Path planning and terramechanics coupling for rovers in rough lunar terrain

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Abstract – It is proposed the research of soil-wheel contact models, known as terramechanics, and integrating those models into path planning algorithms. The coupling of these two domains will enable the development of path planning systems for space explorations rovers in rough terrains. The proposed approach has three main applications. First, terramechanics simulations enable the trafficability evaluation of the terrain, so the paths will be generated to minimize the risk of the rover getting stuck. Second, the energy necessary to drive depends on how much the rover sinks or slips. The proposed simulation will estimate the energy consumption beforehand, and choose paths of minimum energy consumption. And third, it will enable the development of a control system based on marks left by wheels in the soil. The simulation would be used to train such a system. It is planned to validate the developed simulations in a soil-wheel test bed of Tohoku University. Afterwards, tests will be performed with a lunar rover prototype at University of Luxembourg. This research is part of an ongoing project partially founded by a CAPES-PrInt scholarship and will be in cooperation with institutions of Luxembourg, USA and Japan. The simulation platform proposed will help the Japan partners who are developing rovers to search for water on the Moon.

Keywords – terramechanics, rover, path planning, lunar water.

1. Introduction

It is proposed the research of soil-wheel contact models, known as terramechanics, and integrating those models into path planning algorithms. The coupling of these two domains will enable the development of path planning systems for space explorations rovers in rough terrains. The research is a part of the ongoing project partially founded by a CAPES-PrInt scholarship, "Simulation platform as testbed for high and low level control of the Sorato lunar water prospecting robot under realistic conditions". The proposed approach has three main applications: 1 – safe paths, 2 – minimum energy consumption, and 3 – control by camera. First, terramechanics simulations enable the trafficability evaluation of the terrain, so the generated paths will avoid very rugged regions, minimizing the risk of the rover slipping or getting stuck. Second, the energy necessary to drive depends on how much the rover sinks or slips, which is dependent on the slopes and level of aggregation of the terrain. The proposed simulation will estimate the energy consumption beforehand, and choose paths of minimum energy consumption. Third, in a simulation that features terramechanics, the rover wheels will leave marks on the soil. That will enable the future development of a system that uses the rover camera and sensors to control a straight path based on soil marks.

Space exploration missions involving astronauts are more expensive and dangerous than using rovers. On the other hand, there are interactions that occur in the wheels of rovers that must be studied in other to achieve a safe ride. Some of the phenomena that can occur between the rover and the lunar regolith is side slippery, when the rover is traversing a slope, or accumulation of soil around a wheel that can make it stuck. Getting stuck is specially critical for space missions, by not having means to unstuck a vehicle, this can jeopardize a multi-million dollar program. By means of experiments and simulation, the conditions that could hinder a rover stuck can be predicted and prevented.

The technology of space exploration rovers can also be applied to drive in rough terrains found in disaster sites. Dr. Eric Rohmer, while working in the Space Robotics Laboratory has helped the development of the hardware and software of the Quince rescue robot. This robot has faced a real challenge in 2011 when a tsunami hit the East cost of Japan, resulting in the Fukushima nuclear accident. The environment inside the plant was too dangerous for anyone to walk inside. Three Quince robots were retrofitted to carry sensors and enter the accident environment to perform several mapping, inspection and radiation sensing missions inside the Fukushima power plant [1].

Simulation software play an important role in the development of robot hardware and software. They help reducing the cost and time that would otherwise be spent in numerous prototypes and tests. Conversely, simulation helps to define which experiments are more important, hence resources can be focused. Today, the two most popular simulation software for robotics are CoppeliaSim and Gazebo, according to [4], [7] and [10].

CoppeliaSim and Gazebo are able to address multibody dynamics simulations, where several rigid body elements connect and move relative to each other, these are used to simulate the moving parts of a robot. What those simulators lack though, is the ability of performing simulations considering a deformable medium, like tires and soil. Terramechanics is the field that deals with the dynamics of the contact between a wheel and the soil. When the focus is in robot that use legs rather then wheels, the term Terradynamics is preferred. [6] Terramechanics allows to determine the effect on the wheels, i.e loads, as well the effects on the soil, i.e. the wheel impressions. Moreover, a simulator with a realistic terramechanics model can be used as a tool to train machine learning algorithms for many kind of situations, like path planing, slippery detection, path following, optimal exploration or swarm control strategies.

The developed terramechanics models will be integrated as APIs in the robot simulation software CoppeliaSim (previously called V-REP). CoppeliaSim is developed by Coppelia Robotics, a company based in Zurich, Switzerland and managed by Dr. Marc Freese. The supervisor of this research, Dr. Eric Rohmer, has collaborated in the development of CoppeliaSim, notably in the development of APIs [9]. An advantage of using CoppeliaSim in this research is having easy access to the main developer, Dr. Marc Freese, that will be helpful if issues arise during the integration of the terramechanics API into the simulator.

