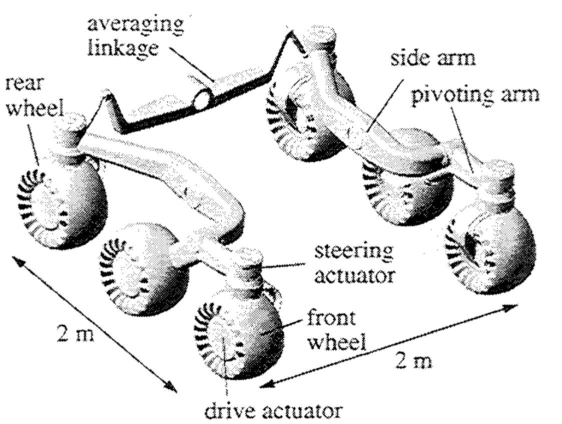


Figure 3: Locomotion configuration

Drive scheme

The six wheels can either be driven by centralized actuators (e.g., right side wheels driven by one actuator and left side wheels driven by a second actuator), or each wheel can be driven individually [9]. The trade-offs between these two options are summarized in Table 5. For robustness against single point failure and drive train simplicity, the individual drive scheme was chosen.

Steering

Ackerman steering is applied in automotive vehicles. However, in our configuration, the Ackerman mechanism becomes complex because the distance varies greatly between the front right wheel center and the front left wheel center due to pivot arm excursion.

Skid steering is simplest because a drive wheel directly contributes to steering without any specific steering mechanism. It also enables rover to turn in place. However skid steering essentially sweeps out soil laterally. Thus lateral resistance causes a high turning moment. The moment increases if a wheel sinks in the soil or collides with an object while turning. After analysis, individual steering in the front and rear wheels was chosen based on its advantages over other steering alternatives.

Drive power and torque

Necessary motor input power and load torque for each wheel is estimated considering a six wheeled model climbing a worst-case terrain profile (20° slope with a superimposed 25 cm step) for both forward and reverse directions. Quasi-static force/moment balance is assumed in the model. Nine situations are considered as the rover negotiates the terrain (expressed as

Table 5: Comparison of drive schemes

Propulsion drive scheme	Centralized drive (2 actuators)	Individual drive (6 actuators)
Thermal protection	+ Simpler (actuators are in the body)	- Hard (actuators are inside the wheels)
Effect of single transmission failure	- Critical	+ Tolerant
Electrical cabling	+ Cabling can be inside the body	- Cable routing from body to wheels
Drive train	- Complex, high friction	+ Simple, low friction
Power	- Many inefficiencies due to complex drivetrain	+ Mechanical simplicity enables high efficiency
Torque distribution	Differential + viscous coupling	Slip or torque control

Table 6: Wheel torque / power in different operational modes

Operational mode (speed)	Wheel torque [Nm]	minimum required friction coefficient (μ)	Motor input power [W]		Assumption
			Centralized drive	Individual drive	
Worst-case terrain such as Fig. 6 (0.1m/s)	37.4 (front) 12.7 (middle) 16.1 (rear)	1.4	129.0	82.0	(1) Each wheel has the same drive friction coefficient μ (2) Vehicle weight = 425 N in lunar gravity. (3) Coefficient of rolling friction = 0.1 (4) Equivalent load support assumed for vehicle's left and right sides (5) Gear efficiency = 0.8
Nominal speed on flat level surface (0.5 m/s)	1.4 (average)	0.1	56.0	34.7	
Max speed on flat level surface (1.0 m/s)	1.4 (average)	0.1	125.0	72.5	

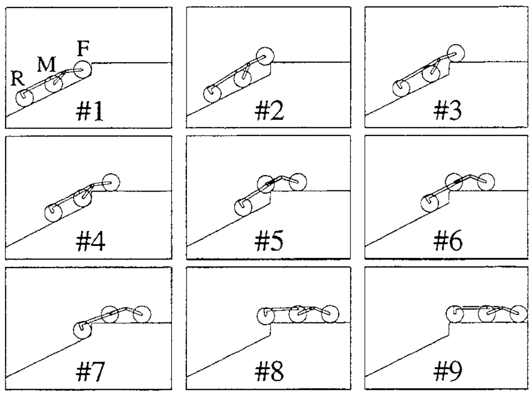


Figure 4: Worst case terrain negotiation. This is the case of forward vehicle approach to the step

#1 ~ #9 in Figure 4).

