A Novel Teleoperated Hybrid Wheel-Limbed Hexapod for the Exploration of Lunar Challenging Terrains

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Successful robotic planetary exploration missions are not without technical and scientific challenges. Appropriate control and mobility of the robot is critical for successful exploration in the unstructured environment. We address these problems, through an overview of an under development telerobotic platform, for exploration missions to the lunar craters. The platform is based on a novel transforming hybrid walking/roving Lunar Exploration Omnidirectional Netbot (LEON). We describe ERode, a versatile dynamic engine based simulator / teleoperation platform, which allows developing, simulating and teleoperation of LEON. We also introduce the novel hybrid wheel / limbs design of LEON, whereby two of its six limbs fold into themselves transforming into wheels. This possibility of transformation results in increased mobility in the environment, by adapting to different soil conditions. Also this system has a limited bulkiness compare to hybrid system owning both wheels and legs, and has an increased wheel diameter compared to hybrid systems having wheels at the tip of their legs. Preliminary experimental or simulated results are also presented, showing the performances of the hybrid system dealing with different types of terrain.

Key Words: Telerobotic platform, Hybrid Robots, Lunar Exploration

1. Introduction

The future of lunar exploration, or the establishment of a permanent lunar base, radically depends on the successful prospecting for ice-water. Proving beyond a doubt the existing of water, or by producing liquid in some other feasible method, on the surface of the Moon, is necessary for a continued human presence. The components of water, and water itself, are the most privileged resource for the survival of astronauts in life support systems and mostly a precious source of hydrogen and oxygen to use as propellant. The reduction of mission costs for long duration missions depends enormously on the feasibility of using In-Situ Resource Utilization (ISRU) for the production of H2O, and other elements for power production. Also, with the flight of the Lunar Prospector in 1998, the theory proposed by 1) about the possible presence of local concentrations of ice on moon in permanently shaded areas received partial confirmation.

This paper focuses first on the novel Hybrid limb/wheels mechanism of LEON. It then presents the concept of the versatile telerobotic platform for planetary exploration and its implementation in ERode. In the third section, preliminary experimental or simulated results addressing the performances of the hybrid system in the different locomotion modes, dealing with different types of terrain conditions, is presented.

2. Lunar Exploration Omnidirectional Netbot hybrid concept

In this section we detail the novel concept of hybrid limbs that are transformable into wheels, and their implementation.

2.1. Novel hybrid limb-wheels concept

On the lunar surface a mobile robot can be expected to move on either deformable soft sandy terrain or uneven firm rocky terrain. Thus suitable design for the locomotion mechanism is critical for a successful mission. Legged robots are known to be efficient on uneven rocky terrain. The main issue is that they are energy consuming and have a relatively slow motion. Alternatively, wheeled robots are faster and less energy consuming, but need to be moving on relatively smooth and flat terrain. In order to overcome these drawbacks, whilst preserving the advantages of both locomotion systems, hybrid robots represent a proper solution for the highly challenging terrain that is expected in the craters.

Previous research on hybrid legs/wheels system propose solutions either with small wheels at the end of the legs 3), or owning both locomotion systems using them simultaneously (or alternatively) 4). However neither of
these approaches is well suited to lunar exploration. End tips wheels are usually reduced in size in order to assure a precise contact of the leg on the ground, or retraction ability, but they prevent the mobility on soft terrain. On the other hand, keeping both independent mechanisms, leads to actuators redundancy and bulkiness.

The innovation seen in our proposed novel Lunar Exploration Omnidirectional Netbot (LEON), contrast with the previous methods. LEON is a hexapod capable of folding two of its limbs and transforms them into wheels. In this way, LEON can become a large wheeled robot as seen in Fig. 1.

Fig. 1. CAD model and current implementation of LEON

Its 3D structure is formed by a hexagonal central body, with six limbs, which are symmetrically distributed around the body. This allows a near omni directional motion on uneven soil and grasping of the surface. The legs can be equipped with the mission necessary tools, and can be used as well for simple manipulations in motion on uneven soil and grasping of the surface. The legs can be equipped with the mission necessary tools, and can be used as well for simple manipulations in cooperation with other similar robots. This could be used in application such as sampling returns, sensor positioning, and surface processing like digging, scratching, or piercing the soil even when in two wheeled mode.

