Part II:

Virtual Reality Based Surgical Simulations

Outline

- Introduction to Virtual Surgery
- Virtual Endoscopic Surgery
- Interactive FEM based cutting and deformation
- Orthopedic surgery simulation with soft tissue deformation and bleeding
- Vascular and Interventional Surgical Simulation
- Ultrasound biopsy simulation with 6DOF haptics

Significance of Virtual Surgery

- Safety – avoid medical errors
- Reusability
- Repeatability
- Cost effective in the long run
- Speed up learning curve
- To enable surgical rehearsal, planning or training in cyberspace

Challenges

- Real-time photorealistic visualization
- Haptic simulation of tissue responses
  - Complexity of tissue mechanics
- Real-time interactivity against Accuracy
  - Accuracy → comprehensive modeling
  - Real-time → 30 Hz for graphics, 1000 Hz for haptics feedback devices

Dilemmas in Surgical Training

on cadaver?

- limited supply
- no dynamic conditions

on animal?

- different from human
- no complications

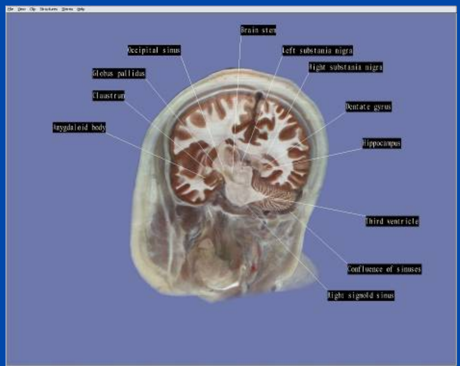
on real patient?

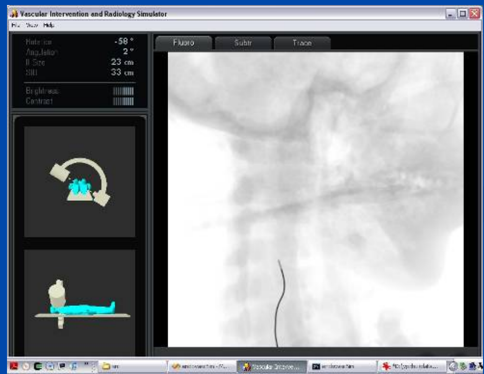
- may harm patients
- non-repeatable

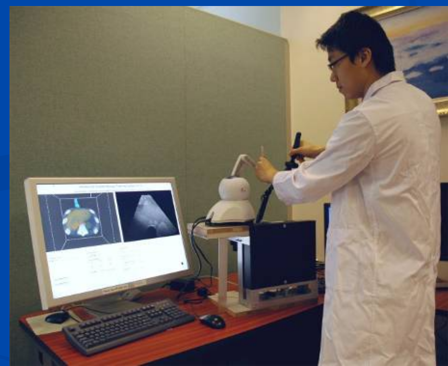
Virtual Reality based Solution

Deliver *cost-effective medical learning*

- with integrated *software* and *hardware*
- in a *3D virtual space*







Surgical Learning & Training

Integrate as *standard teaching curriculum*

- Improved patient safety

Surgical Simulation Research

- Classification of Surgical Simulation
  - Needle-base surgical simulation
  - Minimally Invasive Surgery Simulation
  - Open Surgery Simulation
- Components of Surgical Simulation
  - Deformation Models
  - Collision Detection
  - Virtual and Haptic Display
  - Evaluation

Needle-based Surgical Simulation

- Use needles, catheters, guidewires and other small bore instruments
- Relatively inexpensive
- Cases
  - Vascular Access
  - Pericardiocentesis
  - Diagnostic peritoneal lavage

Minimally Invasive Surgery Simulation

Features

- Use specially designed instruments.
- Visual feedback is obtained via inserted scopes, cameras or fiber-optic devices .
- These instruments have a limited range of motion.

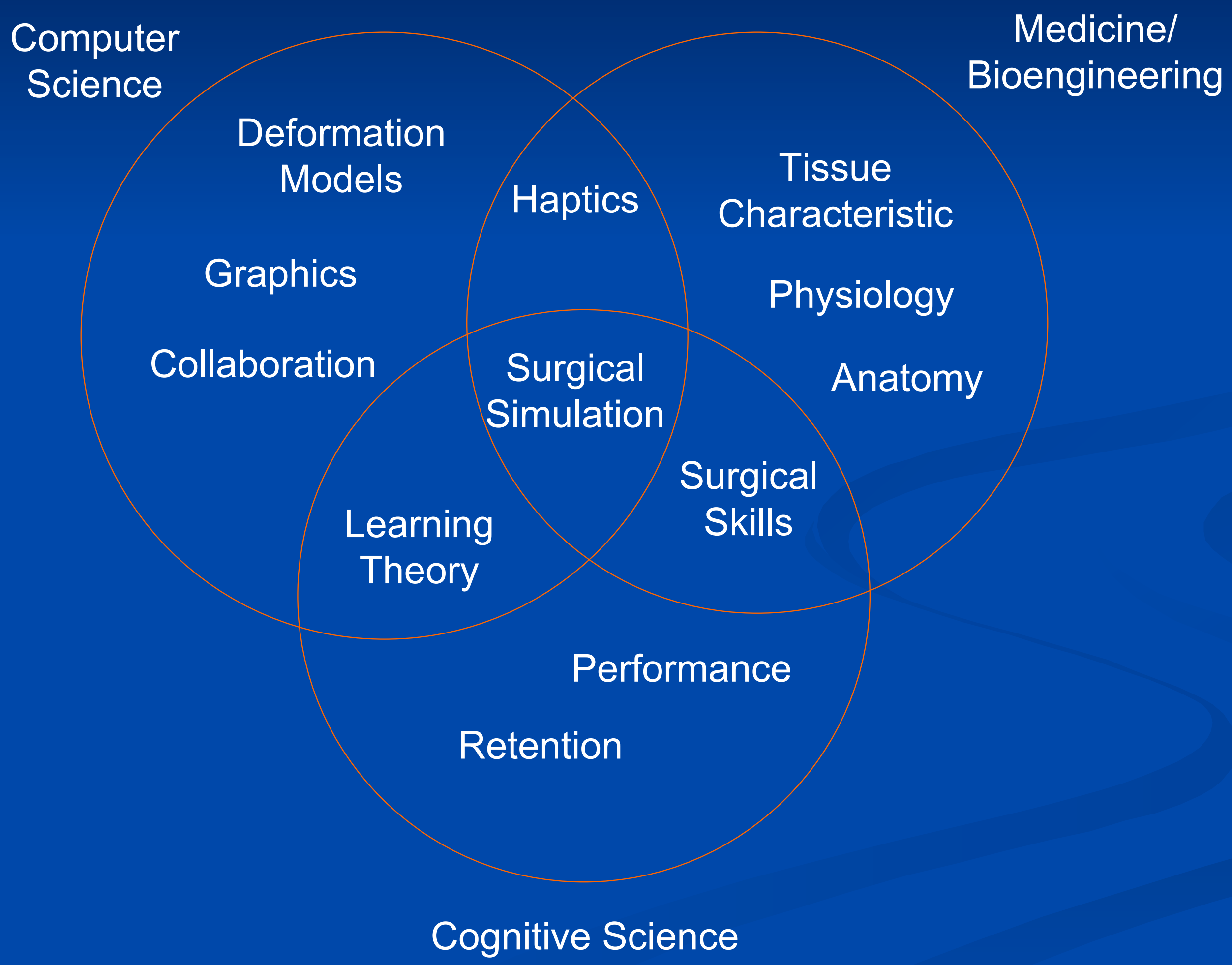
Limitation

- Surgical effects: bleeding, blood pooling, tissues tearing
- Real-time tissue and organ deformation are generally limited to specific organs. Arteries, dusts and other tubular structures

Open Surgery Simulation

- Open surgery requires larger incisions in the body.
- The virtual field, range of haptic feedback and freedom of motion are larger
- Cases
  - vascular anastomosis simulators
  - abdominal trauma simulators

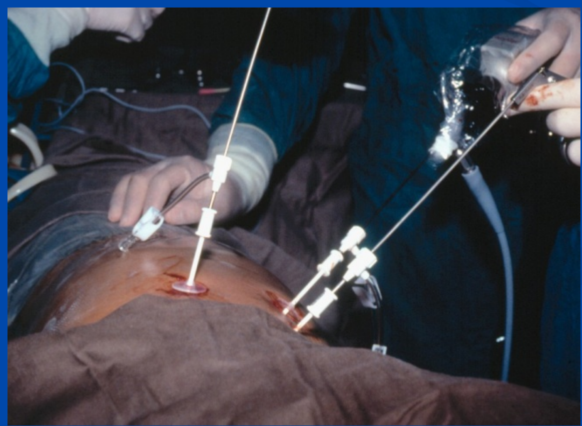
The Components of Surgical Simulation



VR based systems for training on endoscopic surgery

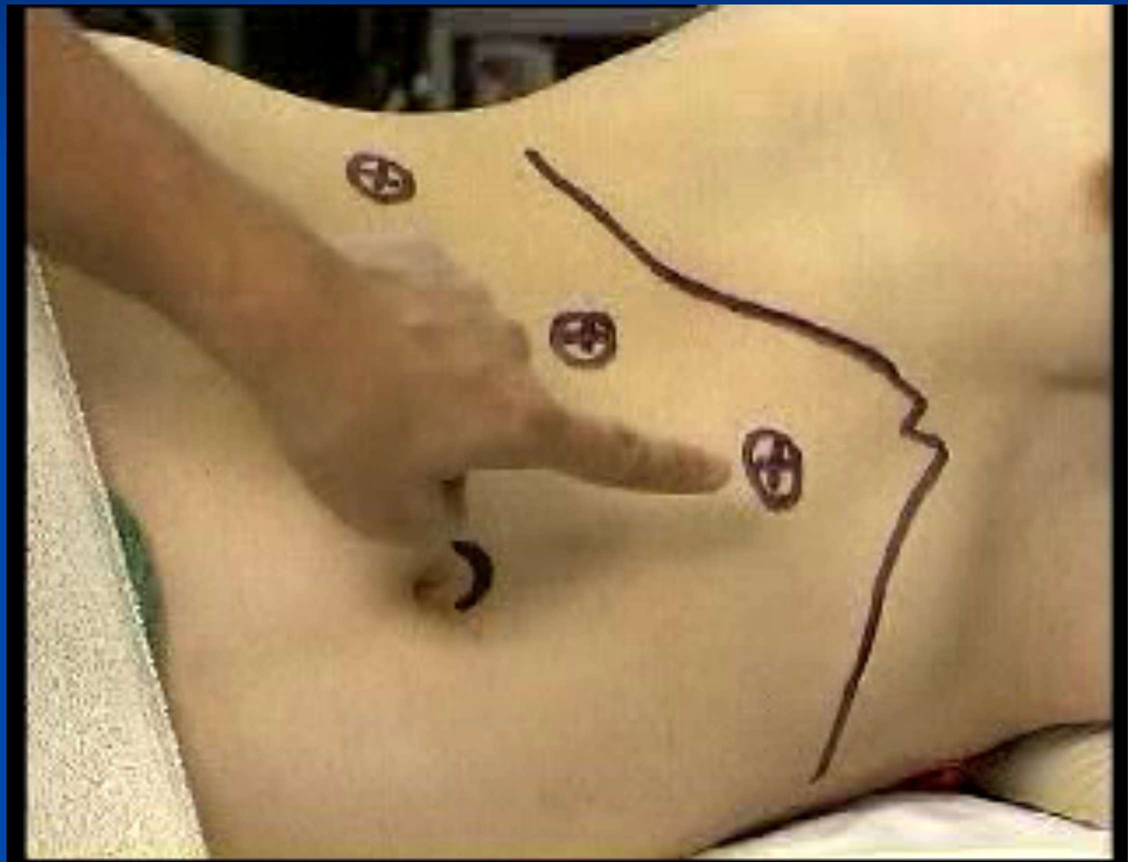
- Funded by Hong Kong RGC Central Allocation Grant
- Focus on the R&D of the following VR based training systems:
  - Virtual arthroscopic surgery
  - Virtual laparoscopic surgery
  - Virtual thoracoscopic surgery

