DEVELOPING PUD –LUNAR ROVER TEST PLATFORM

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ABSTRACT

The Planetary U-Shaped Dolly (PUD) is a configurable rover chassis developed to test various planetary rover mechanical and electrical concepts. This chassis concept emerged from an internal study as one of the solutions to address requirements for a scalable, multifunctional, remotely reconfigurable lunar rover.

This paper presents the work carried out on developing the PUD-II rover prototype by the above team as one implementation of a multi-utility rover concept using a U-shaped chassis. The features of this implementation will be presented alongside all the development activities and field testing. Also, the impact of using a U-shaped chassis on rover subsystems will be discussed.

1. INTRODUCTION

Multi-utility rover concept is based on the idea of using one basic rover chassis with multiple specialized payloads which could be remotely attached and configured on the rover. Combined rover and payload would form a specialized rover which can perform specific function. Such functions could include: drilling, excavation, building material transportation, scientific instruments, ISRU (in-situ resource utilization) processor and others. The concept of a single chassis and multiple payloads is attractive in terms of reducing mass for an otherwise heavier set of specialized rovers.

This development was carried out in parallel with the development of a metal flexible wheel [2] where this platform played an important role in its field testing.

The PUD-II chassis evolved from the original PUD-I chassis which was based on a rigid frame design.

2. PUD-I ROVER DESCRIPTION

Early version of the PUD-I, Fig-1, had a rigid chassis with flexible wheels connected directly to individual gearhead motors. The original concept calls for the basic rover gear motors, 4-jacks, batteries and avionics to be stored within the two hollow tubes bays (the two sides of the U-shaped chassis). This means that only parts of the wheels and jacks shafts (single degree of freedom each) are left exposed to the external regolith and thermal environments. This will make it easier to protect avionics and electromechanical systems from outside lunar environment and also enable the reuse of heat generated by gearhead motors during night operations.

Since we are following a low-cost approach it was decided to simplify the implementation by using a solid U-shaped frame and fasten motors and jacks to the frame while storing avionics and batteries in a separate box.

Before it was decided to prototype the PUD-I a FEM was developed to determine the optimal chassis square tube dimensions that could ensure safe operational limits when chassis experiences maximum torsion. Maximum torsion is experienced by the chassis tube free ends under maximum payload conditions. Torsion is introduced due to offset of the wheel from tube centre point.

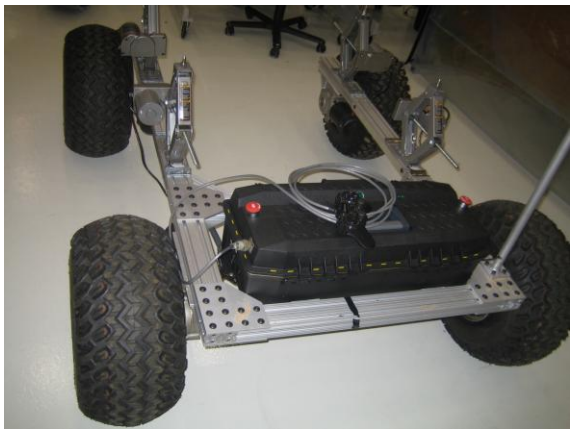

Fig-1 PUD-I Chassis with all-terrain pneumatic wheels
"Notice the four chassis jacks and interface pins"

Fig-2 PUD-I Chassis carrying a payload mock-up
"Notice the four engaged chassis-payload interfaces"

PUD-I chassis has 4 jacks which are used to lift a payload and lock it in to become part of the rover chassis. For now the chassis-payload interface is kept simple. The payload is lifted through four docking points. Each docking point consists of a docking pin, on top of the chassis jack, and a matching hole on the payload interface. Each interface hole is preceded by a cone shaped guide to simplify docking.

The four jacks are controlled by a simple up-stop-down collective manual control. The docking process is performed by the teleoperator driving the rover chassis, with jacks in the down position, under the four interface holes of the payload. Once at the right position, the jacks are raised until the payload is lifted of the ground to the required height. The payload is offloaded by simply lowering the jacks till the payload is free, at which point the empty chassis can be driven away.

It is assumed that in a complete implementation of this concept that the docking interface would mechanically be more rigid, each point can be remotely locked and unlocked and the interface could cater for spring damper component if required. Electrically the interface could include power and data as well. The more sophisticated implementation would use on-board automatic docking.

Limited suspension function was allocated to the flexible wheels. Design simplicity and reduction of component count to improve reliability was the driver. Although such a configuration performs well on flat terrain it was challenging on rough terrain to maintain four wheels traction.