LEON has two locomotion modes that can be activated manually or automatically, depending on the soil conditions, where the robot’s body pose or speed is controlled (Fig. 2): Wheel mode: In this locomotion mode, LEON is using a differential drive model which allows the control of the speed and orientation of the body, where \( \omega_0 = (VR-VL)/L \) and \( v_0 = (VR+VL)/2 \). \( VR \) and \( VL \) are the left and right wheel velocities, and \( L \) is the distance between the two wheels. Also, \( v_0 \) and \( \omega_0 \) are respectively the linear and angular velocities of the body. At this stage there is no balance control like a Segway, but four caster wheels are temporarily located at the end of the non transformable limbs, to ensure the stability of the body when roving.

Leg mode: In this locomotion mode, LEON’s motion is omnidirectional, using a tripod gait for the motion control. The end tips of the legs are equipped with force/torque sensors to detect contact. The control parameters are the heading, the actuators’ speed, and the step length. From those parameters we derive \( v_0 \), the speed of the body, as the control parameter for the body’s pose.

For both locomotion modes, the control parameters allow path following, for a higher level of control. The robot’s position is denoted by \( P \), the shortest distance projection of \( P \) to the reference path is \( P_d \). Moreover, \( le \) is the signed distance between \( P \) and \( P_d \) (distance error); \( \theta_d \), the angle between the x-axis and the tangent to the path at \( P_d \) (vehicle’s desired orientation in wheel mode); and \( \theta_e \), is the orientation error in wheel mode (\( \theta_0 - \theta_d \)). A feedback control law is applied, to satisfy both \( le \to 0 \) and \( \theta_e \to 0 \) in wheel mode, or \( le \to 0 \) only, in leg mode.

2.2. Transformation of locomotion mode

LEON demonstrates the novel concept of hybrid leg wheels as discussed in section 2.1. LEON is designed to transform from a walking-mode, to a wheel-mode, where the locomotion changes from legs to two large wheels. The hybrid legs fold in on themselves, curling dynamically to create a wheel. The exterior of the hybrid wheel-legs have a rubber and foam shell, which when the legs are folded, forms a round wheel capable of supporting LEON on the rugged lunar terrain.

To safety transition from six-legged walking-mode to wheel-mode the criterion of space, terrain bumpiness and terrain gradient, all need to be satisfied. To initiate the switching phase between the respective modes, an area clear of obstacles and debris 300mm in radius is required. This can be determined either by prior knowledge of the terrain, or by taking a local scan using the onboard Laser Range Finder (LRF). This prevents any collisions between the limbs and the environment during the switching phase. The terrain bumpiness also needs to be calculated to ensure the ground can provide a stable enough base for transformation. The terrain bumpiness is determined using Eq. (1) in section 4.3. If the terrain bumpiness is lower than a certain threshold, which needs to be defined empirically after the hardware is further developed, then it is safe to initiate the switching phase. The terrain gradient can be calculated using the onboard inclinometer if not priory known. This ensures that the gradient of the terrain will allow locomotion in the final mode, after
The transformation or switching phase can begin once the above criterion has been satisfied. LEON first creates a stable base, and then lifts its main body up away from the ground, with the four non-hybrid legs (Fig. 3a). The legs are spread at a broad angle to increase the stability of the transformation, whilst not interfering with the hybrid legs. The hybrid legs then lift the ground and swivel into LEON’s main body (Fig. 3b). This allows the hybrid legs to begin to rotate. As the wheel begins to rotate, the hybrid legs fold in on themselves, beginning to form the wheel (Fig. 3c). This style of wheel formation avoids collision between the hybrid legs and occluded obstacles. If the leg was simply to fold in and form a wheel, small debris could get caught in the mechanisms and reduce functionality. Finally, once the wheels are formed, the body is lowered to the surface by the four non-hybrid legs (Fig. 3d). The hybrid wheels are then able to take the load applied by LEON’s mass and begin locomotion. In the case of transforming from wheel to leg mode, the reverse process is used, from Fig. 3d to Fig. 3a.

