Predictive simulation for interventional neuroradiology

Radhouane Jilani

Team: Tangram

Supervisors: Erwan Kerrien Pierre-Frédéric Villard

July 11, 2022
Introduction
Ischemic stroke

The decrease in blood flow to a part of the brain

- obstruction of blood vessels by a blood clot
  - removal of blood clots with medication
  - removal of blood clots *mechanically*

- navigation of instruments is *challenging*
- must be performed *within 6 hours* of stroke onset to reduce risk of disability

*source: my.clevelandclinic.org*
Predictive Simulation for the Planning of Interventional Neuroradiology procedures
Purpose of the thesis: predictability

There are other simulators that are realistic but not predictive:
- e.g. ANGIO Mentor

*Predictability is about faithfully reproducing important events*

Create a predictive simulation of mechanical thrombectomy using highly accurate
- blood vessels surface
- catheter model

and develop a new **contact model**
State of the art
Catheters: wire-like structures

- Long, thin and deformable
- High tensile strength
- Low resistance to bending
- Geometrically non-linear
Catheter models

- **Mass-spring**
  - particles linked with massless linear and angular springs

- **Rigid articulated bodies**
  - set of rigid elements connected using spherical joints

- **Splines**
  - continuous representation
  - some articles consider control points as the degrees of freedom

- Run at interactive rate
- Deformations are not physically exact
- Difficult to precisely tune for some given material
Catheter models

Cosserat rods

- Set of oriented frames
- Length >> radius
- Mechanically exact
- Accurately handle complex deformations
  - bending, torsion, stretching and shearing

Spillmann et Teschner 2007
Contact: penalty-based method

A system of spring dampers at each point of contact is used to penalize penetrations

\[ F_a = (-k\phi - bv \cdot n) n \]
\[ F_b = -F_a \]

Pros:
- fast and relatively easy to implement
- easily converts a constrained problem into an unconstrained problem

Cons:
- it is not trivial to choose the stiffness and damping parameters
- the stiffness parameter must be large enough to eliminate penetration, but setting it too high increases the cost of the simulation
Contact: constrained-based method

Solve the constraints forces $F_c$ and add them to the equation of motion:

$$Ma = F + F_c = F + J^T \lambda$$

$\lambda$: Lagrange multiplier

$J$: Jacobian of the constraints

while ensuring complementarity condition

$$0 \leq \phi \perp \lambda \geq 0$$

$\phi$: Gap function

Solution: solve the linear complementarity problem, minimize $\phi \cdot \lambda$

Pros: it leads to simulations where interpenetration is completely eliminated (but due to discretization errors, stabilization is necessary)

Cons: time-consuming
Blood vessels surface

Polygonal mesh

- slow collision detection
- inaccurate collision response

Implicit surface (e.g. Blobby Model)

- fast collision detection
- accurate collision response

E. Kerrien et al. 2017
Evaluation of a simulation
SOFA Framework

Open source framework for medical simulations

Catheter model:
- beam theory (actual mechanical parameters)
- includes translations and rotations
- configurable resting shape

Contact model:
- polygonal mesh
- LCP constraint solver
- Euler implicit solver
Catheter experience

Three different scenarios
1. tip attached
2. translations and rotations
3. insertion inside a phantom

Materials
- two cameras
- a robot executing translations and rotations
- a phantom forming blood vessels

The output is a sequence of 3D reconstructed points
The chosen approach: geometric evaluation

parameters: resting shape...

simulated shape

reference shape (3D reconstructed)

distance computation

optimization
Results

1. **tip attached (without contacts)**
   - length = 31 cm
   - error = 3.35 mm

2. **translations and rotations (without contacts)**
   - length goes from 0 to 5 cm
   - error is between 0.5 to 1.5 mm

3. **insertion inside a phantom (with contacts)**
   - the catheter exits the surface
Conclusion

This mechanical model cannot be used for prediction

● we have chosen to use a physically correct cosserat Contact model is inaccurate

● we will propose a new contact model that uses implicit surfaces