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A Framework for Designing Excavating Rovers in Low-Gravity Environment Using Project Chrono

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1 Introduction

To establish a sustainable human habitat on the lunar surface, NASA embraced an In-Situ Resrouce Utilization (ISRU) paradigm to harness natural resources, such as minerals and ice water, for oxygen extraction, fuel production, and habitat construction. NASA is evaluating a robotic excavator, Regolith Advanced Surface Systems Operations Robot (RASSOR) and similar designs for efficient regolith extraction and transport. During the digging phase, RASSOR uses two counter-rotating bucket drums on the opposite arms to provide minimum reaction force in both horizontal and vertical direction, allowing a lightweight design. The rover then raises its drums when traveling to the dump location, where it unloads by rotating the drums in opposite directions. Additionally, the drums can assist mobility over steep terrain with both drums in contact with the soil. Autonomous policies are being developed for various tasks to reduce power consumption and improve traction. Gazebo has been used previously to simulate the lunar environment [1]; however, Gazebo does not provide support for modeling and simulating deformable terrain, necessary for capturing the interaction between the regolith and the drum. To address this, an open-source multi-physics simulation platform, Project Chrono [2], is used to provide the simulation framework for the rover and its interaction with the lunar terrain at different levels of fidelity.

2 Rover Model

RASSOR, whose mass is 66 kg, is equipped with four wheels and two arms. Each arm is connected with a rotating bucket drum for excavating the soil, see Fig. 1. The rover has a rigid suspension and a skid-steering mechanism, with only one rotational actuator on each wheel. The rover model will be available in the Project Chrono Github repository. Cosimulation can be performed between the rover and different Chrono modules that support various deformable terrain types, e.g., Chrono::Vehicle for SCM terrain, Chrono::FSI for CRM terrain, and Chrono::DEM for DEM terrain.

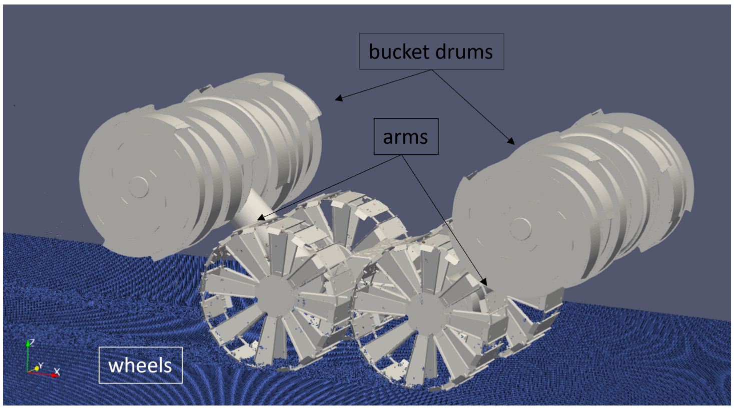

Figure 1: RASSOR setup on CRM terrain.

3 Terrain Model - Continuum Representation Method

Chrono::FSI supports a new terramechanics model called Continuum Representation Method (CRM) to characterize granular terrain when represented as a continuum. The CRM approach in Chrono draws on the framework of Smoothed Particle Hydrodynamics (SPH), a Lagrangian-based solution that requires no background grid. A constitutive model is employed to capture the elasto-plasticity of the granular material with large deformation; see [3] for details. In CRM, the velocity field **u** and the Cauchy stress tensor $\boldsymbol{\sigma} \in \mathbb{R}^{3\times 3}$, enter the mass and momentum balance equations as:

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = -\rho \nabla \cdot \mathbf{u}\,, \quad \frac{\mathrm{d}\mathbf{u}}{\mathrm{d}t} = \frac{\nabla \boldsymbol{\sigma}}{\rho} + \mathbf{f}_b\,, \tag{1}$$

where ρ is the density of the terrain and $\mathbf{f}_b$ is the external force. The stress tensor $\boldsymbol{\sigma}$ is split into two components as $\boldsymbol{\sigma} \equiv -p\mathbf{I} + \boldsymbol{\tau}$, where $p = -\frac{1}{3}\mathrm{tr}(\boldsymbol{\sigma})$ is the pressure and $\boldsymbol{\tau}$ is the deviatoric component of the total stress tensor. For closure, a stress rate tensor formula is employed,