PUD-I is controlled by wire from a manette. The individual motors have separate speed controllers but the two motors on each side are controlled collectively by a single joystick. The rover uses two sticks skid steering. The manette also has an Up-stop-down jack's collective control. Each of the jacks has upper and lower position limit switches. The rover uses sealed lead acid batteries with autonomy of 20 minutes. PUD-I was fitted with available worm gearhead motors and amplifiers. The motors were series wound dc motors. The rationale for the choice is the high starting torque capability of the series wound dc motors and its torque speed characteristics which enables good matching between available torque and speed of the rover without requiring multi-speed gear box. Heritage of this approach is based on the Apollo lunar LRV [3].

The torque produced by the available gear motors was lower than rover requirement. That made it challenging to drive the rover at steep angles and point turns with high payload. However the rover successfully demonstrated the concept of the U-Shaped utility.

Fig-3 CSA PUD-II Rover – Mobility Testing at MET

3. PUD-II ROVER DESCRIPTION

Various lessons learn from the PUD-I development and testing were factored in developing the PUD-II, Fig-3, Table-1. The following are the newly introduced

features:

- New gear box with more torque capability.
- New suspension
- Aluminum tube structure
- New flexible metal wheels
- Lithium-Ion batteries
- Three point payload interface
- New payload basket
- Remote control

PUD-II uses a unique four torsion bar suspension, Fig-4, 6. This was introduced to improve the chassis terrain following, payload vibration and shock isolation, payload attitude holding and centre of gravity control.

The new suspension demonstrated excellent terrain following for terrain with moderate roughness in terms of making sure that the four wheels are in contact with the terrain most of the time. For extremely rough terrain there are configurations where the chassis becomes three points driven.

Fig-4 PUD-II Miniature model for 4-torsion bars suspension concept

As for payload vibration and shock isolation, The PUD-II relies on two mechanisms to reduce vibration, the wheels as a spring and damper, and the possibility of using further springs and dampers at the payload 3-points interface.

A high gear ratio was employed in the PUD-II gearbox due to high power consumption of moving heavy payloads and relatively limited solar panel power generated. In order to give any reasonable traction to operational functions such as plowing, high torque is required. Speed is therefore is traded for high torque.

Different wheel sizes were investigated. Eventually a 25 inch x 10 inch wheel was adopted to assure an adequate clearance for rocks. The FW-350 flexible metal wheel [2] is the baseline wheel for the PUD-II. The wheel was used in most of the field tests, Fig-3.

The FW-350 wheel has a main structure cut from a single spring stainless steel sheet metal. The structure consists of a rib cage bent and folded to ride on a carbon fibre “bead lock” rim. The wheel uses internal spring bands pillows to simulate air pressure distributing rover load on the rim surfaces. Side bands strength ensures torque transmission from rim to wheel tread. The wheel has a flexible grouser system which is designed to trap regolith, making it become part of the bottom part of the wheel tread, leading to a good soil to soil coefficient of friction. The light weight grousers are protected by a web made from multi-strand aircraft cable. Grousers are shaped to improve lateral stability of wheel.

Fig-5 PUD-II Payload basket “chariot basket”

Skid steering was selected to reduce mechanical components count. However skid steering increases structural loads on the drive system and torque demand during point turn.

The PUD-II uses three-point payload suspension to ensure that payload contacts are always attached to the chassis. Each suspension point uses a jack Fig-3, to lock and lift a standard payload interface Fig-5. At this stage only the mechanical component of the interface has been prototyped. It is assumed that the interface will have electrical and data components too.

Fig-6 PUD-II 4-torsion bar suspension flexing

The payload mechanical interface consists of a pin and cone mechanism where the pin is driven by the jack into the cone, which is part of the payload (fig-5). In a complete implementation, it is expected that there would be a lock–release mechanism which would ensure that the payload is positively locked.

Chassis Mass L W H -shaft H-Gear Material L-Tube t-Tube Speed	 256 Kg 1.52 m 1.22 m 0.175 m 0.255 Al 0.152 0.0064 1 Km/hr	Suspension Type Travel	 Torsion bar 0.2 m
Jacks Lift Range Voltage	 100 Kg 0.28 m 12 V dc	Turning	Skid Steer
Basket L W H	 0.77 m 0.68 m 0.75 m	Control Cmnd Type	 Wire + Wireless Torque Open loop
Motor Type Voltage Current	 D.C series 72 Volts 15 A	Rover C.G L W H -shaft	 0.77 m 0.61 m 0.17 m
Gear Head Type Ratio	 Worm 1:100	Payload Mass L W Interface	 100 Kg 3-points
Battery Type Cap	 Lithium Ion 3.6 KW-h	Wheel D W Bolts	 0.635 m 0.26 m 4-.112m

Table-1 PUD-II specification

4. U-SHAPED CHASSIS UTILITY

Although the concept of U-shaped chassis evolved within a lunar rover context, the system is adaptable and scalable to suit missions on mars as well. In this section we will discuss three potential utilizations.