3.3. Current implementation of LEON

In this section we detail the architecture of LEON’s prototype. As this research is a proof of concept, we used servo motors to simplify the control of the motion to build LEON’s prototype. Fig. 4 shows the hardware architecture of LEON.

The Navigation sensor level provides information to navigate and build the 3D environment. While the camera is used for video feedback, using it for visual odometry and trajectory correction in wheel mode is also planned. The laser range finder mounted on a servo allows a 3D digitalization of the environment around the robot.

The body level is the spinal column and the brain of the robot. It centralizes all the data coming from and going to the operator and the actuator/sensors in the main CPU. The main CPU owns the controller and navigation algorithms. The inertia sensors (inclinometers and accelerometers) are also located at this level, for a future posture control and odometry.

Attached to the body are the legs. There are two types of legs (hybrid and standard). Both own a hip, a knee, and an ankle servo that allows walking and simple manipulation. While the four standard legs are fixed to the body, the two hybrid legs are attached to a driving servo that allows the full rotation of the hybrid leg transformed into a wheel. While there is no wiring issue of the standard legs to the body, the continuous rotation of the transformed hybrid legs does not allow direct wiring of its actuators/sensors to the main CPU in the body. The use of sliprings or alternative wireless based (Bluetooth) solution is currently under investigation. Each Hybrid legs own a battery and will be totally independent from the body. The H8 board is used for data communication management between the main CPU and the hybrid leg.

The last level is the contact sensor level. Each legs end tip is equipped with a force/torque sensor to specify a contact with the ground or to maintain an object while manipulating it. The end tip sensors could also be used to define the topology of the close environment, in a similar way as an industrial 3D measuring machine would do.

Besides the wiring issue, one should notice that the hybrid wheel-limb system presented provides other challenges when in wheel mode. The folded legs’ center of inertia is difficult to align in the axe of rotation of the driving servo. Also, the working area of the limb mechanically prevents the wheel to be completely round. The holes in the wheel surface can be filled by a hinge mechanism as seen in Fig. 3. Other less kinematically complex technical solutions using rubber are under investigations, but this one allows hardening on the top of the holes for better driving performances.

3. EROde Telerobotic Platform

LEON is the first robot being used as a part of the telerobotic platform we are developing at the space robotic laboratory of the Tohoku University. In this section, we will describe the versatile dynamic engine based telerobotic platform called EROde, named after the author’s name and ODE 5) (Open Dynamic Engine). The versatility of EROde comes from its ability to handle many teleoperation types and from its use in all phases of a mission project: from the development until the real mission. After defining the required criteria for a telerobotic platform to become versatile, the authors will present the implementation of this concept into EROde.

3.1. Versatile telerobotic platforms for planetary exploration

A versatile telerobotic platform is a platform that is allowing any of the following kind of teleoperation
depending on the degree of autonomy of the robot presented in Fig. 5. In this figure are introduced three types of teleoperation based on the degree of autonomy of the robot on the mission:

- Remote Control: The mobile robot has a much reduced degree of autonomy, and all the commands are managed by the operator. This type is very sensitive to time delay and an appropriate control in this mode should not exceed few seconds of delay in the communication media.

- Supervisory Control: The operator is removed from the control loop as the robot is more autonomous. The human operator becomes a human supervisor whose work is less demanding depending on the autonomy of the robot (from simple motion planning embedded algorithms to path planning or mission planning).

- Offline Control: unlike the two previous control types, this is a discontinuous process. The robot on the mission can have any degree of autonomy and any delay is acceptable, as the actions of the robot are simulated on Earth prior to be sent and replayed by the robot on the site. The drawback of this method is that the environment needs to be accurately reconstructed and very static for low autonomy robots. This mode is widely used in space missions (for example MER missions) to deal with very large time delays (minutes or hours).

We also define as a versatile telerobotic platform, as a reusable and modular platform that is used in each step of the mission’s project: from the conception and tests until the mission itself. The platform’s simulation properties allows in the conception’s phase, the testing of motion algorithms under different environment conditions such as gravity or micro-gravity, or developing the control strategies before the hardware is ready. In the testing phase, the platform allows us to simulate a mission in realistic conditions of communication. Finally, during the mission, the platform is used to communicate with the robot, navigate it and complete the mission tasks.

