CISE-1835674 – Collaborative Research: Elements: Software: NSCI: Chrono - An Open-Source Simulation Platform for Computational Dynamics Problems

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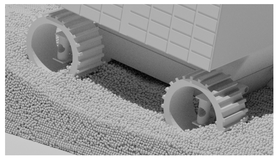
Project Overview

View Chrono on GitHub | View Videos on YouTube

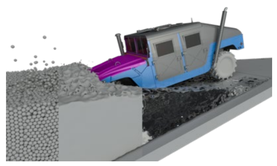
Project Chrono: open source multi-physics simulation engine for robots, AVs. Open source, freely available.

- Chrono software development under this project focused on two areas:
  - Discrete Element Method (DEM): The goal is to accurately simulate (or even fully resolve) granular motion that reveals physics insights with high performance.
  - Smoothed Particle Hydrodynamics (SPH): The goal is to provide an expeditious simulation solution that trades some accuracy for speed.



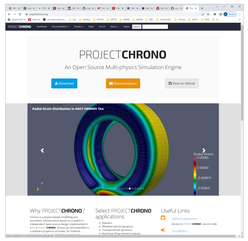
DEM (Chrono::GPU)

- Our Discrete Element Method (DEM) simulations aim to model granular materials in large scale.
- The goal is to accurately simulate (or even fully resolve) granular motion that reveals physics insights with high performance.



SPH-Based FSI (Chrono::FSI)

- Large-scale DEM-based granular simulations could still have bottlenecks in GPU memory, machine precision, runtime etc.
- Our **continuum** simulations via Smoothed Particles Hydrodynamics (SPH) can mimic granular behavior in certain schemes, while keeping the cost relatively low.
- About 10 to 100 times faster than DEM



Chrono software Infrastructure

- Chrono is a scalable, open source, BSD3 platform supporting research that draws on computational dynamics simulation
- Used by NASA for VIPER November 2023 Lunar mission, US Army, and by hundreds of individuals from academia, research labs, industry

Outreach

- Ran the 12th and 13th editions of the "Promoting the Computational Science Initiative" (ProCSI)
- ProCSI brings to University of Wisconsin-Madison students from predominantly underrepresented groups. Six day camp is free
- In 2022: 13th edition of ProCSI-H for high-school students, and 1st edition of ProCSI-C for college students (from Cal State Los Angeles

References

A. Tasora, R. Serban, H. Mazhar, A. Pazouki, D. Melanz, J. Fleischmann, M. Taylor, H. Sugiyama, and D. Negrut. 2016. "Chrono: An Open Source Multi-physics Dynamics Engine". http://projectchrono.org.

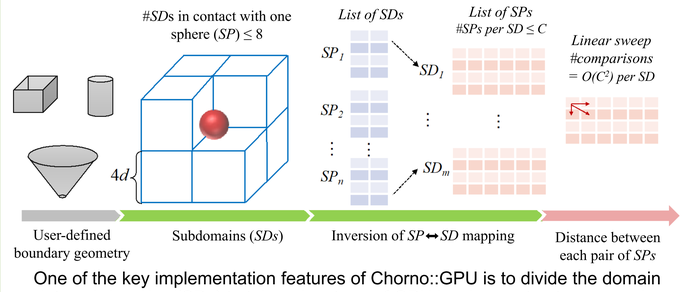
Luning Fang, Ruochun Zhang, Colin Vanden Heuvel, Radu Serban, and Dan Negrut. 2021. "Chrono::GPU: An Open-source Simulation Package for Granular Dynamics using the Discrete Element Method".

Radu Serban, Michael Taylor, Dan Negrut, and Alessandro Tasora. 2019. "Chrono::Vehicle: template-based ground vehicle modelling and simulation". *Int. J. Veh. Perform.* DOI: https://doi.org/ 10.1504/IJVP.2019.10018132

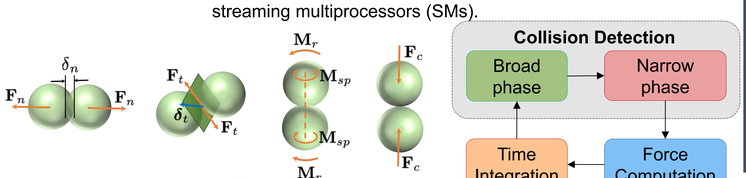
Wei Hu, Milad Rakhsha, Lijing Yang, Ken Kamrin, and Dan Negrut. 2021. Modeling granular material dynamics and its two-way coupling with moving solid bodies using a continuum representation and the SPH method. *CMAME.* DOI: https://doi.org/10.1016/j.cma.2021.114022

Aaron Young, Jay Taves, Asher Elmquist, Radu Serban, Dan Negrut, Simone Benatti, and Alessandro Tasora. "Enabling Artificial Intelligence Studies in Off-Road Mobility Through Physics-Based Simulation of Multi-Agent Scenarios".