The Evolution of Surgery

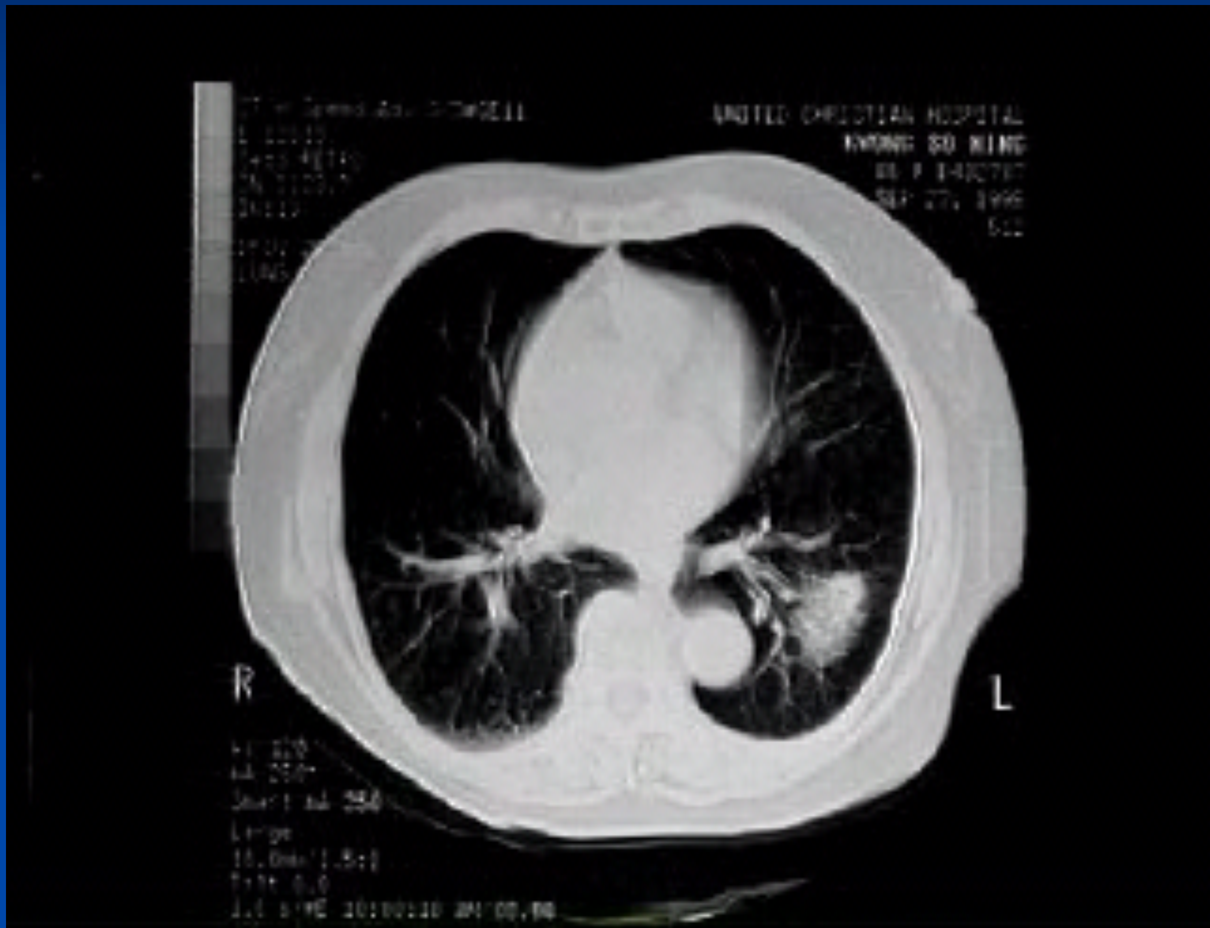


Knee Minimally Invasive Surgery

Minimally Invasive Abdominal Surgery



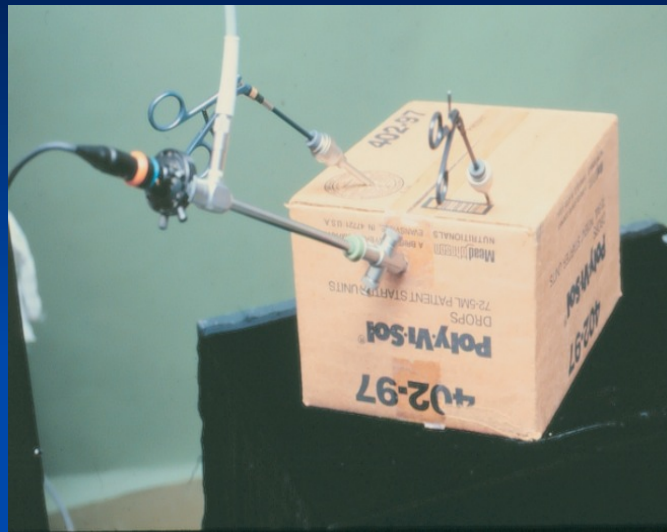
Minimally Invasive Thoracic Surgery



Common Problems in Endoscopic Surgery & Training

- Very different from open surgery
- Steep learning curve exists
- Need adaptation to a new set of skills
    - Loss of depth perception
    - Hand eye coordination
    - Strategic positioning of camera & instruments
    - Technology dependence
- Difficulties in training models, set-up

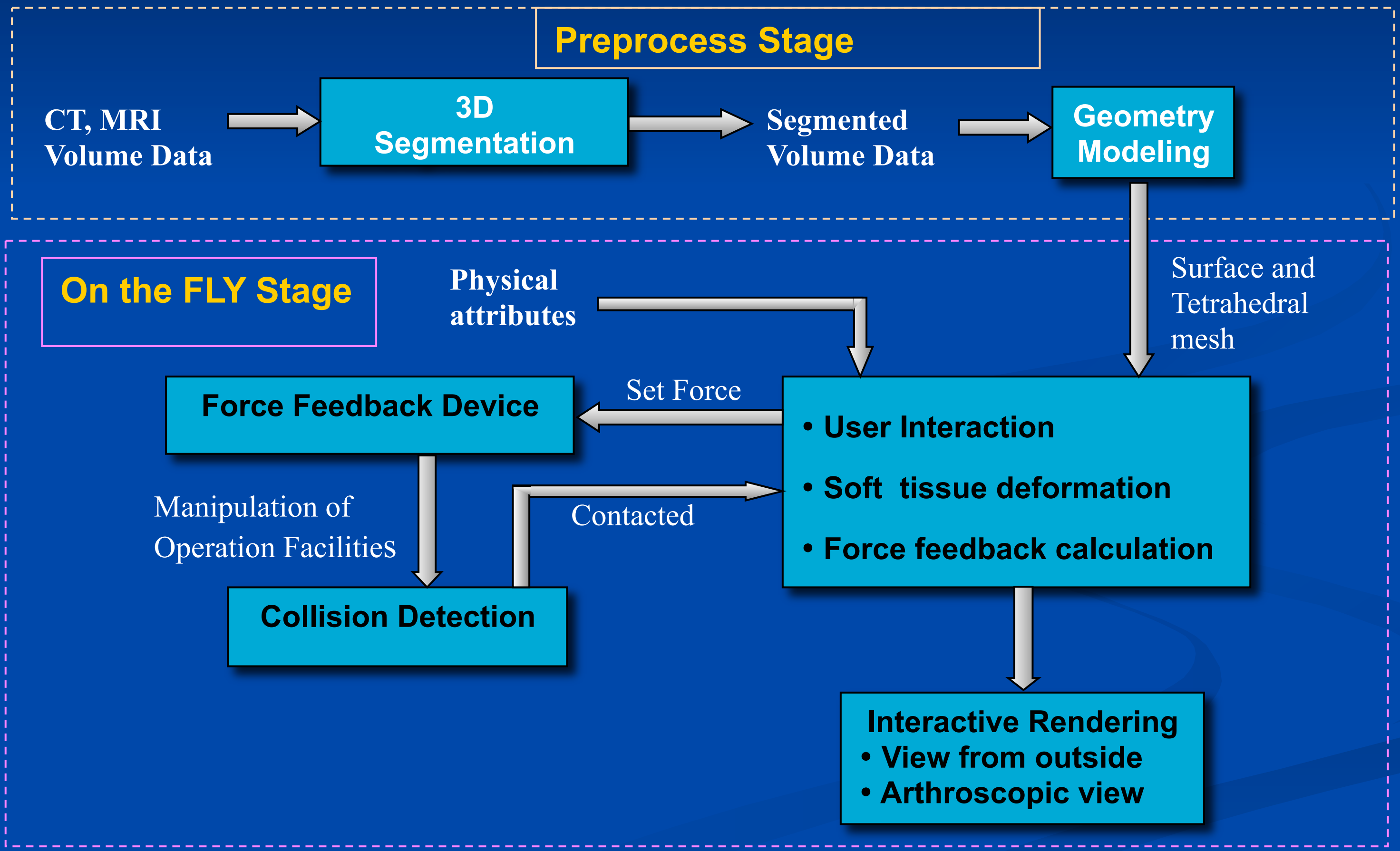
Traditional training in endoscopic surgery



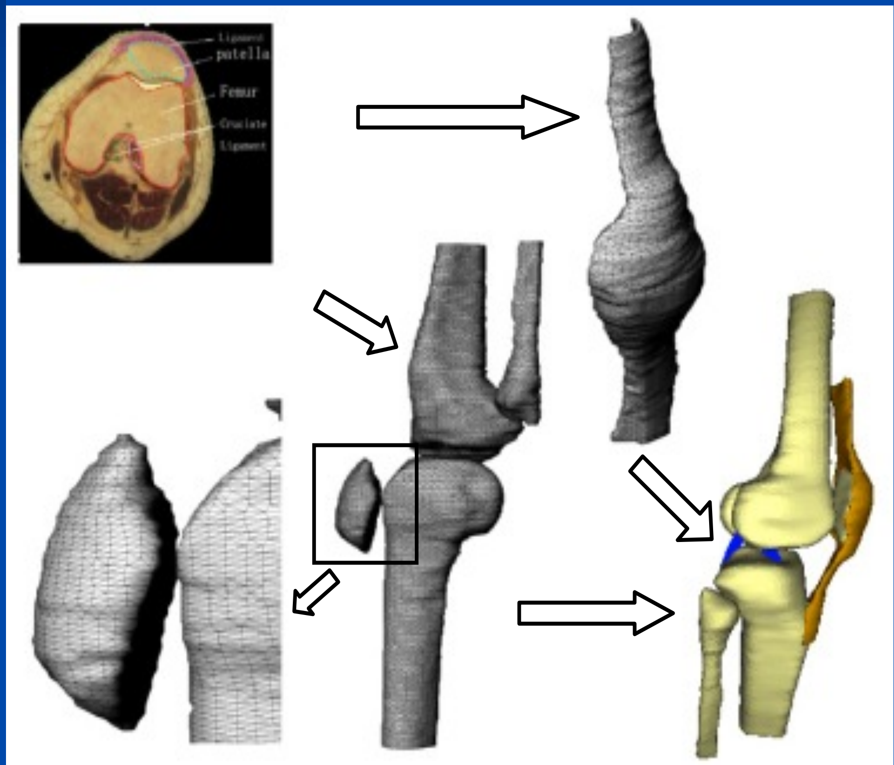
Virtual Arthroscopic Knee Surgery Training System

- Modeling using data from Visible Human Project
- Simulation of the deformation of soft tissue with topological change by FEA
- User interaction
  - Two-hand force feedback interface

Virtual Arthroscopy – software system architecture



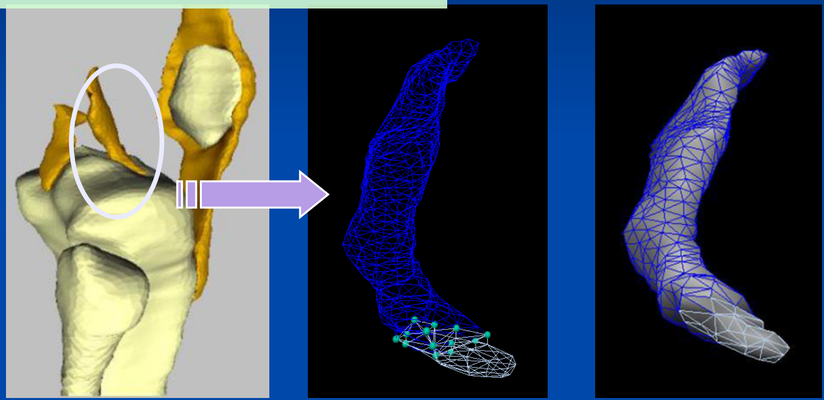
Three-dimensional Reconstruction of the Knee



Implementation and Experiments

- Two tetrahedral models from the Visible Human Project

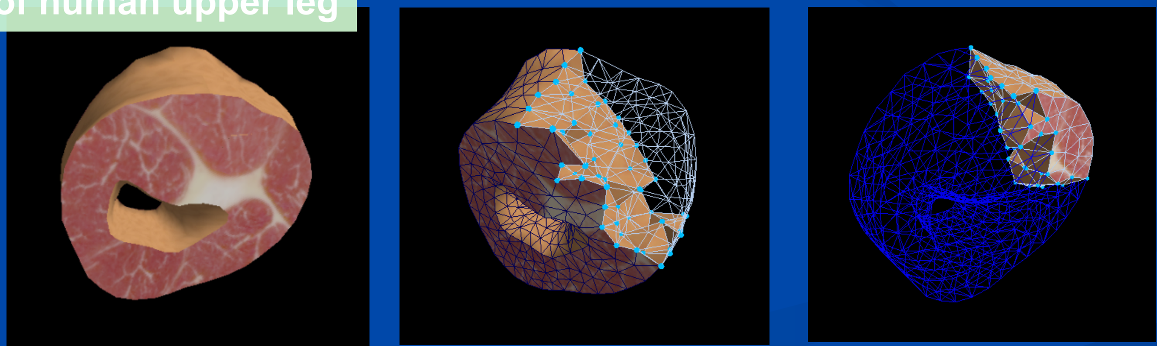
Model of human knee ligaments



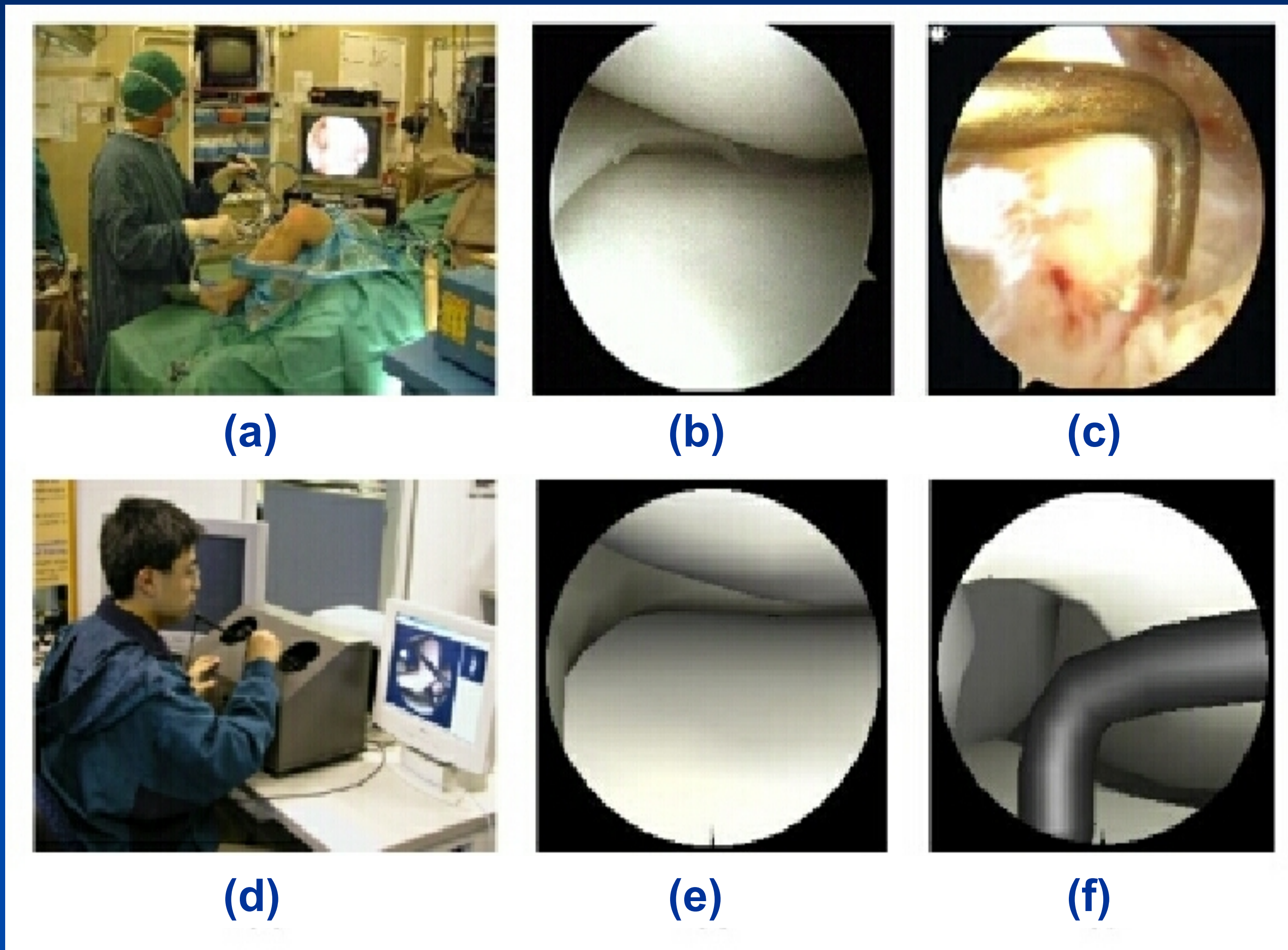
The Scale of the Original Models

Model	The Operational Region (Nodes / Tetrahedra)	The Non-operational Region (Nodes / Sur. Nodes / Tetrahedra)
The Ligament	40 / 71	575 / 438 / 1829
The Upper Leg	152 / 416	633 / 416 / 2134

