Physics-based Medical Simulation using SOFA and H3D

Outline of the workshop

- Short introduction
- SOFA :: principles and examples
- H3D :: principles and examples
- Setup for the tutorial
- Break (around 3 PM)
- Hands-on tutorial SOFA + H3D
- Questions // Discussion
Objectives

- Learn the key features of H3D and SOFA
- Learn how to create a simulation in SOFA, step by step
- Learn how to integrate SOFA with H3D
- See examples of applications based on SOFA and/or H3D
- USB key provided with pre-compiled SOFA+H3D environment and tutorial
SOFA
Simulation Open Framework Architecture

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Interactive numerical simulation for medicine

- Interactive medical simulation for...
  - training
  - pre-operative planning and rehearsal
  - per-operative guidance

- All simulations need to be **interactive** and **realistic**

- Increasing levels of requirements as we get closer to the OR
Multiple scientific challenges...

- Multidisciplinary expertise covering the areas of
  - Anatomical Modeling
  - Physics-based Modeling
  - Advanced Interactions
  - Parallel Computing
  - Software integration and validation
...supported by an advanced simulation framework

- **Objective**
  - Create complex simulations by combining a number of existing components
  - Evolve over time as new research results become available

- **Multiple levels of abstraction**
  - Component abstraction
  - Multi-modal representation of simulated objects
  - Multi-level representation of physics-based objects

- **Rely on a collaborative approach**
  - Do not develop SOFA in a sandbox but with the feedback of other scientists
SOFA :: a quick overview

- **SOFA is Open Source**
  - It has a simple license: GPL for the core // LGPL for everything else
  - Commercial applications based on SOFA are possible

- **SOFA community**
  - More than 20 active developers, including engineers, PhD students, faculty...
  - More than 120,000 downloads
  - More than 300 users from 20 countries
  - Website: [www.sofa-framework.org](http://www.sofa-framework.org)
SOFA :: a quick overview

svn checkout svn://scm.gforge.inria.fr/svnroot/sofa/trunk
SOFA :: a quick overview

- Since end of 2012, a new organization of the code
  - A common public branch for a large part of the code
  - A set of plugins to extend SOFA
    - Public plugins
    - Private plugins
  - Private and public code rely on the same core
  - Private plugins are usually migrated to a public plugin when they are “stable”
Split computations into independent parts

- Separate problems
- Improve reusability

Objects have multimodal representation

- Visual, Mechanical, Collision, Haptic, etc.
- Physics models can be further decomposed
  - Degrees of Freedom
  - Force Fields
  - Solvers
Deformation model

\[ M\ddot{v} = p - f(v, x) + H^T\lambda \]

\[ A x = b \]

ODE Solver

Linear Solver

Degrees of Freedom

Finite Element Forces and Mass

External Loads

Mapped Forces

...
Computation on GPU

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Mapped Forces

...
Deformation model

Collision Model

Visual Model
M\ddot{v} = p - f(v, x) + H^T\lambda

Ax = b

Mappings also allow to add a slave force model e.g. stiffness of the vessels

ODE Solver
Linear Solver
Degrees of Freedom
Finite Element Forces and Mass
External Loads
Mapped Forces
\[ M \dot{v} = p - f(v, x) + \lambda^T \nabla f \]

Mappings also allow to add a slave force model e.g. stiffness of the vessels.
SOFA :: some application examples
Collision detection based on LDI

- LDI: Layered Depth Images
- Use GPU to render the simulation scene along 3 principal directions
- This generates a volumetric image
- From this image we identify the intersection volumes which are used to compute the collision response
- Self-collisions at no additional cost
Collision detection based on LDI

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Real-time soft tissue deformation

- Fine level of parallelism
  - FEM approach developed in CUDA
  - Linear solver (CG) also written in CUDA
- Two models implemented on the GPU
  - TLED (Total Lagrangian Explicit Dynamics)
  - Co-rotational model (geometrically non-linear)

\[
\begin{align*}
(M - hB - h^2K)_{A,x} & \quad dv = hf(x_t, v_t) + h^2Kv_t \\
& \quad b
\end{align*}
\]

Many contacts are presents between organs (due to breathing and other motions).
Constraint-based suturing

- Advanced modeling
  - The beam model can be used for the whole suture (including the needle)
  - Constraint based approach to simulate the suturing task

- Work in progress
  - Use continuous spline based beams
  - Simulation of knot tying
Cardiac electrophysiology

- Simulate electrophysiology anisotropic propagation through the cardiac muscle
- Links to cardiac muscle deformation
- Parametrization using patient data

Four steps of a depolarization wave propagating inside a FEM mesh
Simulation for rehearsal of complex cases

- Interventional radiology
  - The previous idea can be extended to the field of interventional radiology
  - Assist in the planning of interventions, e.g. radio-frequency catheter ablation for the treatment of cardiac arrhythmia
  - Provide guidance (using 3D reconstructed models of the vascular anatomy and physics-based models of flexible devices) during complex procedures
Simulation for rehearsal of complex cases
Augmented Reality on Deformable Structures

- Laparoscopic Surgery
  - Provide augmented reality using a combination of patient-specific modeling, computer vision and real-time physics-based simulation of deformable structures
  - Develop a framework for robust tracking and fast 3D reconstruction
  - Use physics-based simulation to regularize and extrapolate image data
Augmented Reality on Deformable Structures
Guidance for percutaneous procedures
Real-time non-rigid registration

Lateral to supine liver position :: automatic registration
Technology transfer using SOFA

Laparoscopic Training

Eye Surgery Training