In the forward direction, the front of vehicle (F) climbs the step first. In reverse, the rear of the vehicle (R) climb the step first. Centralized drive and individual drive are compared in terms of motor input power using commercial DC brushless motor specifications. In addition, maximum and nominal speed operating modes are analyzed and summarized in Table 6.

Results

- The rover requires the largest total power in #7 (Fig. 4) of reverse climbing motion. In this case the middle (M) and rear (R) wheels are on the horizontal surface and the front wheels (F) are climbing the step.
- In the case of individual wheel drive, power consumption meets the locomotion power budget requirement of 100 W maximum in all operation modes. (Table 6)
- It appears that the rover can negotiate the worst-case geometric terrain only when μ is high (~1.4 such as rock). On lunar soil, which has low shear strength, μ is ~0.7. Therefore, despite high wheel torque, the robot cannot negotiate a terrain as shown in Fig. 4 if most of the materials are soft. However, it may be possible to negotiate the worst-case terrain geometry composed of rock on which a wheel can generate high traction. For the purpose of actuator design, the worst case (reverse motion, #7) was used.

4. Physical prototype

In parallel with the configuration work, we have developed a physical prototype to verify the analysis results and provide additional insight into terrainability. The prototype has centralized drive (without a torque distribution mechanism) and skid steering for implementation simplicity. Figure 5 shows the physical prototype.

4.1 Structure

The prototype is constructed from Al alloys and The right and left side wheel sets are driven from single actuators using chain transmission and sprockets. The mass of the prototype is 45 kg which is 1/6 of the mass of the flight rover to simulate lunar gravity. The protoype scale is 2/3 of the actual rover. The wheelbase is 1.25 m.

4.2 Sensors

Load torques at the right and left axles are independently measured by load cells located within the drivetrain. In addition, body roll and pitch angular velocities are measured by an inertial measuring unit which is rigidly attached to the body chassis. Sensor data was sent to an off-board computer by serial cable. Body oscillation data (amplitude, spectrum) will be used in the active antenna platform analysis.

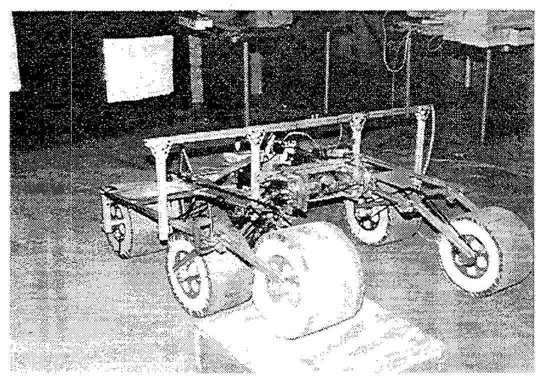


Figure 5: Physical Prototype

4.3 Step climbing test

Test 1

In this test, the left and right front wheels crossed the 20 cm step simultaneously. The front wheels and middle wheels succeeded in climbing over the step. However the rear wheels could not climb over the step but instead either slipped or became stuck. Figure 6 shows the measured result of axle torque and body oscillation. Peak analytical torque in Figure 6 corresponds closely to the measured torque. We detected a torque difference between the right axle and left axle due to non-synchronized motion of the left wheels and right wheels. Possible reasons that the rear wheels became stuck include:

(a) Tire material friction was inadequate to generate traction. The maximum slope which the rover could climb was about 25°, which means the sliding friction coefficient was only 0.48.

(b) From a quasi-static analysis of the centralized drive, we found that rear wheel immobilization occurs due to a torque condition that requires several of the drive chains to exert a compressive force which is impossible. An independent drive configuration would avoid this situation.