3.2. Implementation of the Versatile concept

Erode is the next generation of distributed telerobotic platform for construction machines, developed by the authors and introduced in 6). Erode is “space oriented”, so has to deal with potential longer delays in the communication, more appropriate protocol of communication and different simulation conditions.

Erode is used at the development phase of the project as a simulator to develop and test the behavior of LEON on a mission. This can be done under time delay constraints using the INRIA RESO team’s robust interplanetary communication protocol, or to elaborate the control algorithm on a digital version of LEON in a virtual environment, or on a real robot in an unstructured environment.

During the mission, depending of the degree of autonomy of the robot, the robot can be manually teleoperated, supervised or controlled offline.

Fig. 6 depicts an example of configuration of Erode for the moon’s crater exploration mission. Erode is set for manual teleoperation as the delays between the Moon and Earth are short (few seconds).

In this configuration, the robot has a limited autonomy and the operator is directly controlling its heading, step size and actuators speed using the Remote Control application. The generated commands are sent to the mission site through the communication module forming TCP/IP packets of data.

The communication module is packetizing the stream of data into the interplanetary protocol developed by INRIA RESO team and is emulating hazard of communication like delay, desynchronization or disruption when the platform is tested before the mission.

On site, the Onboard Controller application is managing the motion of the robot, and collects the data from the Laser Range Finder for the 3D reconstruction of the environment. This application handles the low level control of the actuators, and gathers all the data that needs to be sent back to the operator for the navigation, through the communication module.

As the robot is manually teleoperated, the 3D Navigation application does not use Erode’s dynamic engine. It is used as a navigation tool only, where the environment of the robot is reconstructed using the LRF. The posture of the robot is provided to the operator based on the odometry data. Video feedback is also available.
4. Preliminary LEON’s Performances

We describe here the preliminary results of LEON’s performance, and when the hardware is not available or fully developed, ERode’s simulator used in its place. To collect the motion data of LEON’s prototype, a stereo-camera is positioned over the ground of the experimental test bed. Three infrared LEDs are fitted to LEON’s body allowing the stereo camera to track the motion of the robot. Simple calculations give us the position and orientation of the body any time during the experiment.

As LEON is still under development, we rely on the simulation under ERode’s dynamic engine to evaluate the preliminary characteristics of wheel locomotion. The virtual LEON’s specifications have been introduced into the simulator based on the actuator’s specification and CAD model dimensions and inertial parameters. To simplify the modelization and to complete the synchronization of the real and virtual world, the environment properties have been evaluated using two criteria only: the 3D shape of the environment and the static friction coefficient between the robot rubber end-tip and the ground, under Earth gravity. Static friction only is considered due to the relatively slow speed of the motion in both locomotion modes. The static friction coefficient for the following experiments was empirically estimated as 0.7 (rubber/stone). In addition, no deformations of the soil, the rubber in contact, or the robot limbs are considered, to simplify the simulations. The simulator provides the necessary data as posture and speed of the body, or torques and forces in the actuators.

4.1. Mechanical limitations.

Due to the brackets design in the second part of the limbs, LEON’s prototype does not allow the knee (the second actuator) to open more than 90° as seen in Fig. 7. The current tripod gait algorithm allows the robot to overcome obstacles not higher than 105[mm], while keeping the body posture parallel to the ground. This limitation of the hardware can be avoided by a simple modification of this bracket. The robot would be able to walk over higher obstacles but special care would need to be taken in the redesign of the hybrid legs to allow the wheel configuration.

4.2. Performances of LEON on a slope.

In leg mode, LEON is walking on an increased slope to estimate the maximum inclination it can handle without slippage. The simulation is run in the same conditions to verify the synchronization between the real world and the virtual one. When the limit of a servo’s torque is reached (2.9[Nm]), it shuts down and the motion can not continue. Fig 9a shows the simulated and measured maximum torque recorded during a motion on a slope. First, we can observe that the experimental and simulated results show similar torques under same slope constraints. Hence, we can conclude that ERode provides an accurate simulation of LEON. Second, we can read from Fig. 9a that the maximum slope LEON can walk on Earth gravity is 44°.