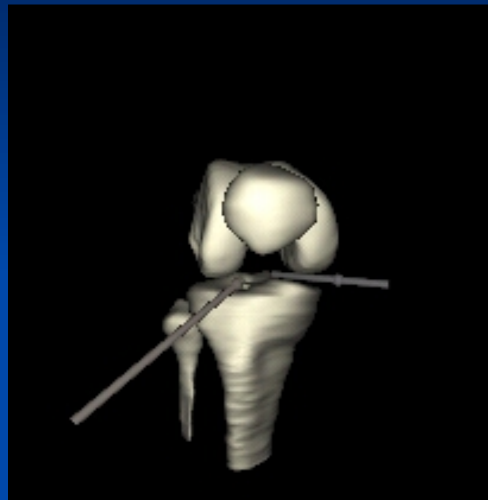
Model of human upper leg

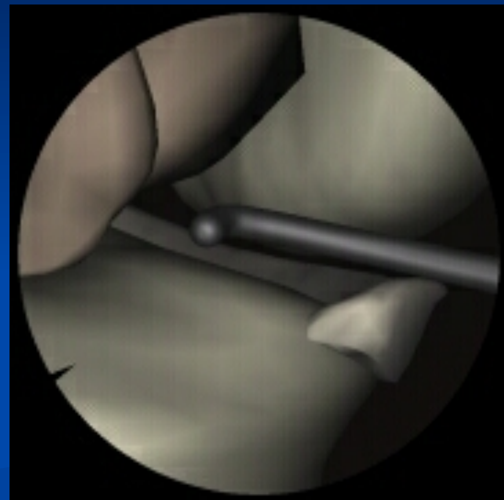


Comparison between Virtual User Interface and Real Environment



Virtual Knee Arthroscopic Surgery





IEEE TRANSACTIONS ON INFORMATION TECHNOLOGY IN BIOMEDICINE, VOL. 8, NO. 2, JUNE 2004 217

A Virtual-Reality Training System for Knee Arthroscopic Surgery

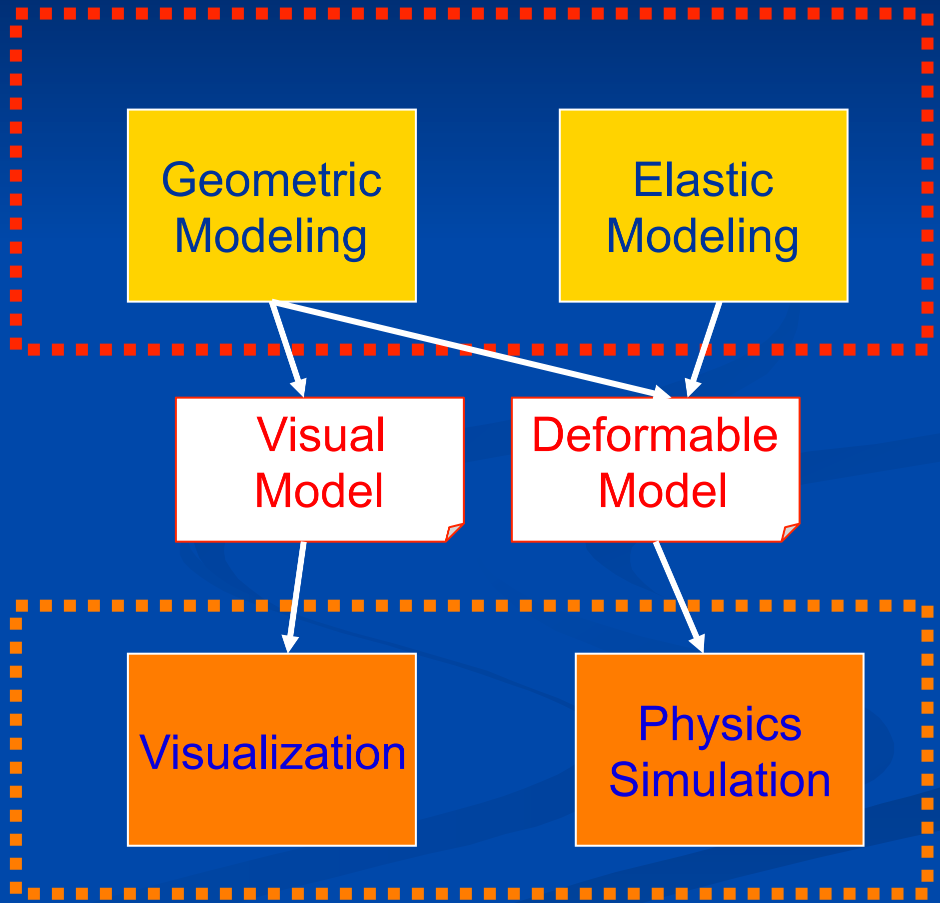
Pheng-Ann Heng, *Member, IEEE*, Chun-Yiu Cheng, Tien-Tsin Wong, *Member, IEEE*, Yangsheng Xu, *Fellow, IEEE*, Yim-Pan Chui, Kai-Ming Chan, and Shiu-Kit Tso, *Senior Member, IEEE*

Virtual Orthopedic Surgery with Soft Tissue Deformation and Bleeding

- Soft tissue deformation
- Bleeding simulation
- GPU & PPU based acceleration

Soft Tissue Deformation

- Modeling
  - Geometric modeling
  - Elastic modeling
- Simulation
  - Visualization
  - Physical simulation
    - MSM model
    - PPU acceleration



Geometrical Modeling

- Deformable and visual models
  - Based on segmented CVH
  - Anatomically consistent
- Human skin and muscle
  - Epidermis
  - Dermis
  - Hypodermis
  - Muscle
- Multilayer structure

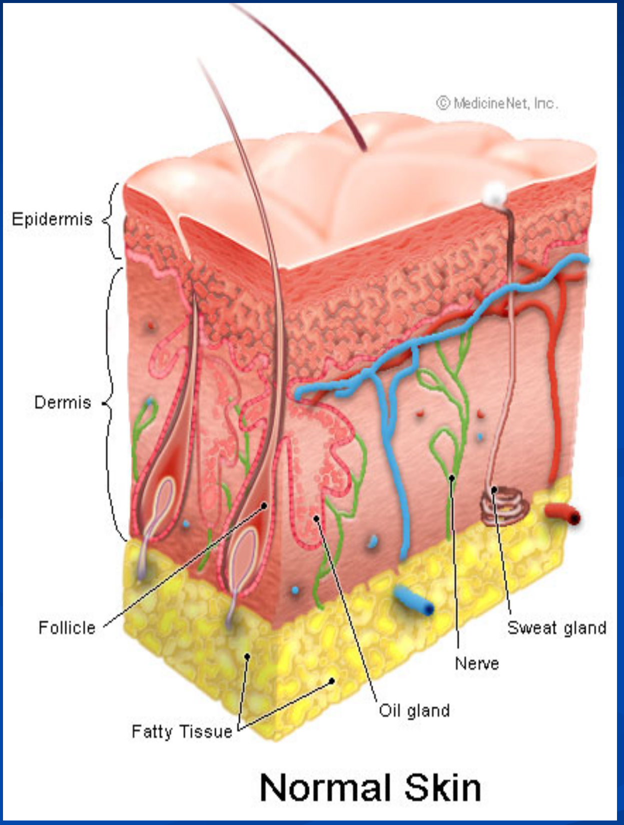
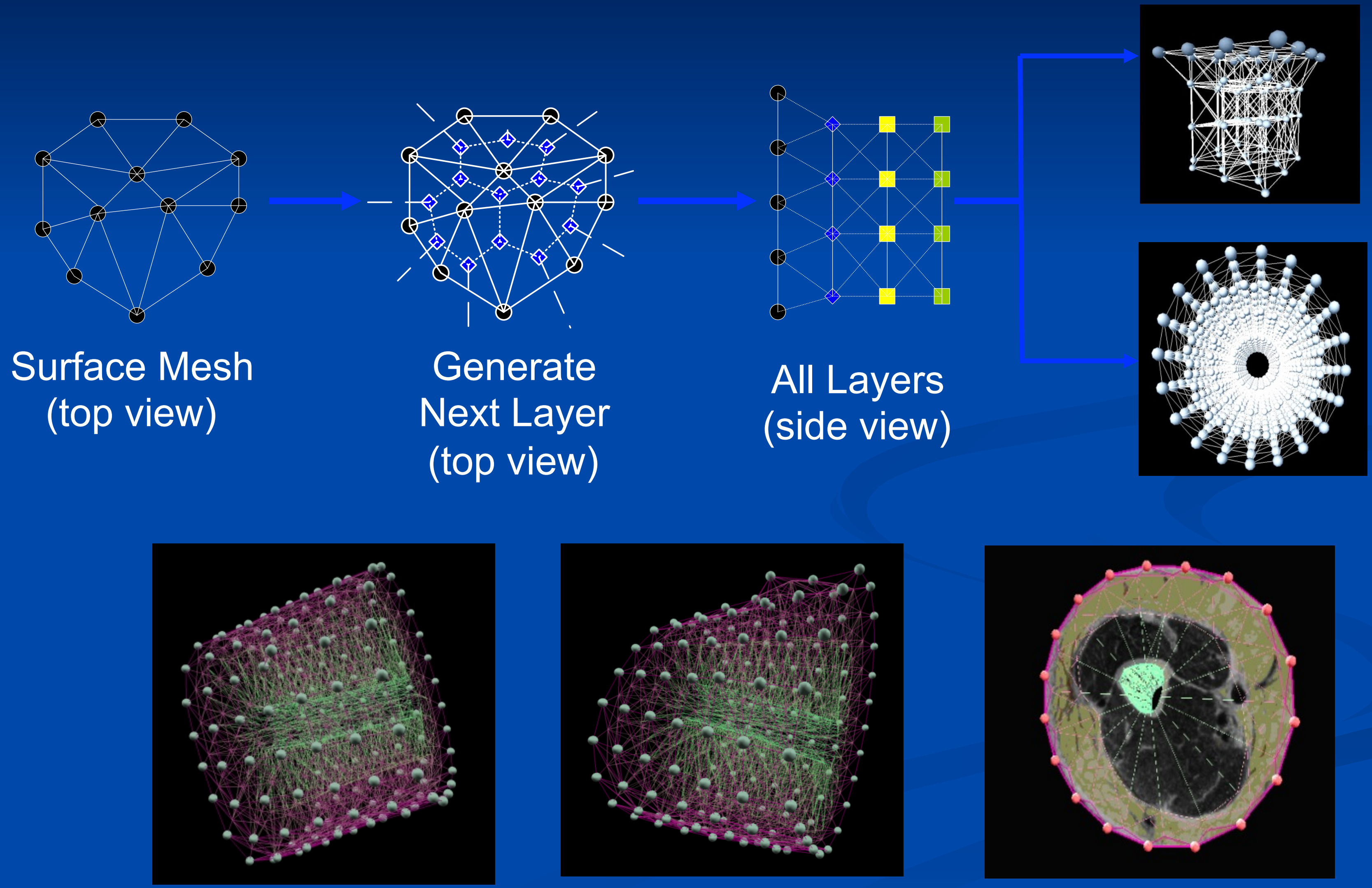


