SOFA: a modular yet efficient physical simulation architecture

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Outline

Motivation

Simple bodies

Layered objects using node hierarchies

Interacting objects

Implementation

Collision detection and response

Parallelism

Conclusion
A complex physical simulation

Material, internal forces, contraints, contact detection and modeling, ODE solution, visualization, interaction, etc.
Open-Source Simulation Software

- Open-source libraries (ODE, Bullet, PhysX, etc.) provide:
  - limited number of material types
  - limited number of geometry types
  - no control on collision detection algorithms
  - no control on interaction modeling
  - few (if any) control of the numerical models and methods.
  - no control on the main loop

- We need much more!
  - models, algorithms, scheduling, visualization, etc.
A generic approach

- Behavior model: all internal laws
- Others: interaction with the world
- Mappings: relations between the models (uni- or bi-directional)
Animation of a simple body

- a liver
  - Glisson capsule
  - Parenchyma
  - Fixed points

- inside: soft material
- surface: stiffer material

A specialized program:

\[
\begin{align*}
f & = M \times g \\
f & += F_1(x, v) \\
f & += F_2(x, v) \\
a & = \frac{f}{M} \\
a & = C(a) \\
v & += a \times dt \\
x & += v \times dt \\
\text{display}(x)
\end{align*}
\]
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Components

- state vectors (DOF): $x, v, a, f$
- constraints: fixed points
  other: oscillator, collision plane, etc.
- force field: tetrahedron FEM
- force field: triangle FEM
- mass: uniform
- ODE solver: explicit Euler
Components

- state vectors (DOF) : \(x, v, a, f\)
- constraints : fixed points
- force field : tetrahedron FEM
  other : triangle FEM, springs, Lennard-Jones, SPH, etc.
Components

- state vectors (DOF): $x, v, a, f$
- constraints: fixed points
- force field: tetrahedron FEM
- force field: triangle FEM

Diagram:
```
    system
     ├── DOF
     └── Constraint ─── FEM-tetra ─── FEM-trian
```
Components

- state vectors (DOF): \( x, v, a, f \)
- constraints: fixed points
- force field: tetrahedron FEM
- force field: triangle FEM
- mass: uniform
  - other: diagonal, sparse symmetric matrix
Components

- state vectors (DOF) : $x, v, a, f$
- constraints : fixed points
- force field : tetrahedron FEM
- force field : triangle FEM
- mass : uniform
- ODE solver : explicit Euler
  other : Runge-Kutta, implicit Euler, static solution, etc.
Multiple objects with their own solvers

Each object can be simulated using its own solver
Multiple objects with the same solver

A solver can drive an arbitrary number of objects of arbitrary types
Processing multiple objects using visitors

- The ODE solver sends visitors to apply operations
- The visitors traverse the scene and apply virtual methods to the components
- The methods read and write state vectors (identified by symbolic constants) in the DOF component
- Example: accumulate force
  - A ResetForceVisitor recursively traverses the nodes of the scene (only one node here)
    - All the DOF objects apply their resetForce() method
  - An AccumulateForceVisitor recursively traverses the nodes of the scene
    - All the ForceField objects apply their addForce(Forces, const Positions, const Velocities) method
  - the final value of f is weight + tetra fem force + trian fem force
Scene data structure

Scene hierarchy:
1. the scene is composed of *nodes* organized in a Directed Acyclic Graph (DAG, i.e. generalized hierarchy)
2. nodes contain *components* (mass, forces, etc.) and a list of child nodes
3. components contain *attributes* (density, stiffness, etc.)

Data graph:
- attributes can be connected together for automatic copies
- attributes can be connected by engines, which update their output based on the values of their input
- the attributes and engine compose a DAG
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Layered object

Detailed geometry embedded in a coarse deformable grid

- independent DOFs (blue)

1. $v_{\text{skin}} = J_{\text{skin}} v$
2. $v_{\text{collision}} = J_{\text{collision}} v_{\text{skin}}$

- apply forces

1. $f_{\text{skin}} = J_{\text{T}} f_{\text{collision}}$
2. $f = J_{\text{T}} f_{\text{skin}}$
Layered object

Detailed geometry embedded in a coarse deformable grid

- independent DOFs (blue)
- skin vertices (salmon)

$$v^{\text{skin}} = J^{\text{skin}} v$$

$$v^{\text{collision}} = J^{\text{collision}} v^{\text{skin}}$$

$$f^{\text{skin}} = J^{\text{T}} \cdot \text{collision} f^{\text{collision}}$$

$$f = J^{\text{T}} \cdot \text{skin} f^{\text{skin}}$$
Layered object

Detailed geometry embedded in a coarse deformable grid

- independent DOFs (blue)
- skin vertices (salmon)
- mapping

\[ \text{skin} = J_{\text{skin}} \text{v} \]
\[ \text{collision} = J_{\text{collision}} \text{v}_{\text{skin}} \]

\[ \text{f}_{\text{skin}} = J_{\text{collision}}^T \text{f}_{\text{collision}} \]
\[ \text{f} = J_{\text{skin}}^T \text{f}_{\text{skin}} \]
Layered object

Detailed geometry embedded in a coarse deformable grid

- independent DOFs (blue)
- skin vertices (salmon)
- mapping
- collision samples (green)
- collision mapping
Layered object

Detailed geometry embedded in a coarse deformable grid

- independent DOFs (blue)
- skin vertices (salmon)
- mapping
- collision samples (green)
- collision mapping
- apply displacements
  1. $v_{skin} = J_{skin} v$
  2. $v_{collision} = J_{collision} v_{skin}$
Layered object

