MULTIPHYSICS SIMULATION USING GPU

Arman Pazouki

Simulation-Based Engineering Laboratory
Department of Mechanical Engineering
University of Wisconsin - Madison
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Motivation and Background
Motivation
Fluid

Flexible Bodies ➞ Rigid Bodies
Fluid Simulation: SPH

- Continuity:
  \[
  \frac{d\rho_a}{dt} = \rho_a \sum_b \frac{m_b}{\rho_b} (v_a - v_b) \cdot \nabla_a W_{ab}
  \]

- Momentum (Navier-Stokes):
  \[
  \frac{dv_a}{dt} = -\sum_b m_b \left[ \left( \frac{p_a}{\rho_a^2} + \frac{p_b}{\rho_b^2} \right) \nabla_a W_{ab} - \frac{(\mu_a + \mu_b) x_{ab} \cdot \nabla_a W_{ab}}{\rho_{ab}^2 (x_{ab}^2 + \varepsilon h_{ab}^2)} v_{ab} \right] + f_a
  \]

- Lagrangian Kinematics:
  \[
  \frac{dx_a}{dt} = v_a
  \]

- Weakly Compressible model
  \[
  p = \frac{c_s^2 \rho_0}{\gamma} \left\{ \left( \frac{\rho}{\rho_0} \right)^\gamma - 1 \right\}
  \]

- XSPH
- Shepard Filtering

Neighbor Search and GPU programming

Case Study: How GPU can affect an algorithmic design

VS
Algorithm 1

Core property: saving contacts list

Parallel threads: Bins

Advantages

• One calculation per intersection
• Possibility of re-using contacts list
• Arbitrary shapes

Successful for rigid body dynamics: $O(1e7)$
Failed for SPH: $O(1e6)$
Algorithm 2

Core property: find intersection whenever needed

Advantages:
- More process, less memory
- Fixed size spheres

Parallel threads: Particles
- Reduces memory access
- Improves cache hits.

Screen shot from particles demo, NVIDIA CUDA (CUDA Samples)
Rigid and Flexible Bodies Dynamics

• 3D rigid body dynamics

\[
\frac{dV_i}{dt} = \frac{F_i}{M_i}
\]

\[
J' \frac{d\omega'_{i}}{dt} = T' - \vec{\omega}' \vec{J}' \omega'_{i}
\]

Kinematics

\[
\frac{dX_i}{dt} = V_i
\]

\[
\frac{dq_i}{dt} = \frac{1}{2} G_i^T \vec{\omega}_i,
\]

\[
q_i^T q_i - 1 = 0
\]

• Gradient-deficient ANCF beam element

Dynamics

\[
M \ddot{e} + Q^e = Q^g + Q^a
\]

\[
Q^e = \int_J E A \varepsilon_{11} \left( \frac{\partial \varepsilon_{11}}{\partial e} \right)^T \, dx + \int_J E I \kappa \left( \frac{\partial \kappa}{\partial e} \right)^T \, dx
\]

\[
Q^g = \int_J \rho_s A S^T g \, dx
\]

\[
Q^a = S^T (x_a) F
\]

Kinematics

\[
e = \begin{bmatrix} r^L_l \\ r^L_x \\ r^L_y \\ r^R_l \\ r^R_x \\ r^R_y \end{bmatrix}; \quad r(x,e) = S(x)e ; \quad v(x,e) = S(x)e
\]

\[
S \in \mathbb{R}^{3 \times 12} \text{ shape function matrix}
\]

• E. Haug, Computer aided kinematics and dynamics of mechanical systems, Allyn and Bacon Boston, 1989.
Fluid-Solid Interaction

Boundary Condition Enforcing (BCE) markers for no-slip condition

- Rigidly attached to the solid body (hence their velocities are those of the corresponding material points on the solid)
- Hydrodynamic properties from the fluid
Parallelization

- `thrust::reduce_by_key` to reduce surface reaction forces and torques on to nodal values
- Custom kernels to update solid objects
- Fine grain parallelization
  - Position
  - Rotation
  - Velocity
  - Angular velocity
  - ...
Example Simulations
Flow in porous media

- Example applications
  - Oil Recovery
  - Biology
    - Diffusion of macro-molecules within tissues
    - Blood flow through muscles
Simulation of dense suspensions

• "Dense" suspension
  • Finite size particles (rigid bodies) interaction
    • Drafting, Kissing, and Tumbling (DKT)
  • Short range interactions
    • Lubrication and collision

• Flow characteristics
  • Particle Reynolds number ≤ 1.0
  • Channel Reynolds number: 66
    • Channel Dimension: (1.1, 1.0, 1.0) m
    • Volumetric concentration: 40%

• Computational aspects
  • 23,000 rigid ellipsoids: (1.5, 1.5, 2.0) cm
  • 2,000,000 SPH markers.
  • Simulation performed on a single GPU, NVIDIA GTX 480
    • 3.2 seconds of dynamics
    • 72 hrs to complete.
Interacting rigid and flexible objects in channel flow

Fluid:
\[ \rho = 1000 \text{ kg/m}^3 \]
\[ \mu = 1 \text{ N s/m}^2 \]
\[ (l_x, l_y, l_z) = (1.4, 1, 1) \text{ m} \]
\[ Re = 45 \]

Ellipsoids:
\[ \rho_s = 1000 \text{ kg/m}^3 \]
\[ (a_1, a_2, a_3) = (2.25, 2.25, 3) \text{ cm} \]
\[ N_r = 2000 \]
\[ Re_p = 2 \]