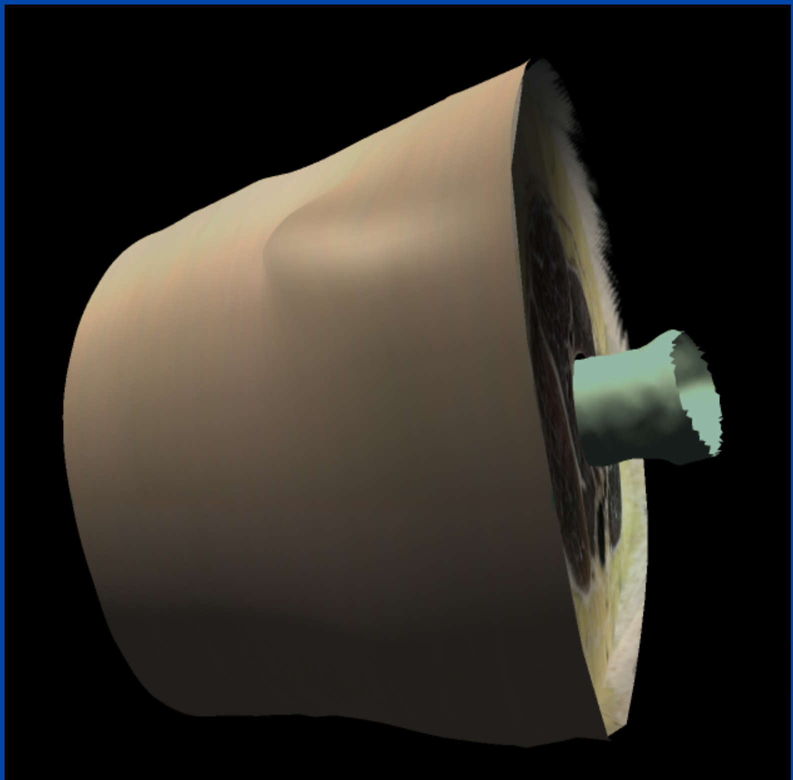
Image Courtesy from MedicineNet.com

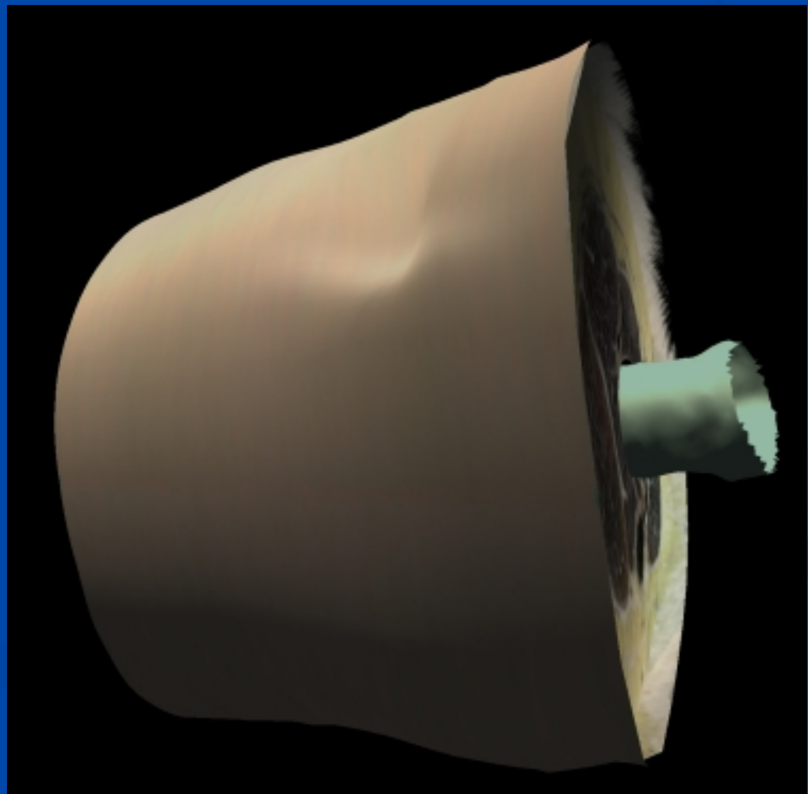
Multilayer Model Generation



Visualization

- Texture mapped using CVH data
- Smoothed with Bezier Patch Interpolation on the skin surface





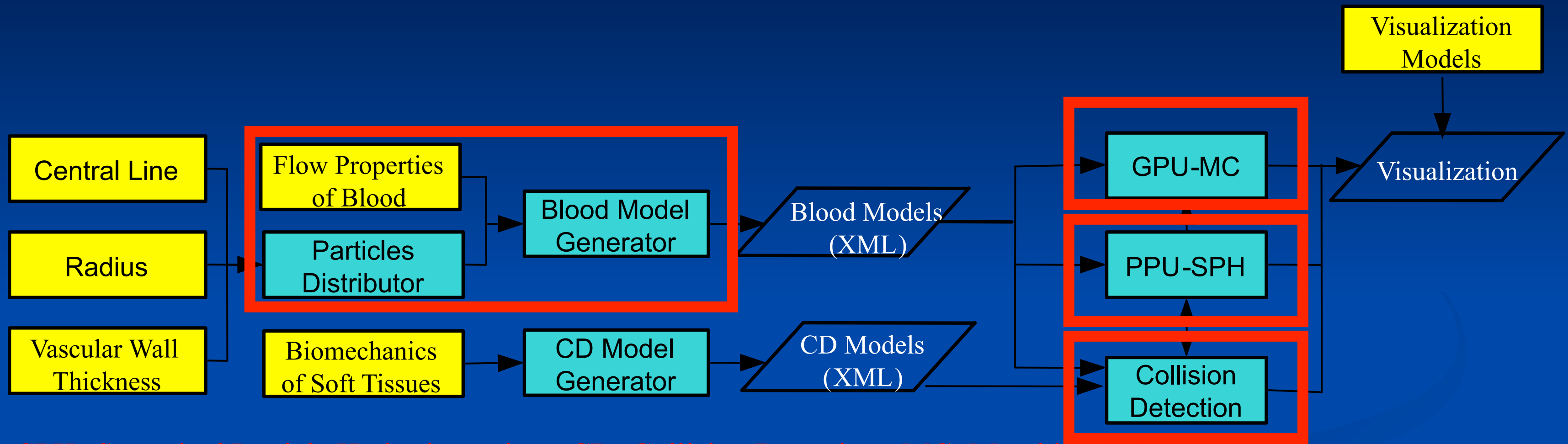
Bleeding Simulation

- Importance of Bleeding Simulation
  - Enhance realism of virtual surgery
    - Hysteroscopic surgery
  - Provide crucial information for surgery training and designing
  - Patient-specific diagnosis planning
- Challenges
  - Physically-based fluid model
  - Complicated biomechanical properties
  - Balance between realism and speed

Hardware Acceleration

- Resolve high computational requirements by special designed hardware
- Graphics Processing Unit (GPU)
  - Parallel pipelines (SIMD)
  - Programmable for various rendering effects
- Physics Processing Unit
  - Tailor for common physics computation
  - Collision Detection, Mass-spring, Cloth

Overall Framework

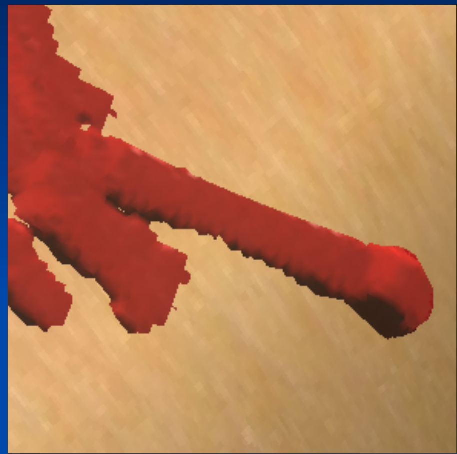


SPH : Smoothed Particle Hydrodynamics   CD: Collision Detection   MC: Marching Cubes

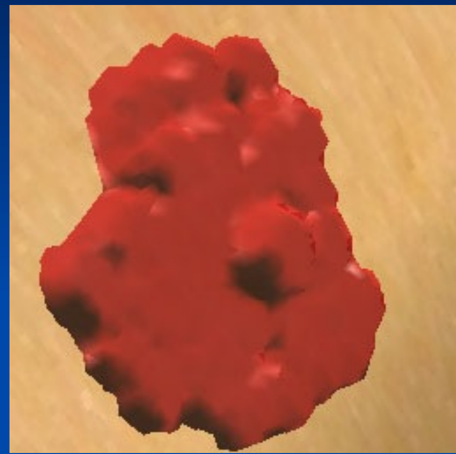
- Blood Modeling
- PPU-Based Bleeding Simulation based on SPH
- Collision Detection between Blood and Soft Tissues
- GPU-Accelerated Marching Cubes for Blood Surface Rendering

Various Bleeding Phenomena

Tricking



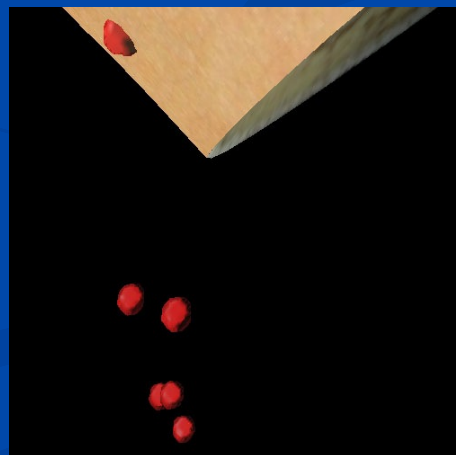
Flowing



Pooling

Gushing

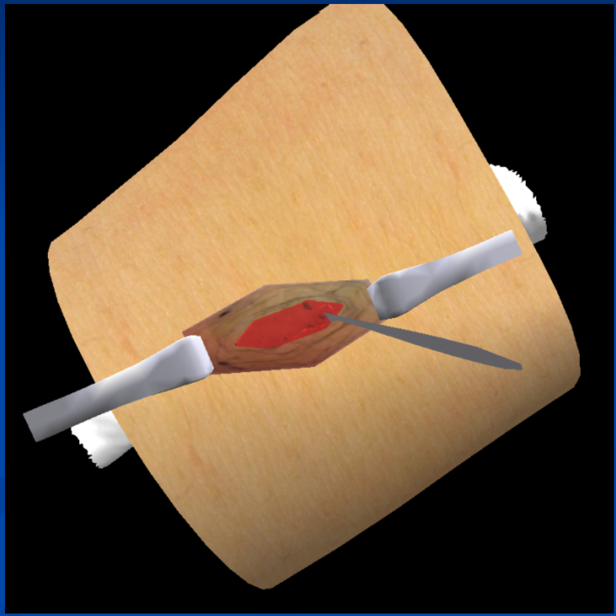
Pouring

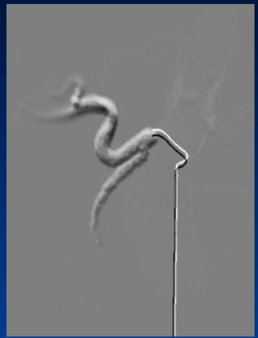


Dropping

Application

- Experimentally Integrated into an Orthopedics Trainer
- Geometry construction and visualization based on Chinese Visible Human Datasets
- PPU-accelerated soft tissue deformation
- Simulate nonlinear soft tissue properties with bi-phasic linear deformable model



Vascular & Interventional Radiology Simulator

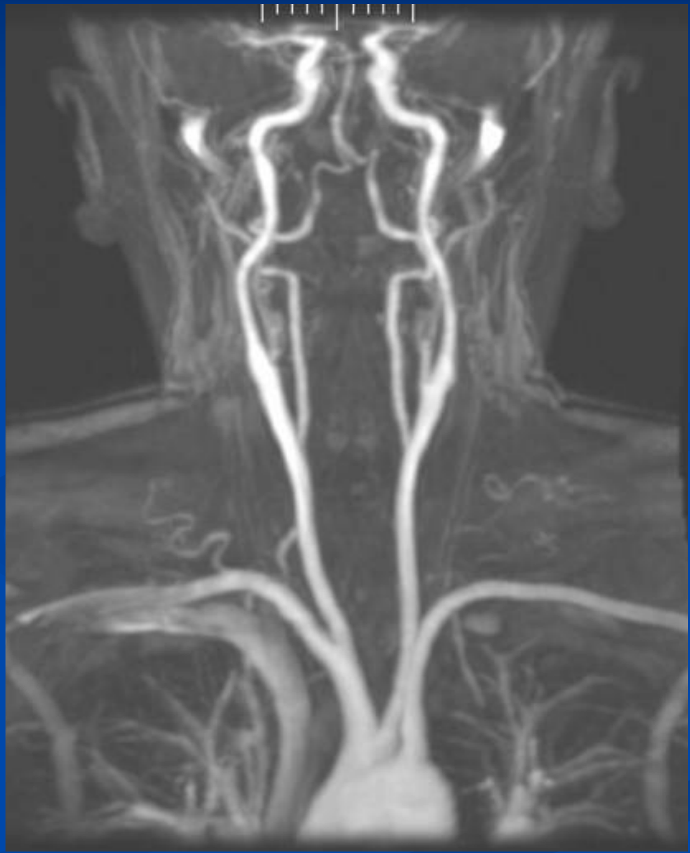
The Chinese University of Hong Kong (CUHK) and
Vascular and Interventional Radiology Foundation Limited (VIRF)

What is VIR

- Vascular and interventional radiology (VIR)
  - *image-guided* and minimally invasive therapeutic procedures through tiny *pin-hole punctures* under the visual control of medical equipment.

Image guidance in VIR

- X-Ray fluoroscopy
- Computed Tomography Angiography (CTA)
- Magnetic Resonance Angiography (MRA)



Common VIR procedures

- Angiography
- Angioplasty
- Embolization

VIR treatment

- Certain common *killer diseases*, previously considered *incurable* or *inoperable*, can now be effectively treated with VIR. E.g:

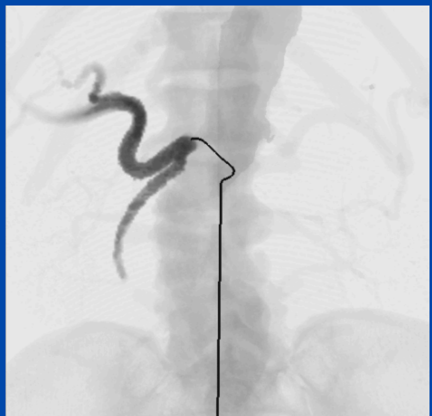
  - Stroke
  - Cancer and other tumors
  - Hemorrhage
  - Blood vessel diseases

Difficulties in VIR training

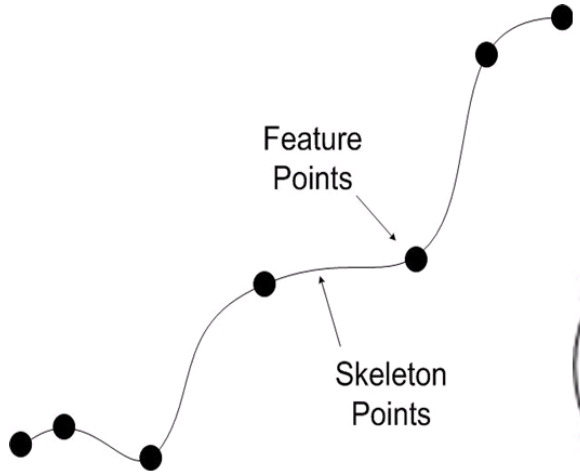
- Real patient: may hurts
- Cadaver: limited supply, non-repeatable, no physiological conditions
- Animal: not conform to human counterpart