Chrono::GPU – DEM Granular Dynamics



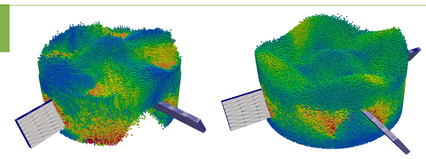
One of the key implementation features of Chorno::GPU is to divide the domain into subdomains (SDs) to take advantage of GPU hardware structure, namely streaming multiprocessors (SMs).



$$\mathbf{F}_n^{ij} = f\left(\frac{\delta^{ij}}{2R}\right)\left(k_n\delta^{ij}\mathbf{n}^{ij} - \gamma_n\tilde{m}\mathbf{v}_n^{ij}\right),$$

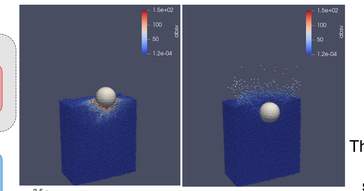
$$\mathbf{F}_t^{ij} = f\left(\frac{\delta^{ij}}{2R}\right)\left(-k_t\mathbf{u}_t^{ij} - \gamma_t\tilde{m}\mathbf{v}_t^{ij}\right) \text{ where } |\mathbf{F}_t^{ij}| \le \mu|\mathbf{F}_n^{ij}|$$

Normal contact forces, sliding friction forces, rolling and spinning frictions, as well as cohesion forces are included in Chrono::GPU's contact model. The friction forces are derived based on friction history.



This mixer demo with a scaling analysis on state-of-the-art GPUs showcases Chrono::GPU's support for large-scale simulations with history-based frictions, interaction with mesh-defined external objects, and linear scaling w.r.t. the size of the DEM problem up to 130M particles.

View on YouTube



This ball impact depth test showcases the co-simulation capability of Chrono::GPU, where the physics of external objects are also simulated rather than prescribed. The simulated impact depth matches the empirical relations well, validating Chrono::GPU.

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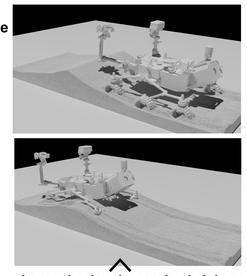
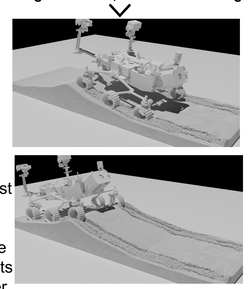


Low cohesion, large wheel sinkage

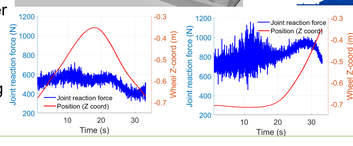
High cohesion, small wheel sinkage



View on YouTube Curiosity rover with low ground cohesion

View on YouTube Curiosity rover with high ground cohesion

Curiosity co-simulations with a fully-functional rover model and DEM granular terrain. We found the ground cohesion (viscosity) plays crucial roles in rover dynamics, and the amount of cohesion needed to match a type of terrain can be determined by an angle of repose test. Both DEM and SPH-based FSI are in support of NASA's 2023 moon mission.



Terrain reaction force vs location for the front and rear wheels. Chrono::GPU can conveniently extract simulation info for post-processing.

Chrono::FSI – SPH-Based Multiphysics

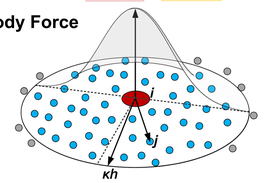
$$m\frac{d\mathbf{v}_i}{dt} = m\mathbf{f}_i + \sum_{i\neq j}\left(\mathbf{F}_n^{ij} + \mathbf{F}_t^{ij}\right) \qquad \frac{d\mathbf{u}}{dt} = \frac{1}{\rho}\nabla\cdot\boldsymbol{\sigma} + \mathbf{f}^b = -\frac{1}{\rho}\nabla p + \frac{1}{\rho}\nabla\cdot\boldsymbol{\tau} + \mathbf{f}^b$$

Normal Force/ pressure | **Friction/viscosity** | **Body Force**

SPH is a mesh-free Lagrangian method and it is used to discretize our governing equations.

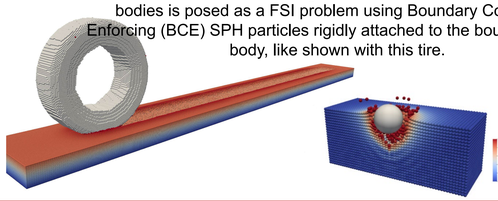
$$f(\mathbf{r}_i) = \int_V \frac{f(\mathbf{r}_j)}{\rho(\mathbf{r}_j)}W(\mathbf{r}-\mathbf{r}_j)\rho(\mathbf{r}_j)dV + O(h^2)$$

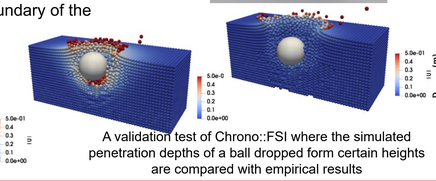
$$\approx \sum_{j\in\mathcal{S}(i)}\frac{m_j}{\rho_j}f(\mathbf{r}_j)W(\mathbf{r}-\mathbf{r}_j,h)$$



SPH approximates a function based on a spatial average of adjacent sampling points.