In robotic exploration missions the focus would be on using this chassis as a multiple utility vehicle either automatically operated with asynchronous high level commanding, GNC and automatic payload docking as is the case in mars missions or teleported directly from earth for lunar operations. In this type of missions the U-shaped rover will demonstrate its full utility in terms of being able to be used for various functions.

As an example, the rover could be used to dig for and erect a shelter close to a lander site. To accomplish that, the teleoperator would control the rover to lift an excavation tool payload from the lander and drive to the site. At the site, a suitable shelter base is excavated. The rover is then driven back to the lander where the excavation tool is offloaded and stored. A packed inflatable shelter is lifted by the rover and transported to the site. At the site, the shelter is placed at the excavated base and then deployed by the teleoperator. Various operational scenarios can be developed to use the rover to perform many other robotic functions around the shelter such as deploying power generation and storage infrastructure or deploying and operating an ISRU payload to extract volatile gases from lunar regolith.

One of the interesting challenges of making the rover more valuable is to make sure it can be stored for long periods and reused at later date. This would require rover and its payloads to survive the lunar environment over long periods.

In the context of science missions this rover configuration also presents further capabilities and choices to the mission designer. The fact that payloads can be interchanged and rover chassis potential reuse with new payloads in a subsequent mission adds further flexibility compared to what is possible with existing fixed rover-payload configurations.

Within a manned mission context, the multi-utility rover again opens new possibilities. One is enabling an astronaut to perform real time function remotely from the safety of a shelter using the rover. This is critical in prolong missions where the radiation dosage needs to be minimized. Another function that a U-shaped multi utility rover can be used for is to transport an astronaut who would drive the rover directly. As a payload the astronaut module could contain life support or just transport a suited astronaut. The suited astronaut is able to just walk into the lowered basket, Fig-5 raise it and drive away, “chariot-horse” concept.

Due to its construction simplicity, the PUD-II can be easily launched disassembled, and assembled on the moon surface by astronauts.

5. FIELD TESTING

As the PUD-II design evolved, various field tests were conducted to validate its functionality and performance. The tests were mainly conducted at the Mars Emulation Terrain (MET) grounds at CSA, Fig 8. The rover

demonstrated good handling capabilities in straight, uphill, downhill driving and turning. The rover experienced some locking when the demand for torque exceeded capabilities of the gearhead motor. Chassis clearance was adequate, the chassis cleared rocks of size equal to half the drive shaft clearance. The suspension can allow traverse of much bigger rocks however this would require more drive torque capabilities. Wheel structure held well, however wheel grousers needed to be reinforced [2].

Trials focused on the rover suspension system, using the FW-350 stainless steel flexible wheel, demonstrated adequate maintenance of payload attitude, See Figure3. Also trails with human driver demonstrated reasonable vibration attenuation. Future work on this issue will include running the rover, instrumented with accelerometers using the drive profile Fig 8.

Due to the configurability of the multi-utility rover it is expected that payloads load distribution would take into consideration the overall location of C.G. For stability reasons, CG height need to be minimized. However, in practice, the height will always be traded with acceptable payload vertical ground clearance, table-1.

Generally speaking and depending on rover configuration, point turn in skid steering manoeuvre requires significantly more power than is required to drive a rover in level drive [1].

Fig-7 CSA PUD-II Rover – Payload Interface Testing

As the turn radius increase the required power reduces to eventually equals level drive power. Field tests, using individual motor current measurement, of the PUD-II confirmed this pattern of power requirement.

Skid steering introduces lateral forces load on the wheels and chassis structure including the torsion bars. High lateral forces drove the lateral stiffness of the FW-350 flexible metal wheel [2].

Utility of the U-Shaped chassis to dock around a payload, lift the payload, transporting it to another location and offloading it was tested exhaustively. The results showed that the concept, in principle, works.

Testing payload basket,Fig-5, 7 as a payload mock-up highlighted various operational issues which should be considered further in a future development. These include: locking of jack-payload pin after docking, how to introduce flexibility in the interface to allow for pitch and roll movement of payload relative to the chassis while driving up or on the side of a hill.

Ultimately there are few system design trades that need to be carried out to address issues such as: should the payload be just mechanically coupled to rover while each maintaining own power, thermal and wireless intercommunication? Such issues would most likely depend on the target mission.

Field tests showed that the PUD-II autonomy was extended by 3 times by replacing lead acid with Lithium Ion batteries. Adopted charging strategy, for now, is to charge battery on the module level to reduce charging time while preserving battery modules life. However, eventually, there will be a need to charge the rover from a single or two sources such as on-board solar panels or external power source.