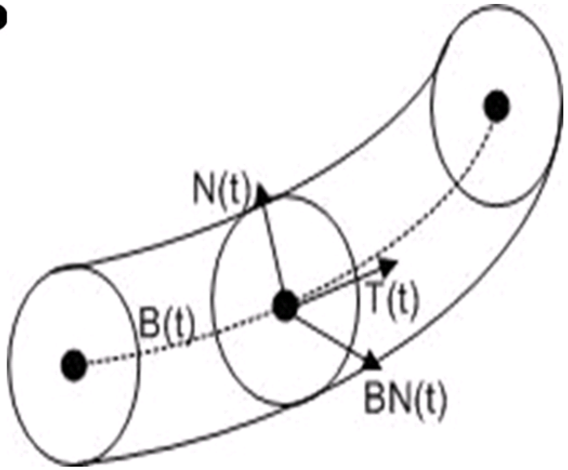
Our work

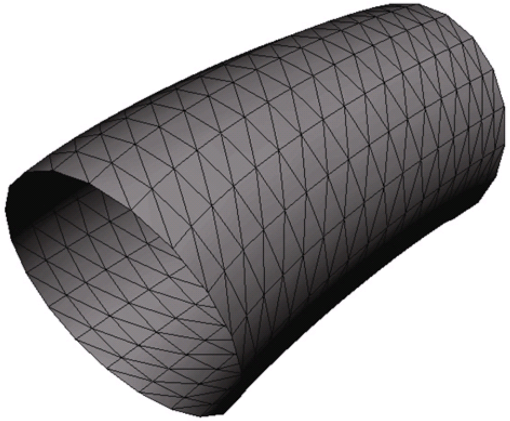
- A virtual reality (VR) based platform for
  - *learning* VIR related anatomy
  - *training* VIR procedures

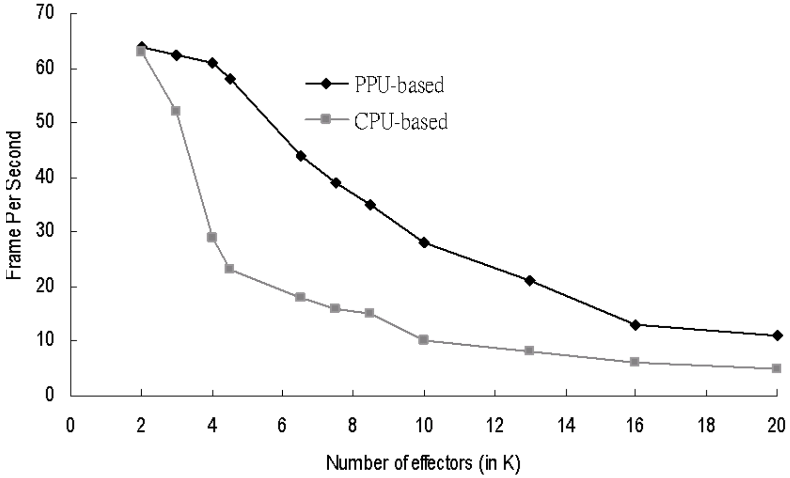


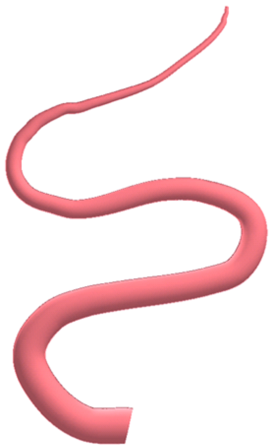
Research in Surgical Simulation

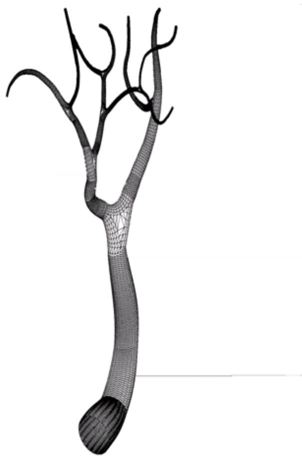


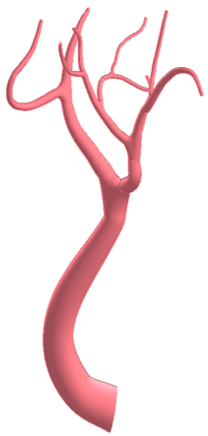






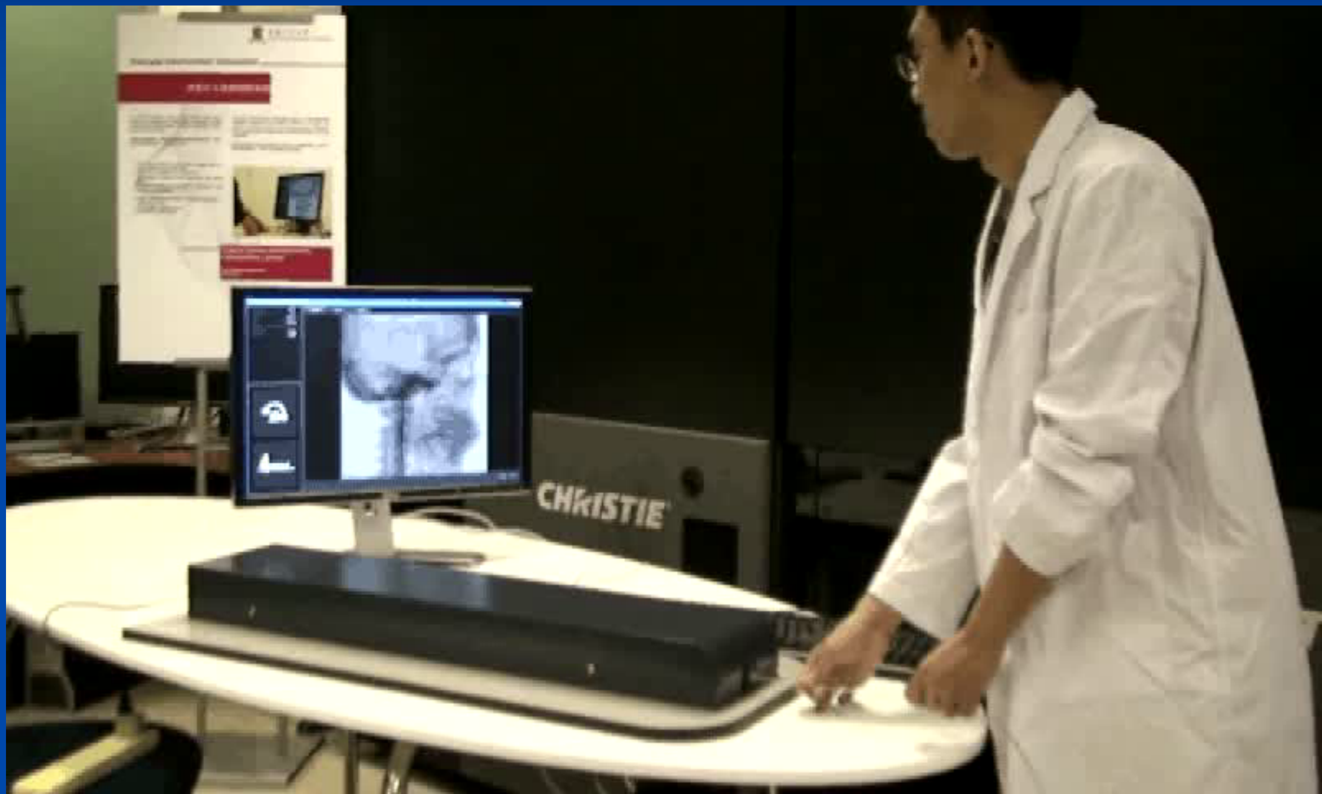




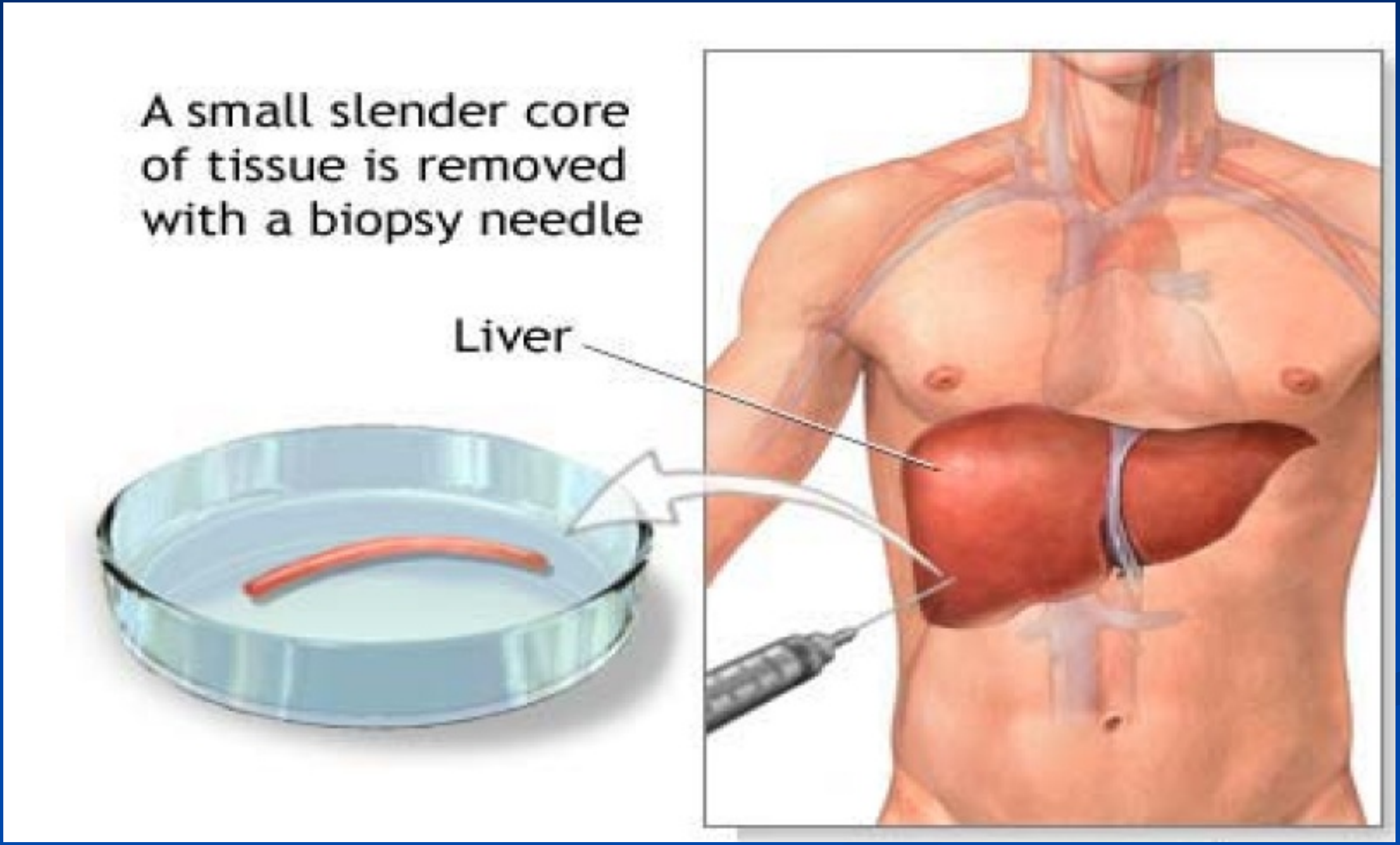


J. Guo, S. Li, Y. P. Chui, Q. Meng, H. Zhang, C. H. Yu and P. A. Heng, "PPU-based Deformable Models for Catheterisation Training," Proceedings of Computational Biomechanics for Medicine II, a *MICCAI 2007* Workshop, Brisbane, Australia.

Vascular Interventional Simulation

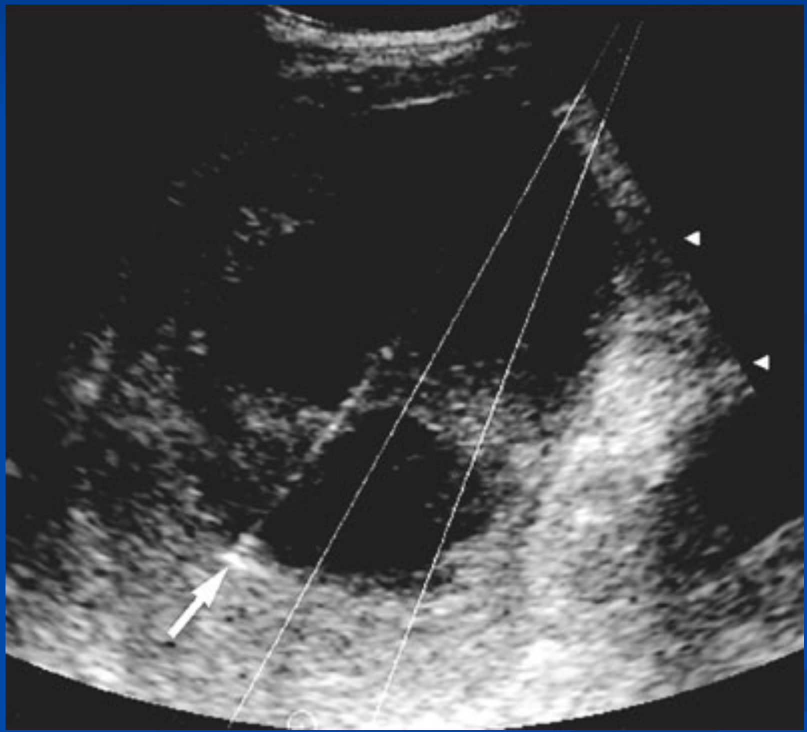


Ultrasound-Guided Biopsy Simulation



Introduction

- Ultrasound guided biopsy

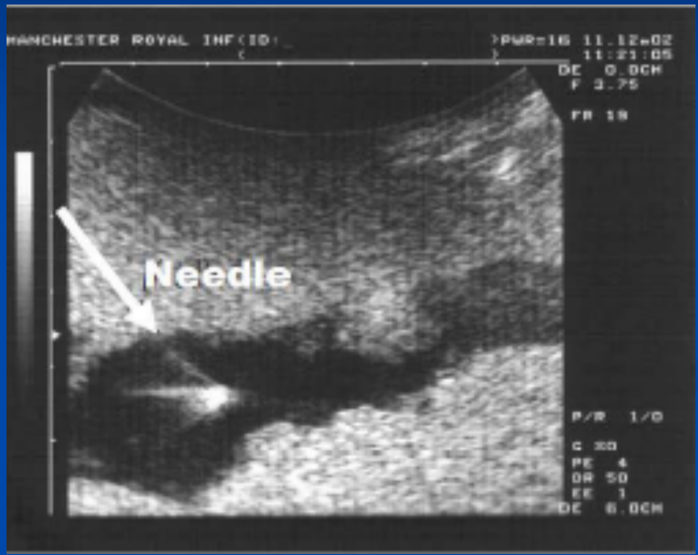


Motivation

- Ultrasound guided biopsy is highly risky for an inexperienced doctor.
- The only reliable approach to acquisition of such professional skills is practicing in a specialized training regime.
- Practicing needle placement on human patients is dangerous and impractical.
- An obvious solution is using simulation systems for training.