The interaction between the granular material and immersed rigid bodies is posed as a FSI problem using Boundary Conditions Enforcing (BCE) SPH particles rigidly attached to the boundary of the body, like shown with this tire.





A validation test of Chrono::FSI where the simulated penetration depths of a ball dropped form certain heights are compared with empirical results

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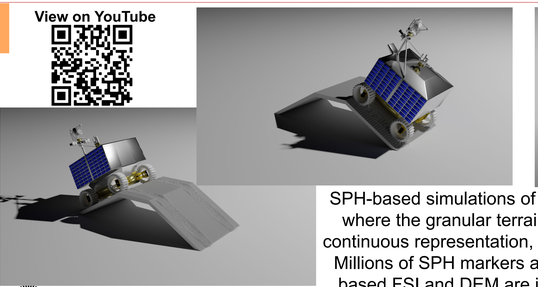

SPH-based simulations of VIPER and Curiosity, where the granular terrain is modelled with a continuous representation, then solved with SPH. Millions of SPH markers are in use. Both SPH-based FSI and DEM are in support of NASA's 2023 moon mission.

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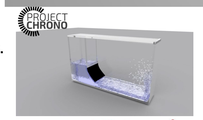
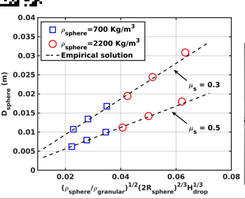


View on YouTube SPH simulation of dam break



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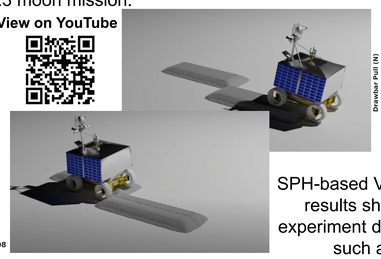
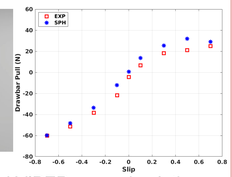


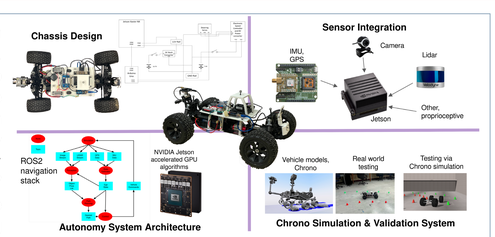


SPH-based VIPER rover simulation results show agreement with experiment data in terms of metrics such as drawbar pull.

Software Infrastructure

Latest release	7.0.2 (April 2022)
Website	projectchrono.org projectchrono.org/pychrono
Software	github.com/projectchrono/chrono anaconda.org/projectchrono/pychrono
Latest developments	github.com/projectchrono/chrono/blob/develop/CHANGELOG.md
Documentation	api.projectchrono.org (develop version) api.projectchrono.org/7.0.0 (release 7.0.2)
User forum	groups.google.com/forum/#!forum/projectchrono

The work in this project focused on Chrono::Granular and Chrono::FSI. Several other modules combine to make up Chrono: Chrono::Engine (the core dynamics solver, with support for rigid & flex body dynamics), Chrono::Sensor (sensor simulation for robotics and AV applications), SynChrono (scalable simulation of multiple agents using parallel computing), PyChrono (support for use of Chrono within Python), GymChrono (support for machine learning and AI).



Chrono builds on progress made in this project to assist other research projects. The picture shows another facet of Chrono, in which off-road simulation is used to design autonomy stacks in simulation. Rather than testing robots in the field, an ongoing project enables adjacent work at UW-Madison and several other universities that focuses on designing better robots.

Edu Outreach

ProCSI-H: SBEL has run ProCSI-H since 2008. Each year, a group of 15-20 students typically underrepresented in STEM, who most often come from low-income families, spend one, no-cost week on campus at UW-Madison. A thorough description of ProCSI's statement of purpose, activities, schedule, and 700+ pictures are available online. Since its inception, more than 200 high-school students from Wisconsin, Illinois, Tennessee, California, Missouri, Iowa, New Jersey, Guam, Minnesota, and Arkansas have participated in ProCSI.

2022 edition of ProCSI – 25 students of which 20 are part of ProCSI-H and 5 of ProCSI-C. Shown with other UW-Madison students involved in the ProCSI program. ProCSI is a volunteer program run by students in the Simulation-Based Engineering Lab at UW-Madison. For ProCSI-H students, the emphasis is on learning about engineering in general and computing in engineering in particular. For ProCSI-C students, the emphasis is on using simulation in robotics and research engagement with me members of SBEL.

The five Cal State Los Angeles students who spent two weeks at UW-Madison in July 2022 to learn about computer modeling & simulation. Shown here with their own robot, brought along from California. All five students are first-generation college students. Parents immigrated from Vietnam, Cambodia, Philippines, and Mexico (two of them). PIs Negrut & Shen shown in pic.