In wheel mode, as the hardware is not ready yet, we only present the simulation results in Fig. 9b. The maximum torque each of the drive servos is providing is 6.4 [Nm]. Slippage occurs before the torque limit is reached in both case of higher grip (on rock) and lower grip (on sand) with respective friction coefficients of 0.7 and 0.3. The maximum slope LEON can climb is then about 22° on sand and 35° on rocks.

4.3. Performances of LEON on a rough terrain

In order to evaluate the performances of LEON on a rough terrain, we define B, the index of bumpiness of the terrain. B is given as the standard deviation of the terrain elevation over the region $R_i$ the robot is crossing for the experiment 6):

$$B = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (z(R_i) - \bar{z}(R_i))^2} \quad (1)$$

As shown in Fig. 10, the region $R_i$ includes the set of
terrain elevation points inside the region the robot is crossing, in wheel or leg motion mode. In Eq. (1), \( n \) represents the number of node inside the region and \( z(R_i) \) and \( \Sigma(z(R_i)) \) respectively denote the elevation of the node and an average elevation in \( R_i \). The rougher the terrain is, the larger \( R_i \) becomes.

![Fig. 11. Experimental and reconstructed terrain from LRF data](image)

A Laser Range Finder located on the top of the scene is used to scan the rough environment of Fig. 11a. Its data are generating the Digital Elevation Map in EROde seen in Fig. 11b and the heights on \( R_i \) used to compute the roughness of the terrain \( B \) from Eq. (1). LEON’s position is recorded as previously described. The Experimental protocol is that different sizes of stones are placed on the path of LEON. The experiment is successful if LEON, traveling straight, can cross the 1.2m goal ahead of it. For the walking motion, we use the real LEON, and for the driving one, the virtual model of LEON is used to drive over the 3D reconstructed experimental setup. We used three sets of terrain with an increased roughness for this experiment: low roughness \( B < 0.04[m] \), middle roughness \( 0.04[m] < B < 0.06[m] \), and high roughness \( B > 0.06[m] \). For each terrain, stones of about the same caliber were homogeneously distributed on the surface to be scanned. The first set of stones has a diameter of \( 0.04[m] \) with \( B = 0.03[m] \). The second one has an average size of \( 0.092[m] \) with \( B = 0.08[m] \). The last set of stones has an average of \( 0.13[m] \) and \( B = 0.1[m] \).

![Fig. 12. Measured leg and simulated wheel motions on rough soil](image)

Fig. 12 shows the results of the experiment in leg mode (Fig. 12a) and the simulation in wheel mode (Fig. 12b), across rough terrains. The simulation is based on the DEM, so the dynamic of the reconstructed stones is not taken into account. When the simulated LEON drives over stones in the virtual environment, the stones would remain static. In the real world, they could be moved due to the traction force the wheels apply on them.

As expected, LEON leg mode is more able to cross rougher terrains than in wheel mode. The rougher terrain LEON could cross in leg mode is for \( B = 0.08[m] \) and failed at \( B = 0.1[m] \). In wheel mode, LEON’s simulation could not cross the rough section with a roughness index \( B = 0.08[m] \).

5. Conclusion and Future work

In this paper we introduced the Lunar Exploration Omnidirectional Netbot (LEON), a novel type of hybrid wheels / limbs hexapods for challenging terrains. The required transformation phases have also been presented. LEON’s versatile telerobotic platform EROde, was depicted. EROde owns a dynamic engine for simulation and is allowing any type of teleoperation. We proposed a configuration for EROde, to address a mission of lunar’s crater exploration for \( H_2O \) prospection.

EROde’s accuracy was confirmed through a comparison between experimental and simulated results. Then LEON’s preliminary performances have been gathered either experimentally or simulated through EROde.

Further hardware development is required to obtain more specifications on LEON’s potential, especially concerning the implementation of the wheel mode. Investigations to make LEON more autonomous, in order to allow supervisory control, are also considered. A human supervisor could select a point of scientific interest, and depending on the topology and on the performance, LEON would automatically select the optimal path to reach it. It would also define in which locomotion mode the path should be addressed (path and action planner).

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