Related Researches

- Franck(2005) presented a simulator for needle guidance training.



- Simulated ultrasound images are produced by moving an ultrasound scanner on a foam filled box and can't guarantee the realism .

Related Researches

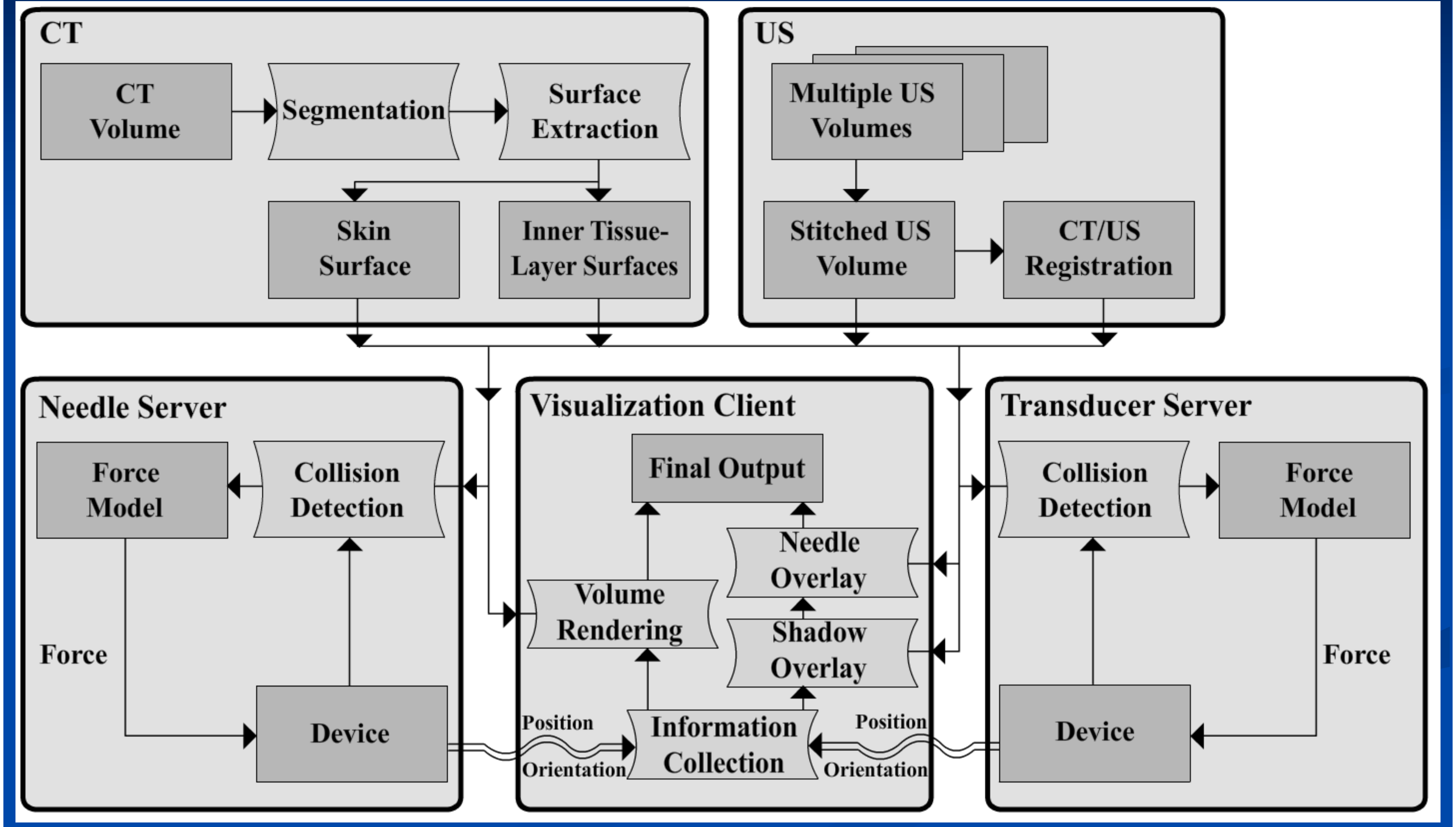
- Magee(2007) introduced an augmented-reality system for ultrasound guided needle placement training.

- The limitations in the system is that it cannot provide realistic force sensation.

Related Researches

- Forest(2007) presented a simulator with haptic devices for ultrasound guided needle insertion.
- US images is mainly based on CT or MRI.
- The needle is simulated by adopting a 3DOF force feedback device which cannot provide resistance torque force in maintaining the needle insertion path.

System Framework



System Overview

Demo

Volumetric Ultrasound Panorama Based on 3D SIFT

- Introduction
- Related Works & Motivation
- Methods
  - Ultrasound Preprocessing
  - 3D Feature Detection and Descriptor Construction
  - Ultrasound Volume Registration and Stitching

Volumetric Ultrasound Panorama --- Introduction

- US Panorama is used to widen the field of view of US images for clinical diagnosis.
- 2D US panorama has been prevalent in routine clinical practices.
- Over the past few years, 3D US has been popular.
- The key issue is the registration of US volumes .

Volumetric Ultrasound Panorama --- Difficulties

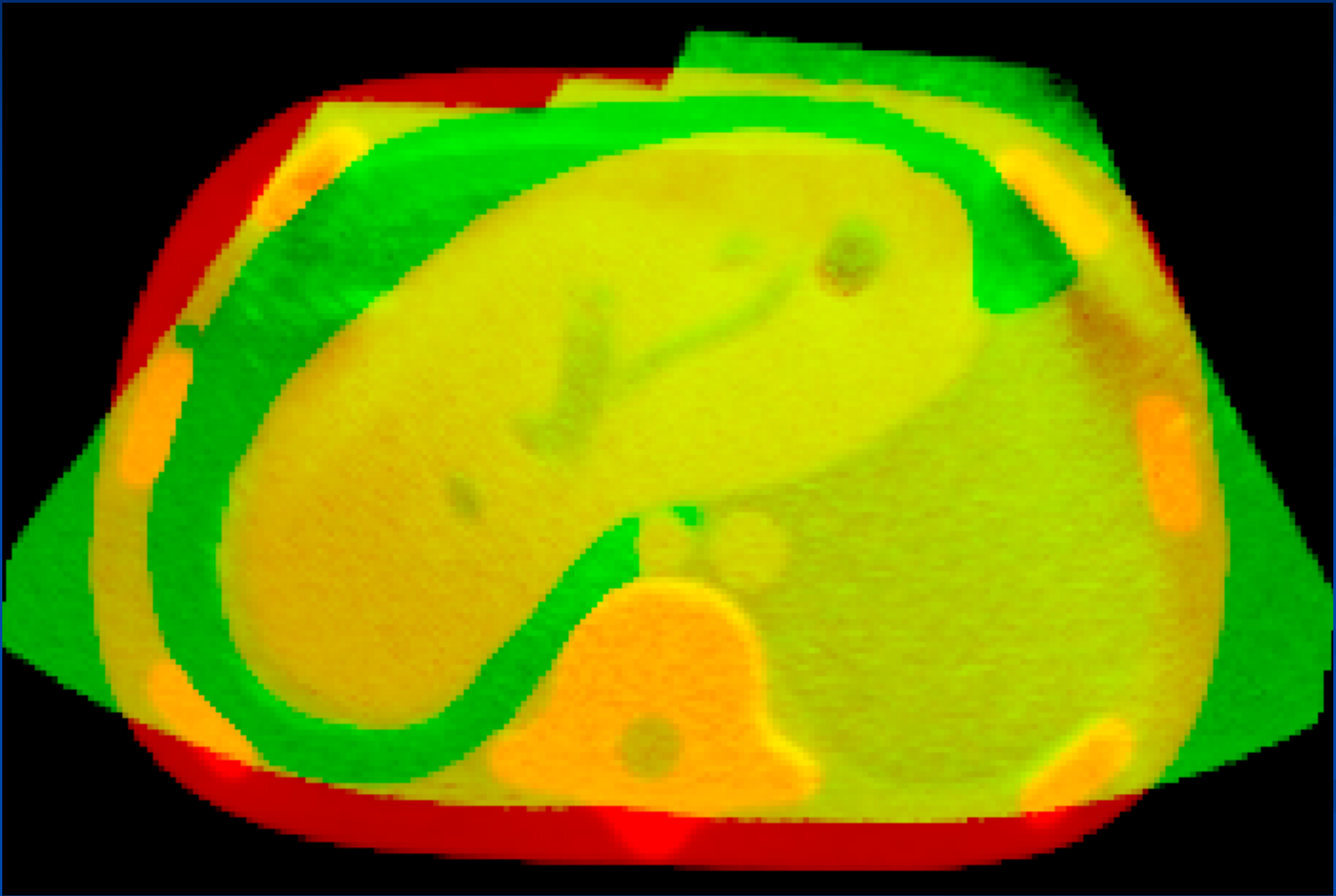
- Low signal to noise ratio
- Shadows, speckles and other artifacts
- Direction-dependent imagery
- Ultrasound probe is arbitrarily oriented during scanning.

Volumetric Ultrasound Panorama --- Motivation

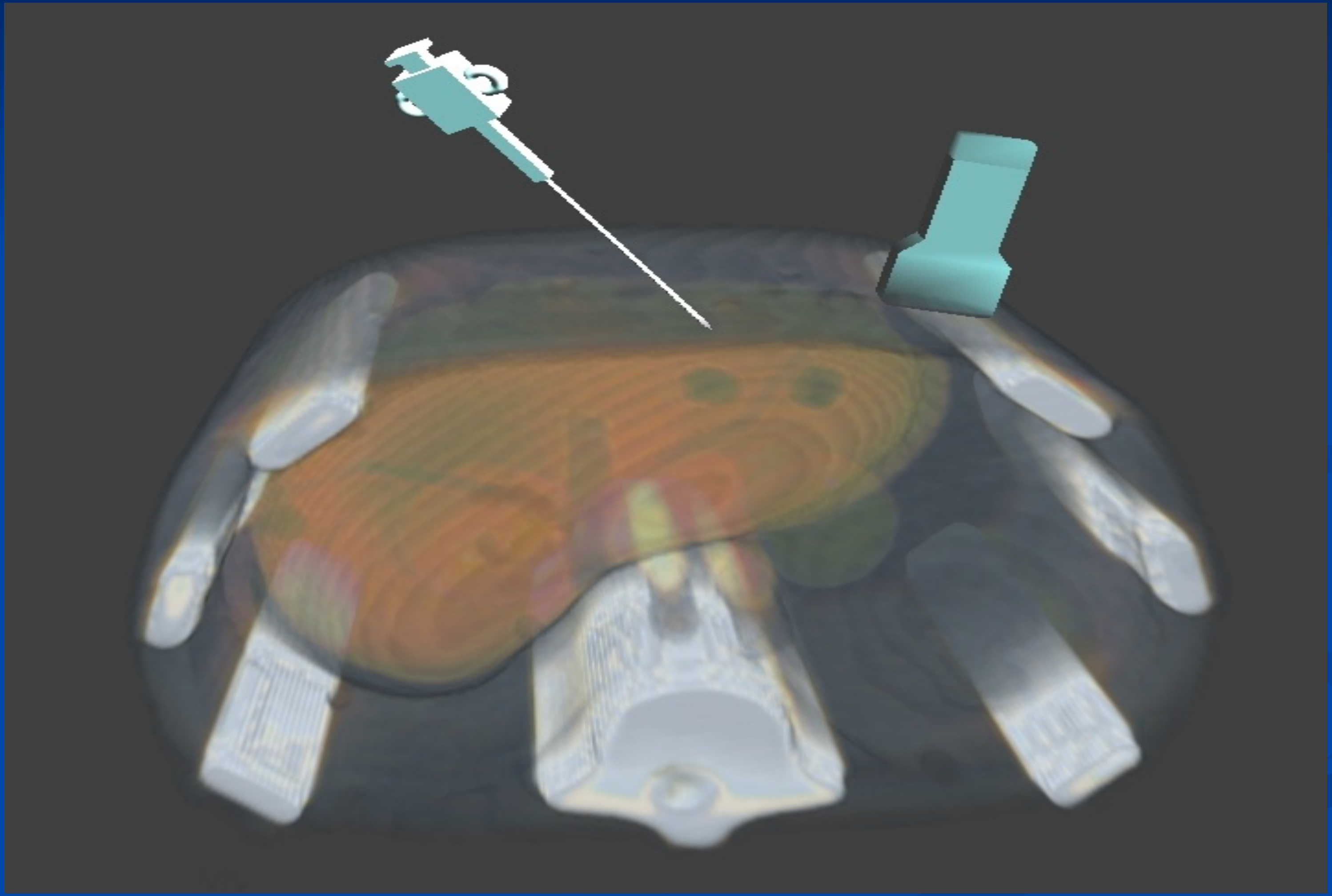
- Traditional intensity based registration methods perform poorly on US data.
- Position tracker is affected by metals (in case of magnetic sensors) or sight occlusions (in case of optical sensors).
- SIFT features are invariant to rotation and robust to noise and intensity change.