$$\frac{\mathrm{d}\boldsymbol{\sigma}}{\mathrm{d}t} = \dot{\boldsymbol{\phi}} \cdot \boldsymbol{\sigma} - \boldsymbol{\sigma} \cdot \dot{\boldsymbol{\phi}} + 2G[\dot{\boldsymbol{\varepsilon}} - \frac{1}{3}\mathrm{tr}(\dot{\boldsymbol{\varepsilon}})\mathbf{I}] + \frac{1}{3}K\mathrm{tr}(\dot{\boldsymbol{\varepsilon}})\mathbf{I}\,, \tag{2}$$

where $\dot{\boldsymbol{\sigma}}$ and $\dot{\boldsymbol{\varepsilon}}$ are the elastic and rotational strain rate tensors, respectively, computed from the velocity gradient $\nabla\mathbf{u}$; K is the bulk modulus of the material. The plasticity strain rate and shear stress are updated according to the $\mu(I)-$rheology model. Table 1 lists the CRM parameters for lunar regolith.

Table 1: CRM solver parameters (SI units).

kernel size	step size	soil density	Youngs modulus	Poisson ratio	μ_2	μ_s	particle diameter
4×10^{-3}	2×10^{-4}	1734	1×10^{6}	0.3	0.9	0.8	5×10^{-3}

4 Terrain Model - Discrete Element Method

For higher fidelity simulation, we use Chrono::DEM [4], a fast GPU-based solver for handling clump-shaped particles. In DEM, the contact force and torque at the area of contact can be evaluated based on the material properties and contact laws. The rover parts that interact with soil can either be modeled with a triangular mesh or a cluster of particles using sphere decomposition. Figure 2 shows snapshots of the drum traversing a bin of two-meter length and digging at different prescribed angular velocity. The vertical motion of the drum is unconstrained, while the lateral one is constrained. The images show the drum once it reached the end of the soil bin. Approximately similar amount of material is dug up after traveling the same distance regardless of the drum speed.

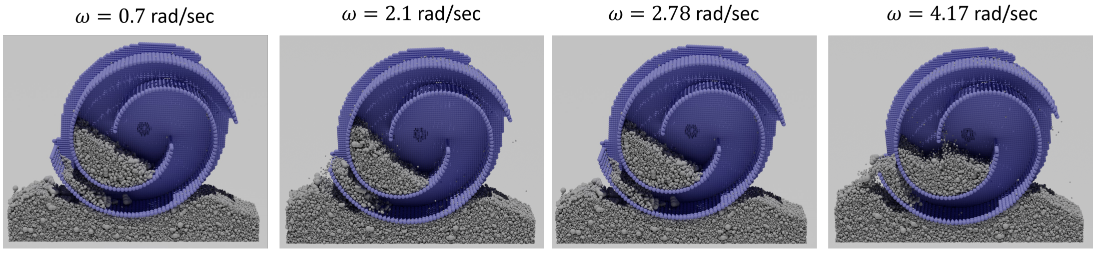

Figure 2: Snapshots of RASSOR drum digging at different rotation speed using Chrono::DEM. Front side wall of the drum not visualized.

References

[1] EZRASSOR Team. *EZRASSOR*. GitHub repository. `https://github.com/FlaSpaceInst/EZ-RASSOR`, 2021

[2] A. Tasora, R. Serban, H. Mazhar, A. Pazouki, D. Melanz, J. Fleischmann, M. Taylor, H. Sugiyama, D. Negrut. "Chrono: An open source multi-physics dynamics engine." *High Performance Computing in Science and Engineering – Lecture Notes in Computer Science.* Springer International Publishing, 2016.

[3] W. Hu, M. Rakhsha, L. Yang, K. Kamrin, D. Negrut. "Modeling granular material dynamics and its two-way coupling with moving solid bodies using a continuum representation and the SPH method." *Computer Methods in Applied Mechanics and Engineering.* 385, 114022, 2021.

[4] R. Zhang, B. Tagliafierro, C. Vanden Heuvel, S. Sabarwal, L. Bakke, Y. Yue, X. Wei, R. Serban, D Negrut. "Chrono DEM-Engine: A Discrete Element Method dual-GPU simulator with customizable contact forces and element shape." *arXiv*, preprint arXiv:2311.04648, 2023.