Beams:
\[ \rho_s = 1000 \text{ kg/m}^3 \]
\[ E = 0.2 \text{ MPa} \]
\[ a = 1.5 \text{ cm} \]
\[ l = 64 \text{ cm} \]
\[ N_f = 40 \]
\[ n_e = 4 \]
Performance
Scaling analysis on NVIDIA GeForce GTX 680

- Rigid body dynamics
  \[ N_m = 0, \ N_f = 0 \]
  \[
  \begin{array}{c|c|c|c|c|c|c}
  N_r (\times 10^3) & 0.49 & 2.87 & 16.59 & 56.77 & 118.23 \\
  t (\text{ms}) & 5 & 8 & 16 & 44 & 78 \\
  \end{array}
  \]

- Flexible body dynamics
  \[ N_m = 0, \ N_r = 0 \]
  \[
  \begin{array}{c|c|c|c|c|c|c}
  N_f (\times 10^3) & 0.78 & 3.51 & 17.55 & 56.94 & 115.05 \\
  t (\text{ms}) & 8 & 14 & 48 & 122 & 238 \\
  \end{array}
  \]

- Fluid flow
  \[ N_r = 0, \ N_f = 0 \]
  \[
  \begin{array}{c|c|c|c|c|c}
  N_m (\times 10^6) & 0.06 & 0.32 & 0.93 & 1.79 & 4.13 \\
  t (\text{ms}) & 27 & 121 & 331 & 538 & 1150 \\
  \end{array}
  \]
Scaling analysis (all together, table)

<table>
<thead>
<tr>
<th>$N_m$ ($\times 10^6$)</th>
<th>0.08</th>
<th>0.16</th>
<th>0.29</th>
<th>0.63</th>
<th>0.95</th>
<th>1.54</th>
<th>2.50</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_r$ ($\times 10^3$)</td>
<td>0.17</td>
<td>0.52</td>
<td>1.12</td>
<td>4.48</td>
<td>7.84</td>
<td>14.56</td>
<td>24.64</td>
</tr>
<tr>
<td>$N_f$ ($\times 10^3$)</td>
<td>0.16</td>
<td>0.42</td>
<td>0.84</td>
<td>2.10</td>
<td>3.36</td>
<td>5.88</td>
<td>9.66</td>
</tr>
<tr>
<td>$t$ (ms)</td>
<td>45</td>
<td>74</td>
<td>120</td>
<td>230</td>
<td>343</td>
<td>522</td>
<td>820</td>
</tr>
</tbody>
</table>

$N_m \approx 3.0 \times 10^6, N_f = 0$

<table>
<thead>
<tr>
<th>$N_r$</th>
<th>0</th>
<th>36</th>
<th>120</th>
<th>480</th>
<th>1800</th>
<th>8400</th>
<th>33,600</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t$ (ms)</td>
<td>906</td>
<td>919</td>
<td>923</td>
<td>925</td>
<td>926</td>
<td>926</td>
<td>921</td>
</tr>
</tbody>
</table>

$N_m \approx 3.0 \times 10^6, N_r = 0$

<table>
<thead>
<tr>
<th>$N_f$</th>
<th>0</th>
<th>45</th>
<th>140</th>
<th>440</th>
<th>1152</th>
<th>2100</th>
<th>4704</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau = 10$</td>
<td>$t$ (ms)</td>
<td>906</td>
<td>923</td>
<td>928</td>
<td>916</td>
<td>960</td>
<td>950</td>
</tr>
<tr>
<td>$\tau = 50$</td>
<td>$t$ (ms)</td>
<td>906</td>
<td>973</td>
<td>978</td>
<td>965</td>
<td>1066</td>
<td>1060</td>
</tr>
</tbody>
</table>
Validation
Particle migration in 2D and 3D Poiseuille flow

- Transient Poiseuille flow
  \[ Re \approx 5 \]

- Cylinder in channel flow
  \[ Re \approx 1, \ t^* = t \times V/L \]

- Sphere in pipe flow, \( Re \approx 60 \)
  - Effect of rigid body rotation

Radial distribution of particles in suspension [1/2]

- 192, 10 hour long simulation
- 14 seconds real time
- Bootstrapping method, 95% confidence interval

Increasing distance from inlet

$\frac{a}{R} = 0.07$

$L = \left( \frac{a}{R} \right) \left( \frac{a v \rho}{\mu} \right) \left( \frac{l}{R} \right) = [0, 0.69]$

$Re \approx 60, \ \phi = 0.027\%$


A Lagrangian-Lagrangian Approach For the Simulation of FSI Problems
Applications
Hanging flexible beam in viscose fluid

- Flexible cantilever in contained fluid
- Track position of beam tip

\[ L = 1.0 \, \text{m} \]
\[ \rho_s = 7200 \, \text{kg/m}^3 \]
\[ E = 20 \, \text{MPa} \]
\[ d = 0.04 \, \text{m} \]
\[ \mu_{trans.} \approx 10 \, \text{N s/m}^2 \]
Flow cytometry using microfluidic techniques

- Fluorescence and laser-beam cell sorting
  - Limited particle size, $a < 50 \mu m$
  - Unknown effect of external field on cell viability

- Purification of 3D micro-tissues and cell aggregates
  - Finite size particles, $a \approx 25..500 \mu m$
Work in progress
THANK YOU!

Chrono::FSI (Project Chrono: https://github.com/projectchrono)

Simulation Based Engineering Lab (SBEL)

University of Wisconsin-Madison

Email: pazouki@wisc.edu