Experience gained from field testing the PUD-II at the MET is being put to use to develop a standard experimental rover test drive profile "Luna-00-CSA-MET" see Fig-8. The objectives of this test profile are to measure the functions and performance of rovers (mass 50 to 500 Kg) and their subsystems. The testing is also expected to feed into rover reliability studies being carried out. This will include obtaining data on early, random and wear out failures.

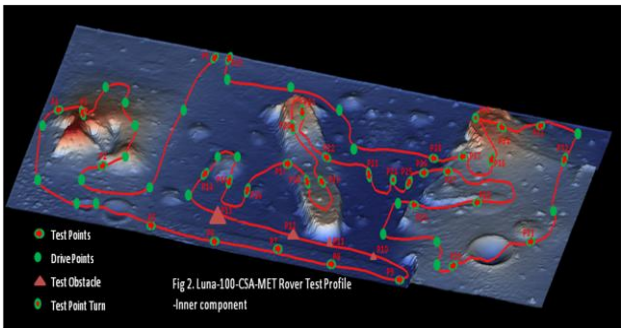

Fig 8 Lun-100-CSA-MET Rover Test Profile **

*** Drive Profile by first author, DEM by David Gingras-CSA, Helicopter Image curtsey NGC Inc.*

6. U-SHAPED CHASSIS CHALLENGES

The U-shaped chassis configuration presents new challenges compared to traditional rover chassis. Those challenges include: managing rover space envelope, payload and rover having separate thermal systems and the generic electromechanical rover payload interface.

Logically the space volume above the U-Shaped payload area will be reserved for the payloads with their various requirements. Consequently, little space is left for the chassis subsystems, such as power panels, satellite tracking antenna and navigation and driving cameras.

New generation of rovers will require more power to perform functions other than mobility (digging, plowing, drilling etc.). This drives more demand on solar power generation which translates to larger solar panels with tracking functionality and more frequent deploy and retract. Those panels affect the dynamics of the rover when they are deployed. This would lead to much lighter panels construction and it becomes more likely to deploy them only at low rover speeds and level driving.

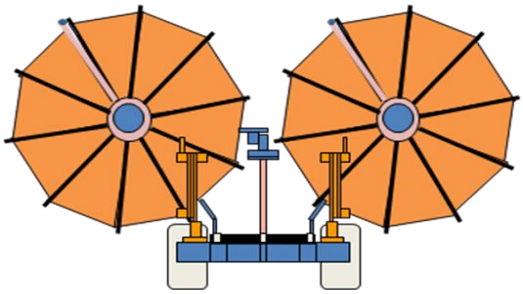

Figure-9 U-chassis high power deployable solar panels

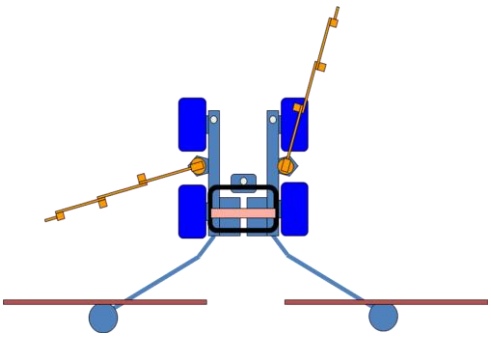

Figure-10 U-chassis robotic arms work space

For a multi utility U-shaped chassis the operational envelope of large tracking solar panels would also compete with the already scarce rover space access envelope, especially knowing that it is hard to predict space access requirements of the potential payloads. Fig 9, 10 present one of the potential solutions where the two solar panels are offset from the rover back side. It can be seen that such solutions need to maximize the two robotic arms access to payloads and ground. It also should provide the satellite transponder with adequate visibility to orbiting satellites; although at certain operational settings there would still be conflict and that need to be resolved by clear conflict resolution rules.

7. CONCLUSION

We have presented in this paper various aspects of the concept of using a multi utility U-shaped chassis. Experimental results demonstrated the utility of the concept using the PUD-II experimental prototype in lifting, transporting and offloading a typical payload over various terrains. The operational utility of this configuration was then discussed, as well as the various challenges and implication of using the U-shaped chassis.

8. FUTURE WORK

To commit this type of chassis configuration to an actual space mission will require further work such as adding damping mechanism to the current 4-torsion bars suspension system. The PUD-II experimental prototype requires significant reduction of mass and an increase of the payload to chassis mass ratio. More efficient motor gearhead is definitely required to meet the high torque requirements. The challenge of having de-centralized thermal system needs to be assessed. Managing the chassis space volume need to be prototyped and field tested to understand space access constraints and conflicts between various chassis based sensors, actuators and solar panels and allocated space for the payloads.

9. ACKNOWLEDGMENT

We would like to acknowledge the continuous support of Pierre Lortie, Ralph Nolting in building the PUD-I and PUD-II chassis and related mechanical subsystems.

10. REFERENCES

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