Detailed geometry embedded in a coarse deformable grid

- independent DOFs (blue)
- skin vertices (salmon)
- mapping
- collision samples (green)
- collision mapping
- apply displacements
  1. $v_{\text{skin}} = J_{\text{skin}} \mathbf{v}$
  2. $v_{\text{collision}} = J_{\text{collision}} v_{\text{skin}}$
- apply forces
  1. $f_{\text{skin}} = J_{\text{collision}}^T f_{\text{collision}}$
  2. $f = J_{\text{skin}}^T f_{\text{skin}}$
More on mappings

- Map a set of degrees of freedom (the parent) to another (the child).
- Typically used to attach a geometry to control points (but see Flexible and Compliant plugins).
- Child degrees of freedom (DOF) are not independent: their positions are totally defined by their parent’s.
- Displacements are propagated top-down (parent to child): \( \nu_{child} = J\nu_{parent} \)
- Forces are accumulated bottom-up: \( f_{parent} + = J^T f_{child} \)
The physics of mappings

Example: line mapping

\[ v_c = \begin{pmatrix} a & b \end{pmatrix} \begin{pmatrix} v_1 \\ v_2 \end{pmatrix} = Jv \]

\[ \begin{pmatrix} f_1 \\ f_2 \end{pmatrix} = \begin{pmatrix} a \\ b \end{pmatrix} f_c = J^T f_c \]
Examples of mappings

- RigidMapping can be used to attach points to a rigid body
  - to attach a visual model

- BarycentricMapping can be used to attach points to a deformable body

- More advanced mapping can be applied to fluids
Examples of mappings

- RigidMapping can be used to attach points to a rigid body
  - to attach collision surfaces

- BarycentricMapping can be used to attach points to a deformable body

- More advanced mapping can be applied to fluids
Examples of mappings

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▶ RigidMapping can be used to attach points to a rigid body
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▶ More advanced mapping can be applied to fluids
Examples of mappings

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- BarycentricMapping can be used to attach points to a deformable body
- More advanced mapping can be applied to fluids
On the physical consistency of mappings

- Conservation of energy:
  Necessary condition: $v_{child} = Jv_{parent} \Rightarrow f_{parent} + = J^T f_{child}$

- Conservation of momentum:
  Mass is modeled at one level only. There is no transfer of momentum.

- Constraints on displacements (e.g. incompressibility, fixed points) are not easily applied at the child level
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Two objects in contact

Example: 2-layer liver against 3-layer liver using a contact force. Use extended trees (Directed Acyclic Graphs) to model trees with loops.
Soft interactions: independent processing, no synchronization required
ODE solution of interacting objects

- Soft interactions: independent processing, no synchronization required
- Stiff interactions: unified implicit solution with linear solver, synchronized objects
ODE solution of interacting objects

- Soft interactions: independent processing, no synchronization required
- Stiff interactions: unified implicit solution with linear solver, synchronized objects
- Hard interaction constraints using Lagrange multipliers
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Actions implemented by Visitors

- No global state vector
- Operation = graph traversal + abstract methods + vector identifiers
Example: clearing a global vector

- The solver triggers an action starting from its parent system and carrying the necessary symbolic information.
- The action is propagated through the graph and calls the appropriate methods at each DOF node.
Example: accumulating the forces

- The solver triggers the appropriate action
- the action is propagated through the graph and calls the appropriate (bottom-up) methods at each Force and Mapping node
Efficient implicit integration

- Large time steps for stiff internal forces and interactions
- Solve \((\alpha M + \beta h^2 K)\Delta v = h(f + hKv)\) iteratively using a conjugate gradient solution

Actions:
- `propagateDx`
- `computeDf`
- vector operations
- dot product (only global value directly accessed by the solver)

System assembly in the Compliant plugin
Efficiency

- No global state vector
  - they are scattered over the DOF components
  - each DOF component can be based on its own types (e.g. Vec3, Frame, etc.)
  - symbolic values are used to represent global state vectors
- Action = graph traversal + global vector ids + call of abstract top-down and bottom up methods
  - Displacements are propagated top-down
  - Interactions forces are evaluated after displacement propagation
  - Forces are accumulated bottom-up
  - virtual functions applied to components
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Collision detection and response

CollisionPipeline component orchestrates specific components

- BroadPhase: bounding volume intersections
- NarrowPhase: geometric primitive intersections
- Reaction: what to do when collisions occur
- GroupManager: putting colliding objects under a common solver

Recent work uses the GPU
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Parallelism in time integration

Different levels of parallelism :

- Low level: GPU implementations of components
- High level: task-based using data dependencies
- Thread-based using the Multithread plugin

We can combine them!
GPU Parallelism

- StiffSpringForceField, TetrahedronFEMForceField, HexahedronFEMForceField are implemented on the GPU
- The DOF component makes data transfer transparent
- CPU and GPU components can be used simultaneously
- Nice speedups
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Conclusion - Features

High modularity:
- Multimodel simulations using mappings
- Explicit and implicit solvers, Lagrange multipliers

Efficiency:
- Global vectors and matrices are avoided
- Parallel implementations

Implementation:
- Currently > 750,000 C++ lines
- Linux, MacOS, Windows
Ongoing work

- models and algorithms: better numerical solvers, cutting, haptics, Eulerian fluids...
- asynchronous simulation/rendering/haptic feedback
- multiphysics (electrical/mechanical)
- parallelism for everyone
- more documentation

www.sofa-framework.org