Test 2

Only the right side wheels of the rover were going over the 20 cm height step (step length > 0.63 m, as seen in Figure 5). In this case all right side wheels climbed over the step.

4.4 Discussion

Through prototype testing, several common locomotion problems were identified.

(1) Differential effect in drive train due to synchronized transmission:

When a pivot arm rotates with respect to the body with rotational speed Ω, the rotational speed of the front and middle wheels is the speed of the rear wheel minus Ω. If the wheel speeds are not appropriately adjusted, wheel slip or drag can occur. A torque distribution mechanism (differential, viscous coupling) should have been incorporated. On the contrary, for individual drives, there should be a locomotion strategy to reduce wheel slip or drag by torque detection in each wheel.

(2) Wheel motion competing due to link kinematics:

As shown in Figure 7, in order for the front wheel to climb up a step, the pivot retreats backward resulting

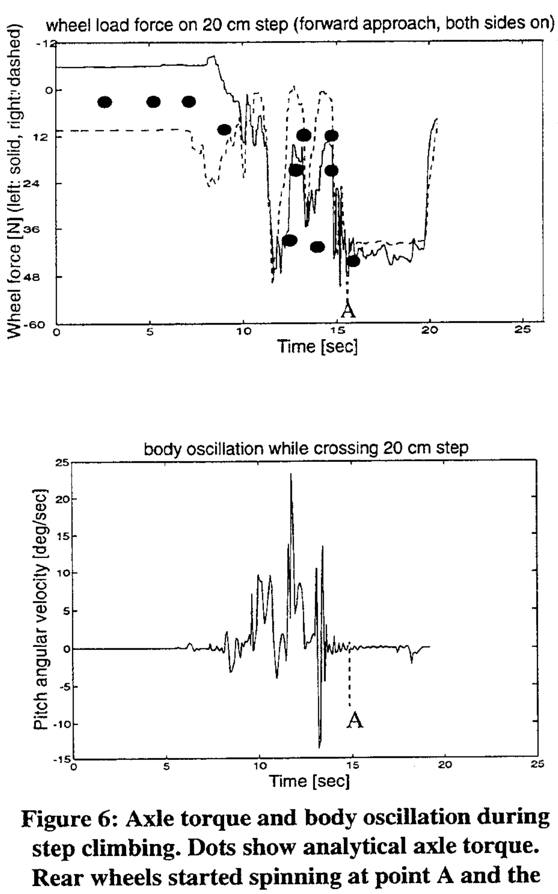


Figure 6: Axle torque and body oscillation during step climbing. Dots show analytical axle torque. Rear wheels started spinning at point A and the vehicle was not able to complete climbing the step

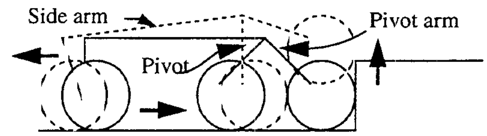


Figure 7: Step climbing effect

in rear wheel slippage. An addition of compliance in some of the linkages may improve this situation.

5. Summary

Various locomotion configurations were investigated for a lunar robotic vehicle. Based on the primary requirements (survivability, terrainability, reliability, reduced body motion), several locomotion types were compared and a six-wheeled configuration with pivot arm linkages was chosen as the most suitable for our mission. The propulsion drive scheme, steering and drive torque / power were also analyzed during the configuration work. Through physical prototype testing, it was found that theoretical torque was consistent with empirical values and the validity of analytical model of locomotion was verified. However several shortcomings with respect to traction and kinematics were found that should be remedied to improve locomotion.

To further understand the locomotion system, a second physical prototype with individual drives is being designed. Tests including terrainability, wheel torque/ power, body oscillation, hang-up, nose-in failure will be conducted. The followings issues are identified as remaining work:

- Failure mode analysis related to rover safeguard, fault recovery, reliability.
- Tribological issues (lubrication, sealing against dust) and heat transfer from the wheel actuators.

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