Volumetric Ultrasound Panorama
--- Ultrasound Preprocessing

Visualization Rendering
--Fusion of CT and US

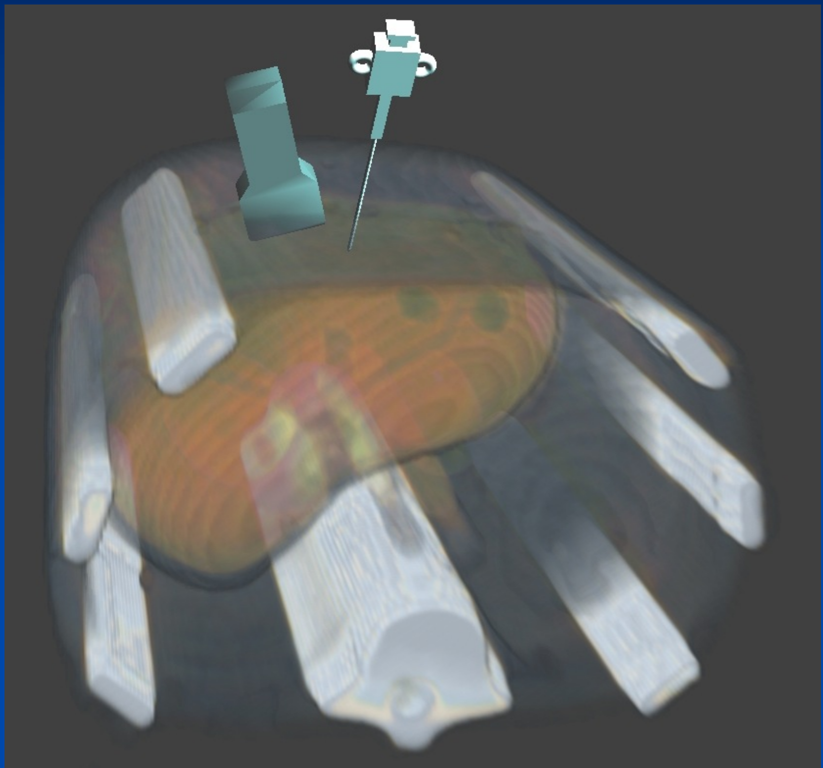


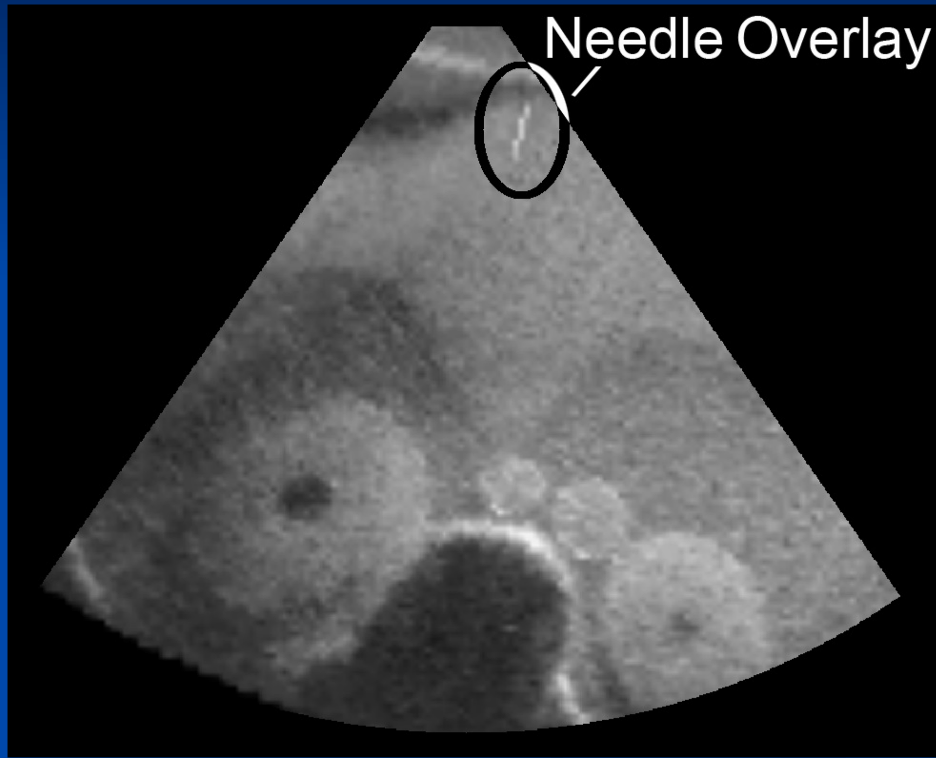
Visualization Rendering
--Volume Rendering of CT Volume



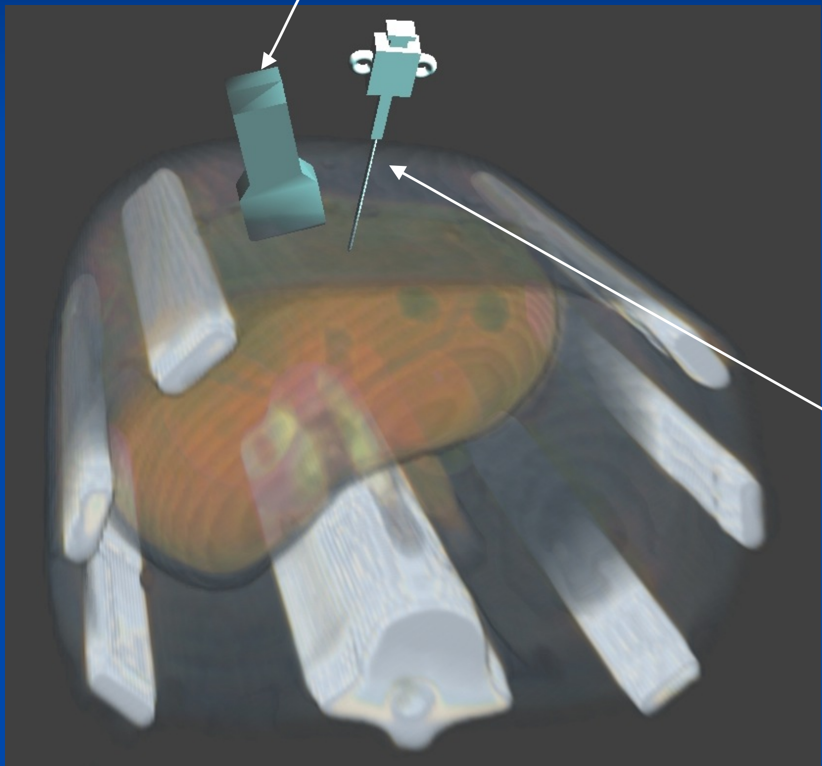
Visualization Rendering --Shadows

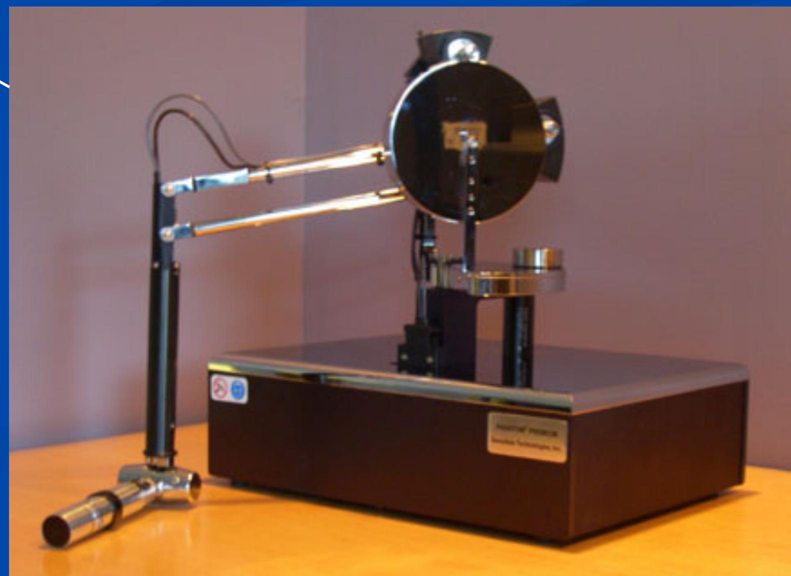
Visualization Rendering --Needle Overlay





Haptic Rendering



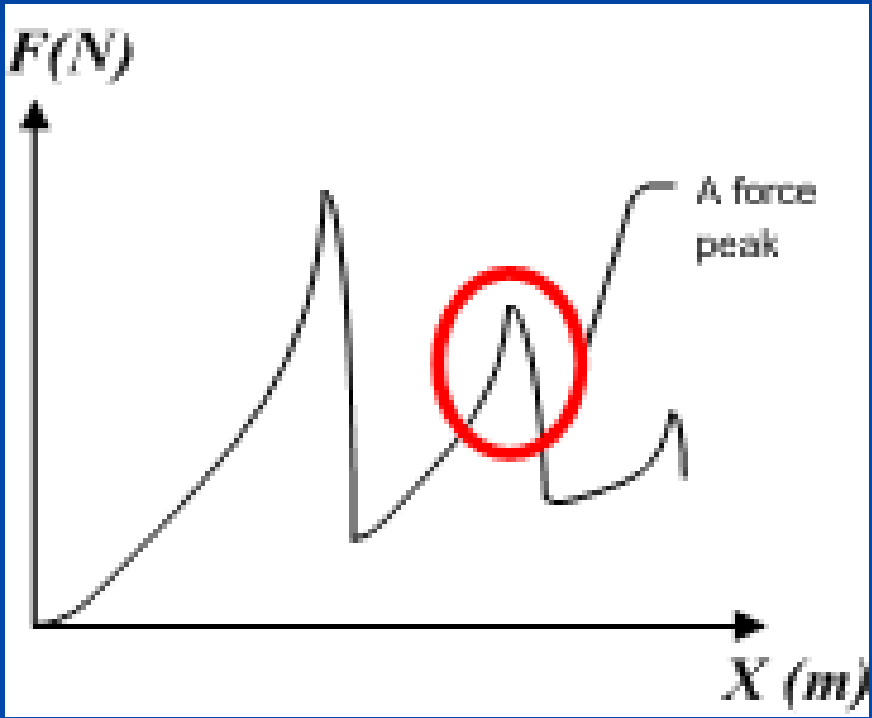


Haptic Rendering
--Virtual Transducer

- We set a constraint on the skin surface to restrict the virtual transducer from passing through it.
- Users can feel a resistance force when the virtual transducer collides with the skin.

Haptic Rendering
--Virtual Needle

- Typical force profile of needle insertion from skin into liver.



Including the pre-puncture force, friction force and cutting force

Haptic Rendering
--Force Modeling

- **Friction Force Modeling**
  - Occur along the needle insertion path and caused by the relative motion between the needle and tissues;
  - Gradually increase with the contact area between the needle and tissues;
  - Fluctuate during the penetration procedure due to the needle clumping .

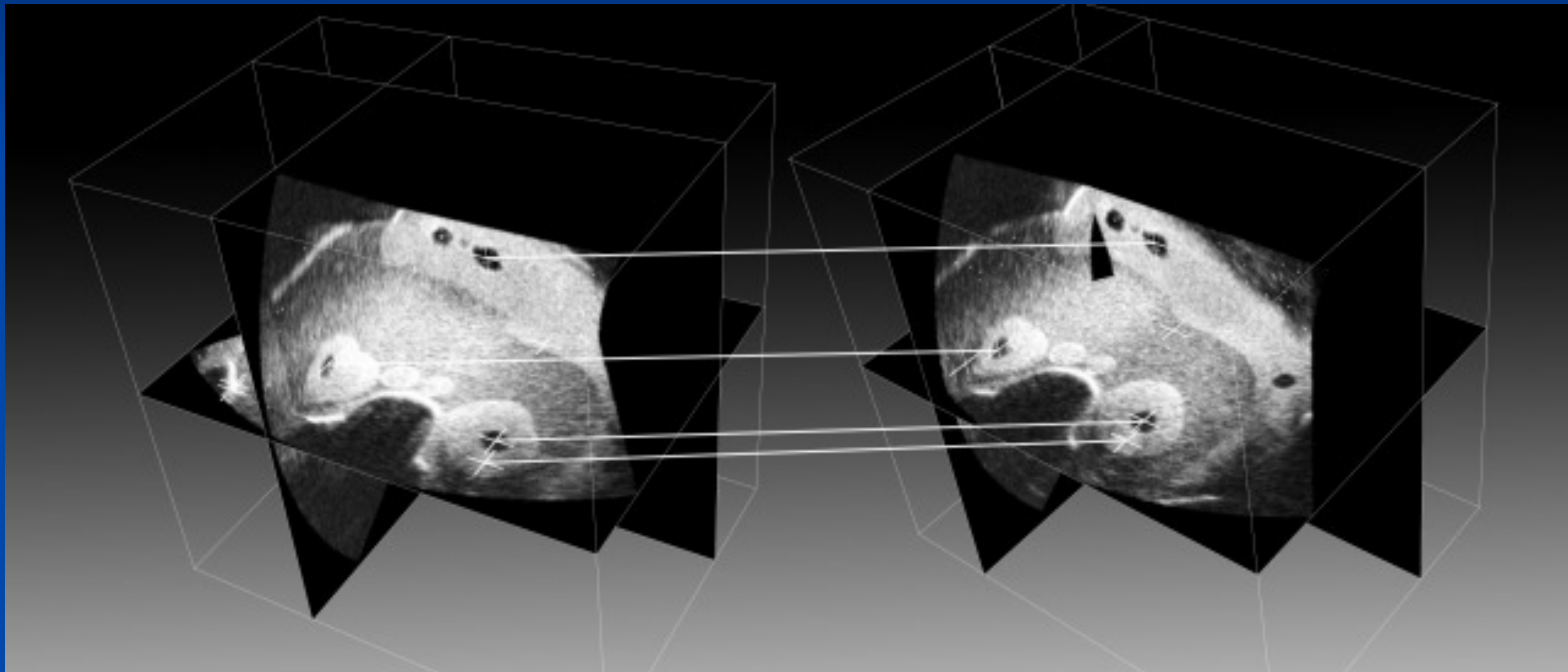
Haptic Rendering
--Force Modeling

- **Cutting Force Modeling**
  - The cutting force is caused by the collisions with and puncture of the interior structures of liver;
  - Cutting force can be approximated to a constant force.