2. Proposal

It is proposed the development and coupling of terramechanics and path-planning models. The models will be integrated as plugins into the robot simulator CoppeliaSim (former V-REP). Then, CoppeliaSim with the plugins will be used to simulate the motion of a rover in lunar regolith. This would allow obtaining paths that are optimum in terms of safety against the risk of getting stuck and energy saving. It will also make possible to represent marks left in the soil by wheels, see figure 1 for an example. Future research can use these wheel marks to develop control based on marks captured by the rover camera. Besides simulation, tests in a single-wheel test bed will be used to calibrate the parameters of the terramechanics model. Then, a rover prototype, Explorer 1 (EX1) will be used to validate the developed models. The rover EX1 is being developed in the Space Robotics Lab at Tohoku University, Japan. The supervisor of this research, Dr. Eric Rohmer, participated in the development of rovers for space exploration [8] as a post doc and researcher at Tohoku University. Nowadays Dr. Eric Rohmer is in active collaboration with the Space Robotics Lab. The simulator used in this research, CoppeliaSim, was developed by the Swiss company Coppelia Robotics. Dr. Eric Rohmer also participated in the development of CoppeliaSim and collaborated with plugins.

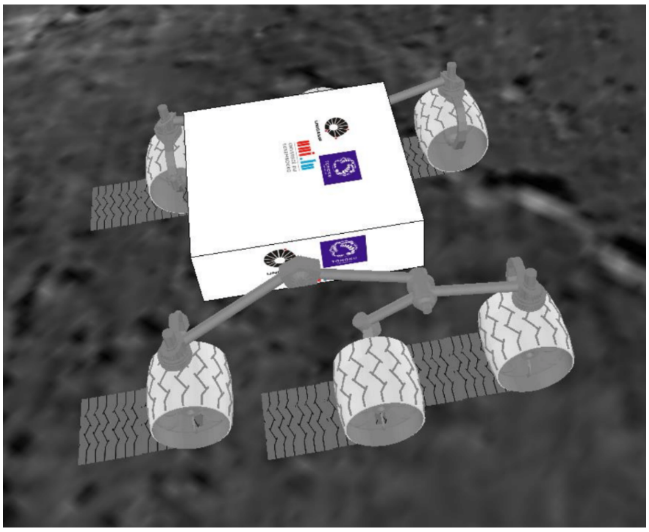

Figure 1. Wheel marks.

The locomotion dynamics can exhibit longitudinal and lateral slip. Longitudinal slip is measured by the slip ratio, which is the ratio between the circumference velocity of the wheel and the longitudinal traveling velocity of the vehicle [3], expressed by the equation:

$$s = \left\{ \begin{array}{ll} (r\omega - v_x)/r\omega & (r\omega > v_x : driving) \\ (r\omega - v_x)/v_x & (r\omega < v_x : braking) \end{array} \right\}$$

The lateral slip is measured by the slip angle, which is the arc-tangent between the lateral and longitudinal traveling velocities [3], given by the expression:

$$\beta = arctan(v_y/v_x)$$

To understand the phenomena that takes place between a wheel and granular media, three approaches can be used: experimental, analytical and numerical simulation. For the later option, a useful tool is the Discrete Element Method. Figure 2 shows a contact model of two particles, the basis for the Discrete Element Method.

A terramechanics model will be implemented in the C++ programming language. It will then be integrated

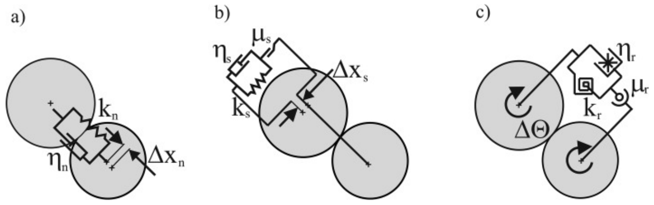

Figure 2. Contact model for Discrete Element Method [2]. Reactions forces of the type normal (a), tangential (b) and rolling (c).

as a plugin in the CoppeliaSim robot simulator. Experimental validation of the terramechanics model will be carried out in the test bed of Space Robotics Lab. The experimental setup is shown in figure 3. In this setup, the conveyance and the wheel can be drive independently by motors, this allows to vary the slip ratio as desired. The steering part enables to choose a steering angle. As the conveyance moves in a single direction, the steering angle is equivalent to the slip ratio β. With a force and torque sensor it is possible to measure forces in 3 directions and torques in 3 directions.

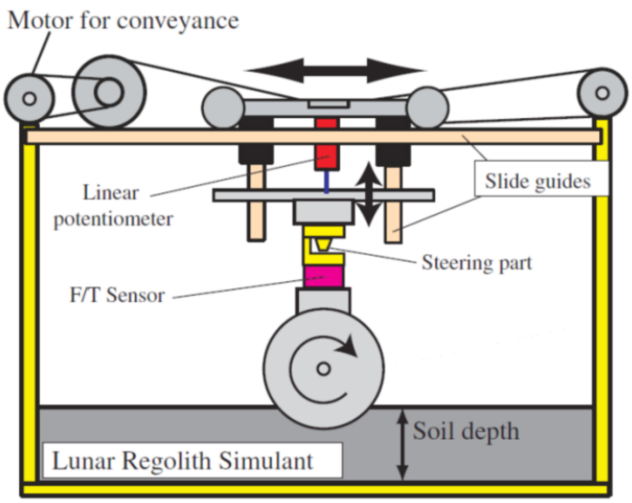

Figure 3. Terramechanics experimental setup to measure forces in a single wheel. [3].

2.1. Objectives

The proposed research intends to meet the following objectives:

1. Study existing terramechanics models, implement and compare them regarding accuracy and computational cost. Calibrate and validate models in a single-wheel test bed;
2. Implement models in C++ for fast computation and integrate in CoppeliaSim. This will help Tohoku University researchers in rover development;
3. Develop new path-planning models, that consider trafficability evaluation and terramechanics simulations. Run simulations to verify capabilities of safe and energy efficient path generation;
4. Run simulations of a real rover, EX1, in CoppeliaSim, aiming for accurate simulation of lunar conditions. Perform laboratory tests with rover EX1 to validate the simulations.

Figure 4 shows the Lunar Testbed of Luxembourg University, where it is intended to accomplish objective 4.

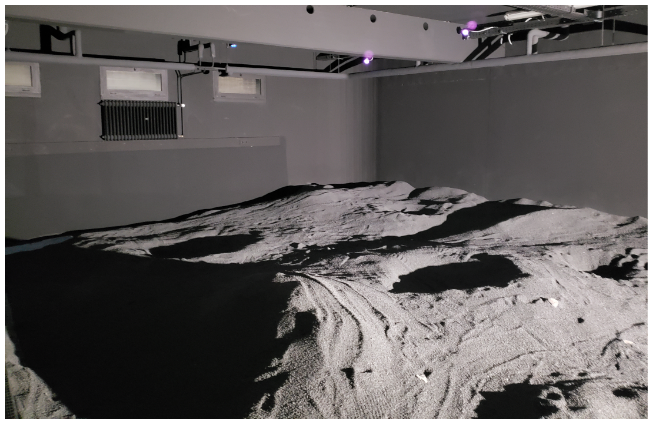

Figure 4. Luxembourg lunar test bed.

3. Expected Results

There are two aspects that will be analysed and validated: the rover simulation platform and the terramechanics path planner. The lunar test bed experimental setups of universities of Luxembourg and Tohoku are important to validate the rover simulation platform. Once it is validated, it can be used to evaluate the performance of the terramechanics path planner.

3.1. Validation of the rover simulation platform

In the lunar test bed, it will be prepared a terrain topology set up. Then that terrain topology will be scanned to create a digital elevation map. Wherefore we will have two versions of the same terrain topology, one real and other virtual. In that topology we propose two paths, one straight line path connecting two spots, and one path with curves. Those two paths are then run in the rover simulation platform and in the lunar test bed with the rover prototype. The energy consumed during the runs are recorded and compared, simulation versus experimental test. Depending on the difference found, the rover simulation platform will be considered validated, otherwise further refinements will be implemented.

3.2. Performance analysis of the terramechanics path planner

The evaluation of the proposed path planner will have two goals:

1. Check whether the terramechanics path planner is able to generate safer paths (less risk of getting stuck) compared to reference path planners.
2. Check whether the terramechanics path planner is able to generate paths with lower energy consumption compared to reference path planners.

The path planners used as reference for comparisons will be A*, RRT [5] and RRT*. For goals 1 and 2, candidate paths are generated in reference path planners and in the terramechanics path planner. Then, those candidate paths are run in the rover simulation platform and in the lunar test bed. After those runs, it is compared the number of times the rover got stuck and how much energy was consumed in the path.

4. Conclusion

With the scientific literature perused it was possible to find relevant gaps in the research area and thus define a research subject. This field is particularly interesting for research because the technologies of terramechanics and path planning has broad application like self-driving cars, off-road vehicles, agricultural robotics, and socially assistive robots.

Acknowledgments

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