Chrono: An Open-Source Multi-physics Simulation Package

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Overview. Distributed under a permissive BSD license, Chrono [1] is an open-source multi-physics package used to model and simulate (*i*) the dynamics of large systems of connected rigid bodies governed by differential-algebraic equations (DAE); (*ii*) the dynamics of deformable bodies governed by partial differential equations (PDE); (*iii*) first-order dynamic systems governed by ordinary differential equations (ODE); and (*iv*) fluid-solid interaction problems whose dynamics is governed by coupled DAEs and PDEs. Started almost 20 years ago, Chrono provides a mature and stable code base that continues to be augmented with new features and modules. The core functionality of Chrono provides support for the modeling, simulation, and visualization of rigid multibody systems with additional capabilities offered through optional modules. These modules provide support for additional classes of problems (e.g., deformable multibody systems through finite element analysis and fluid-solid interaction), for modeling and simulation of specialized systems (such as ground vehicles and granular dynamics problems), or for providing specialized parallel computing algorithms (multi-core, GPU, and distributed) for large-scale simulations [2]. We provide here a brief overview of current capabilities, ongoing efforts, and future developments.

Multibody and frictional contact. While providing a full-fledged multibody simulation framework, a unique characteristic of Chrono lies with its support for large-scale granular dynamics, i.e., simulation problems with millions of bodies interacting through contact and friction. For such problems, Chrono implements both non-smooth (NSC) and smooth (SMC) contact approaches. These two approaches lead to different forms of the equations of motion – differential variational inequalities (DVIs) and differential algebraic equations (DAEs) for NSC, and exclusively DAEs for SMC. NSC and SMC also differ in terms of their modeling capabilities, parameterizations, as well as in their computational complexity and amenability to parallel computing. A salient feature of Chrono is that it provides full-fledged support for both, making it a valuable open platform for testing new methods and approaches that target either NSC or SMC. The two approaches to frictional contact implemented in Chrono and Chrono::Parallel have been compared and validated in [3].

Nonlinear finite element. Chrono implements flexible body dynamics support for problems in which bodies are expected to sustain large deformations that take place while the body might experience large translational and/or rotational accelerations. For large deformations, Chrono currently resorts to the Absolute Nodal Coordinate Formulation (ANCF) for structural elements (beams, plates, shells) and a corotational (CR) approach for both structural and volumetric elements. The FEA implementations in the Chrono::FEA module were validated against analytical results and/or verified against commercial codes. Ongoing development effort focuses on improving computational performance and parallelization.

Ground vehicle modeling. Chrono::Vehicle makes available a collection of templates (parameterized models) for various topologies of both wheeled and tracked vehicle subsystems, as well as support for modeling of rigid or flexible tires, operation on granular terrain, support for closed-loop and interactive driver models, and run-time and off-line visualization of simulation results [4]. Chrono::Vehicle provides a comprehensive set of vehicle subsystem templates (tires, suspensions, steering mechanisms, drivelines, sprockets, track shoes, etc.), templates for external systems (powertrains, drivers, terrain models), and utility functions for vehicle visualization, monitoring and collection of simulation results. Vehicle-level validation studies were conducted as part of NATO's effort to define and develop the next generation of reference models for ground vehicle off-road mobility.

Fluid-solid interaction. Chrono::FSI is a general-purpose fluid-solid simulation framework for analysis of the fluid-solid, two-way coupled dynamics at low Reynolds numbers [5]. The fluid dynamics problem is formulated and solved either using an Smoothed Particle Hydrodynamics (SPH) approach with fluid-solid coupling using boundary condition enforcing markers, or else using the so-called *constrained fluid* method. The current implementation in Chrono::FSI uses weakly compressible SPH and provides limited support for fluid interaction with deformable solids. Ongoing work focuses on providing an implicit SPH solver (ISPH), use of variable resolution SPH, and implementations on multiple GPUs. Coupled with Chrono::Vehicle, Chrono::FSI has been used for vehicle mobility studies in fording operations and liquid sloshing.

Co-simulation and hybrid parallel computing. One of Chrono's strengths is its reliance on advanced computing hardware at various stages of the solution process. Chrono embraces cache friendly data structures suitable for vectorization and algorithms that expose parallelism at data and task levels. The software infrastructure draws on three modules – Chrono::Cosimulation, Chrono::Distributed, and Chrono::Parallel – that enable Chrono to map for execution each of the many components of a complex model onto the appropriate parallel computing hardware architecture [6]. This approach establishes a flexible, object-oriented infrastructure that (1) relies on Chrono::Cosimulation to handle in parallel and independently sub-systems of a complex *system*; (2) uses the MPI standard to further partition a large *sub-system* via Chrono::Distributed into parallel sub-groups; and, (3) invokes services provided by Chrono::Parallel to accelerate execution within each *sub-group* using two hardware platforms GPU computing or multi-core processors.

Conclusions. Chrono is an open source software infrastructure used as a vehicle to promoting new modeling approaches, numerical solution techniques, and hardware-aware software designs. Prioritizing accuracy over speed, Chrono is developed with a stated goal of validation against experimental or reference data available in the public domain. Chrono is used in a wide spectrum of real-world applications in additive manufacturing, rheology, ground-vehicle interaction, soft-matter physics, and geomechanics. Its most salient attribute is the ability to solve multi-disciplinary problems that require the solution of coupled differential algebraic equations, ordinary differential equations, partial differential equations and variational inequalities.

Its modular software architecture based on modern object-oriented C++ programming coupled with its open-source attribute and permissible licensing model make Chrono a robust foundation that one can build upon. An illustration of such an extension is the on-going effort to develop the Synchrono multi-agent framework for distributed simulation in robotics and autonomous vehicle applications. Looking beyond support for multi-agent sensing and communication for robotics applications, the immediate future will bring in Chrono enhanced support for fluid-solid interaction modeling and simulation as well as scalable support for distributed computing via the Message Passing Interface in terramechanics and granular dynamics applications.

References

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