Data Acquisition

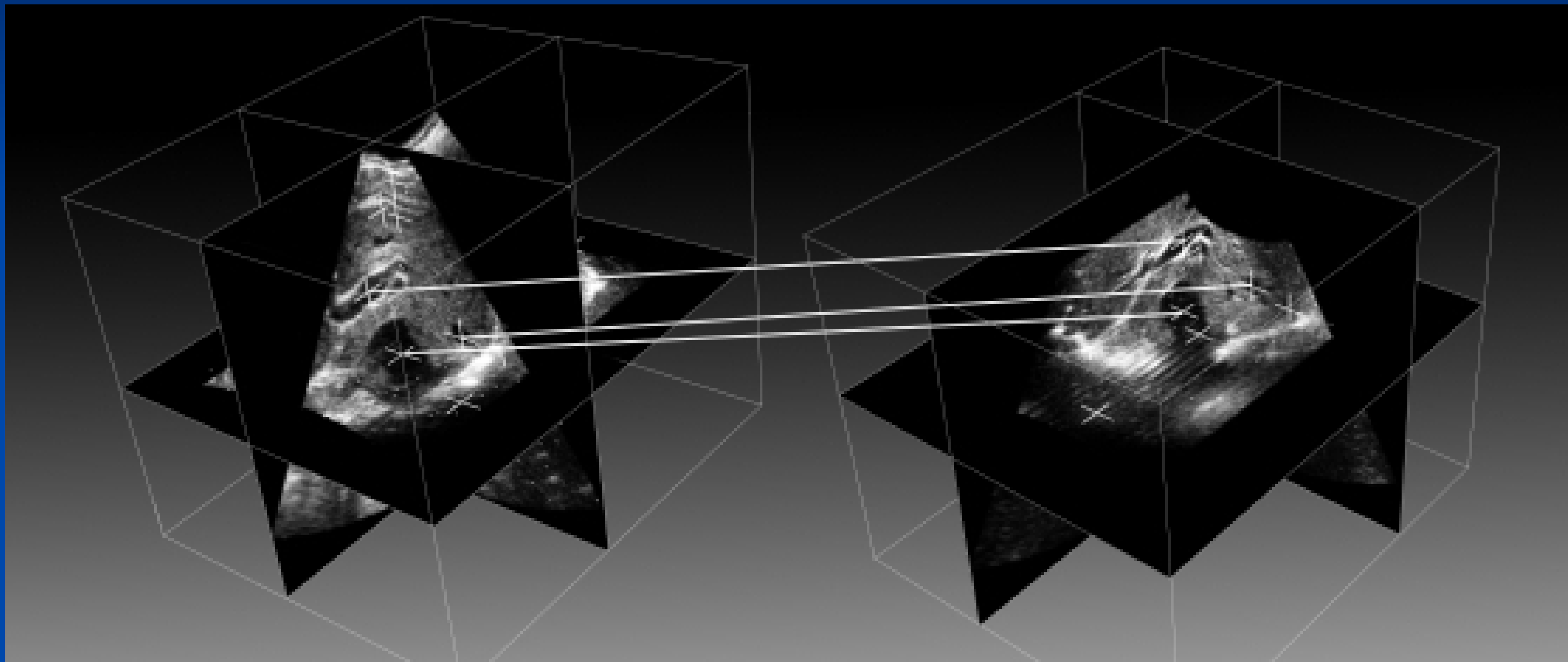
- Ultrasound
  - Acquired using a GE Voluson 730 ultrasound scanner with a dedicated 3D ultrasound probe.
  - Two sets of data were collected: 5 volumes from a phantom (CIRS Model 057, mimicking human liver tissues) , 3 volumes by scanning the liver of a patient.
- CT volume
  - Acquired from a GE Lightspeed 16-slice multi-detector on the same phantom.

Volumetric US Panorama

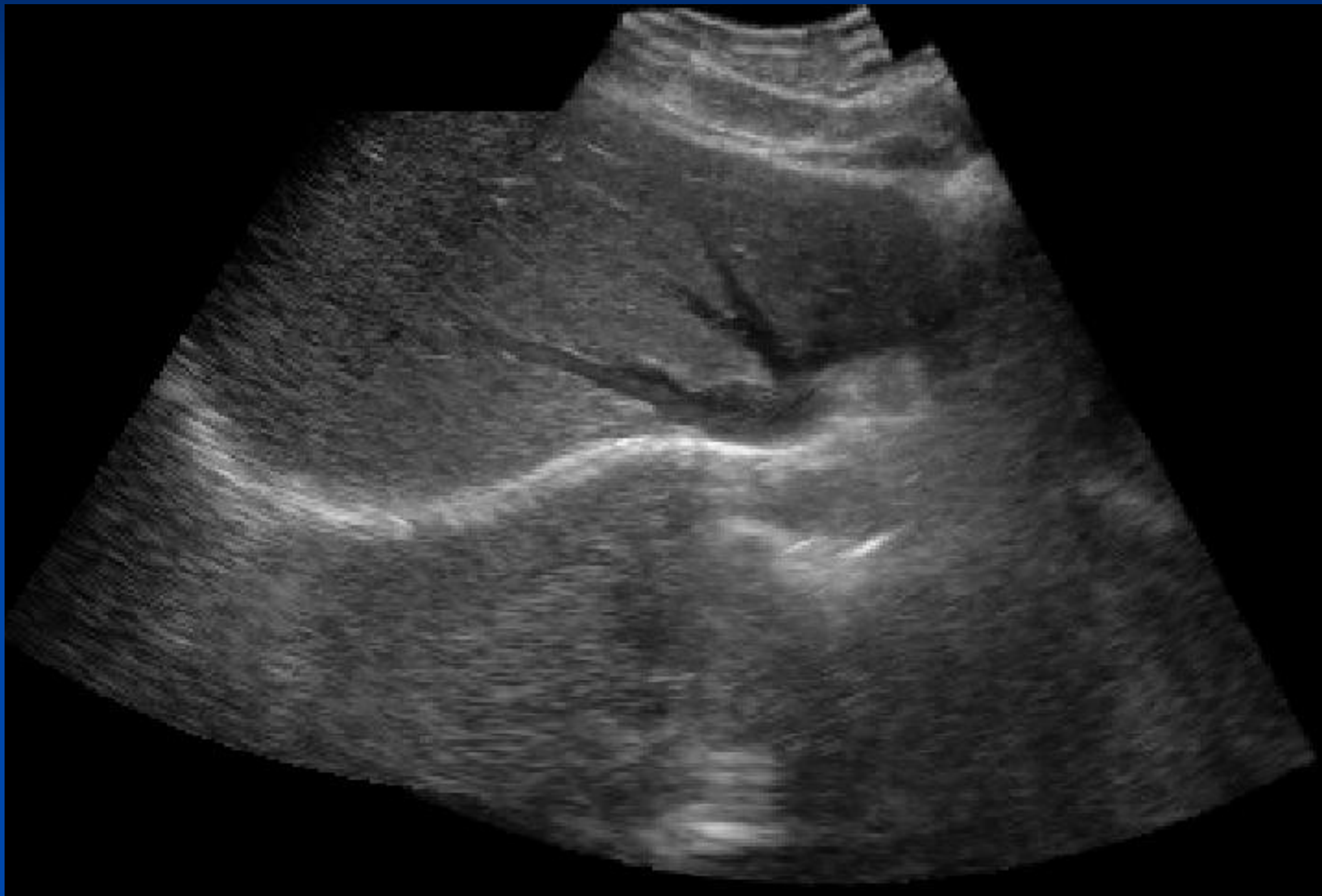


Volumetric US Panorama

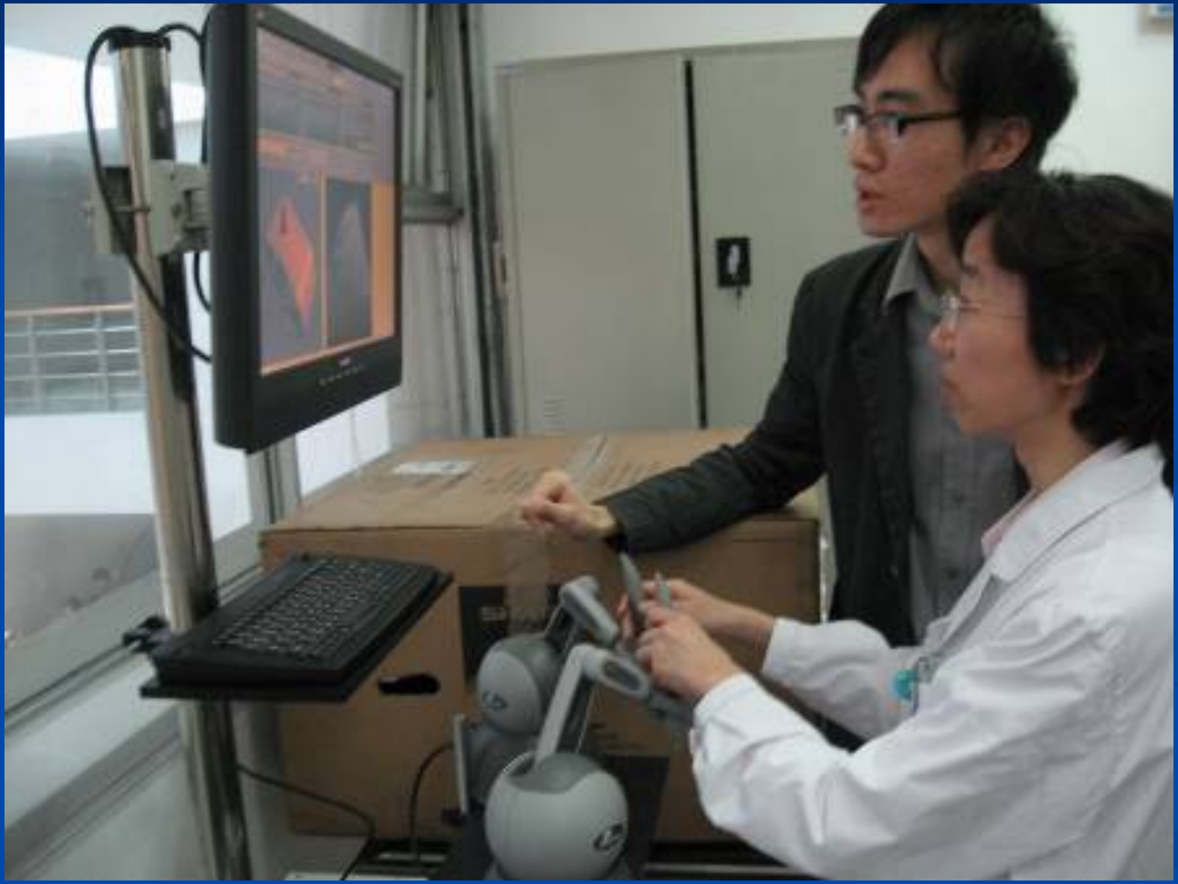
Volumetric US Panorama



Volumetric US Panorama

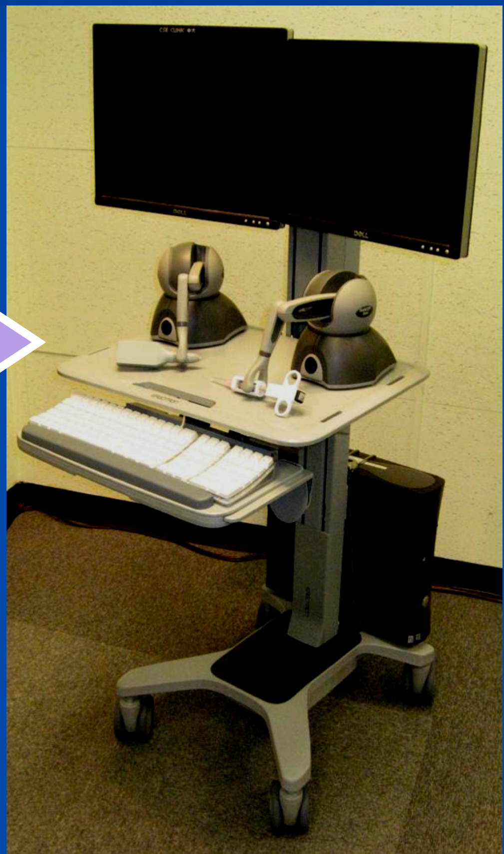


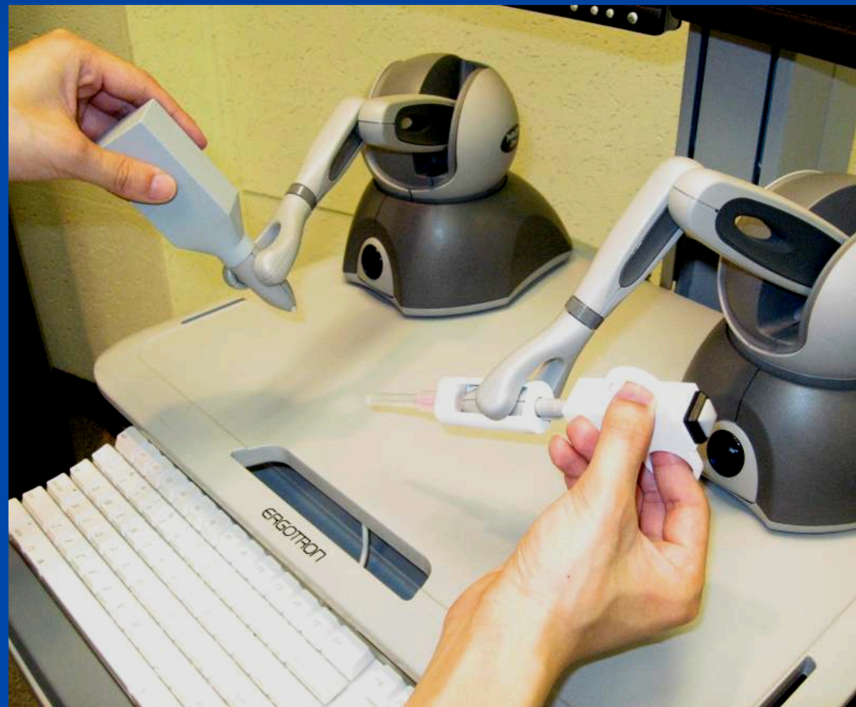
Ultra-Sound Guided Biopsy Simulation



Ultra-Sound Guided Biopsy Simulation

- Improved version

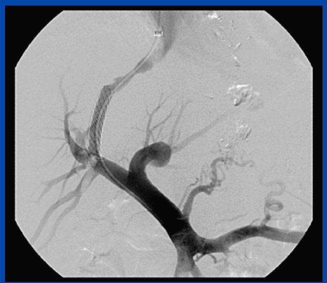




Collaborative Research Direction

- Information-enhanced medical image computing
- