Open-Source High-Performance Computing for Applications in Engineering: DEM, SPH and Multi-Agent Vehicle Simulations with Project Chrono

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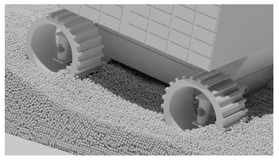
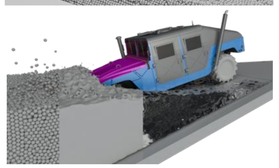
Application Overview



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.**

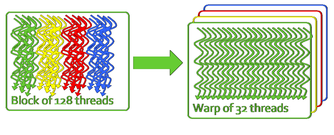


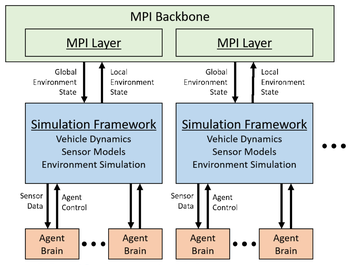
SPH-Based FSI (Chrono::FSI)

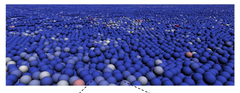
- Large-scale DEM-based granular simulations could still have bottlenecks in GPU memory, machine precision, runtime etc.
- Our **continuum** non-Newtonian fluid simulations via Smoothed Particles Hydrodynamics (SPH) can mimic granular behavior in certain schemes, while keeping the **cost relatively low.**

Multi-Agent AV (SynChrono)

- We aim to provide a scalable, **multi-agent platform** for physics-based **Autonomy Vehicle (AV)** development.
- It interacts with other Chrono modules (Chrono::Vehicle, Chrono::Sensor) and allows scaling to large numbers of vehicles.







DEM and **SPH-Based FSI** uses simulation elements (particles, SPH markers) that naturally bear a resemblance to CUDA threads. They thus employ GPU computing.

Multi-Agent AV leverages Chrono system for dynamics simulations and synchronizes the outcome of the dynamics between ranks using MPI.

Project Chrono, the open source multi-physics simulation engine that makes these researches possible, is freely available to the community.

View Chrono on GitHub

View Videos on YouTube

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".

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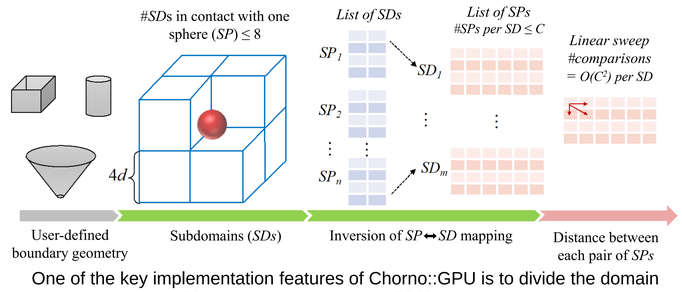
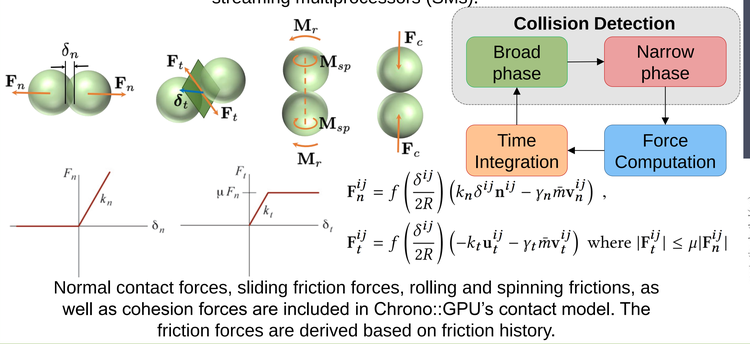
Wei Hu, Milad Rakhsha, Lijing Yang, Ken Kamrin, and Dan Negrut. 2021. Modeling granular material dynamics and its two-way coupling with moving solid bodies using a continuum representation and the SPH method. *CMAME.* DOI: https://doi.org/10.1016/j.cma.2021.114022

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



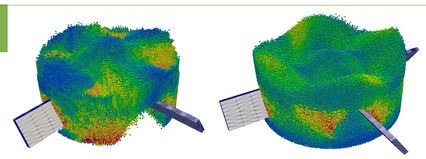
One of the key implementation features of Chorno::GPU is to divide the domain into subdomains (SDs) to take advantage of GPU hardware structure, namely streaming multiprocessors (SMs).



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

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

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.



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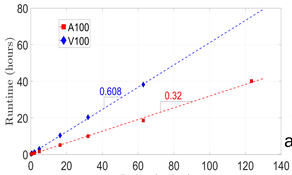
This mixer demo with a scaling analysis on state-of-the-art GPUs showcases Chrono::GPU's support for large-scale simulations with history-based frictions, interaction with mesh-defined external objects, and linear scaling w.r.t. the size of the DEM problem up to 130M particles.



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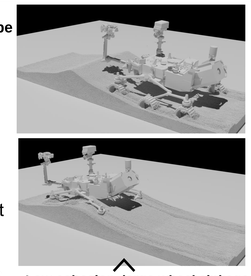
This ball impact depth test showcases the co-simulation capability of Chrono::GPU, where the physics of external objects are also simulated rather than prescribed. The simulated impact depth matches the empirical relations well, validating Chrono::GPU.



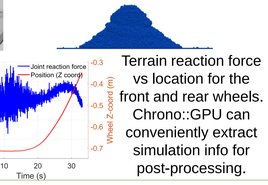
Low cohesion, large wheel sinkage

High cohesion, small wheel sinkage

View on YouTube Curiosity rover with low ground cohesion

View on YouTube Curiosity rover with high ground cohesion

12M DoF 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

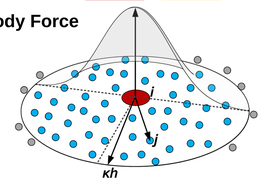
$$m\frac{d\mathbf{v}_i}{dt} = m\mathbf{f}_i + \sum_{i\neq j}\left(\mathbf{F}_n^{ij} + \mathbf{F}_t^{ij}\right) \qquad \frac{d\mathbf{u}}{dt} = \frac{1}{\rho}\nabla\cdot\boldsymbol{\sigma} + \mathbf{f}^b = -\frac{1}{\rho}\nabla p + \frac{1}{\rho}\nabla\cdot\boldsymbol{\tau} + \mathbf{f}^b$$

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

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

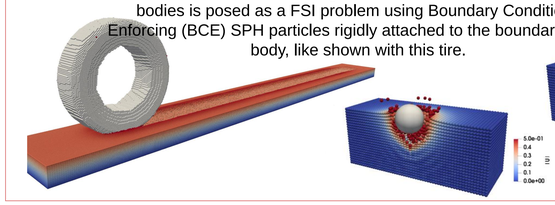
$$f(\mathbf{r}_i) = \int_V \frac{f(\mathbf{r}_j)}{\rho(\mathbf{r}_j)}W(\mathbf{r}-\mathbf{r}_j)\rho(\mathbf{r}_j)dV + O(h^2)$$

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

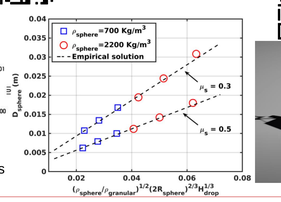


SPH approximates a function based on a spatial average of adjacent sampling points.

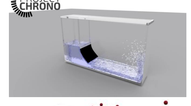
The interaction between the granular material and immersed rigid bodies is posed as a FSI problem using Boundary Conditions Enforcing (BCE) SPH particles rigidly attached to the boundary of the body, like shown with this tire.



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



View on YouTube SPH simulation of dam break



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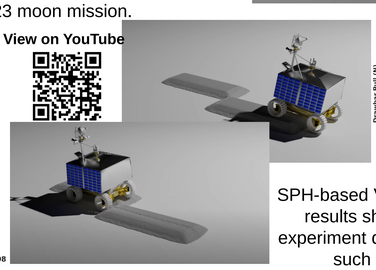

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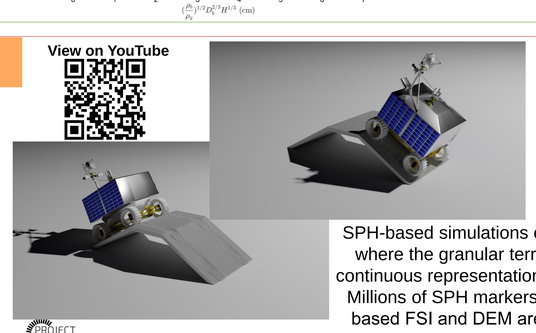
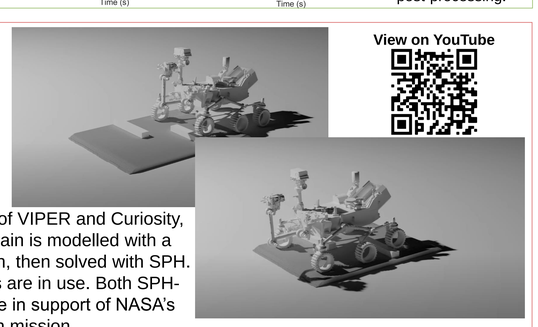
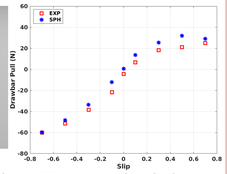


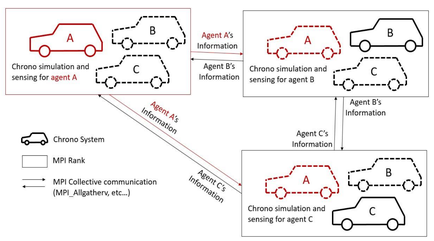
SPH-based simulations of VIPER and Curiosity, where the granular terrain is modelled with a continuous representation, then solved with SPH. Millions of SPH markers are in use. Both SPH-based FSI and DEM are in support of NASA's 2023 moon mission.





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

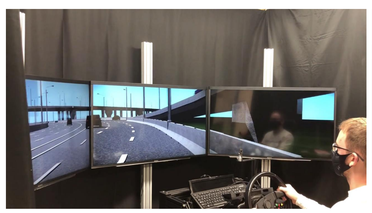
SynChrono – Multi-Agent AV Simulation



SynChrono enables distributed AV simulation through MPI

- Each rank uses a separate Chrono system
- State information is synchronized via MPI
- Scales to hundreds even thousands of vehicles
- Simulations (all three thrusts, SynChrono especially, DEM and FSI as well) are made possible with Euler, a heterogeneous supercomputer which employs a different hardware configurations to facilitate research and education at UW–Madison.

Learn more about Euler



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Human interaction through a dedicated physical simulator, in a virtual world simulating multiple vehicles.

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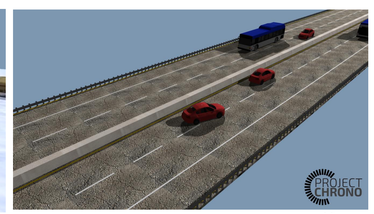
Vehicles interacting (via Chrono::Sensor) with the traffic light and many other vehicles in order to properly move through the intersection.

View on YouTube

Four vehicles navigate an obstacle field while maintaining a convoy on soft deformable (Bekker–Wong) terrain. Their behavior comes from a learned (through machine learning interface GymChrono) policy.



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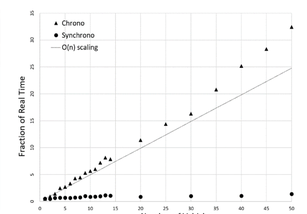
Human takeover of autonomous vehicle in a highway lane change scenario. Vehicle simulations running on rigid and deformable terrains are shown in this section; in the future development, the DEM and SPH terrain can also be potentially incorporated into SynChrono framework.



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Scaling analysis showing the strength of SynChrono is in coordinating Chrono::Vehicle and Chrono::Sensor (an instance of those modules is running on each rank), ensuring physics-based simulations of large numbers of vehicles run close to real time (fraction of real time = real world time / simulation run time).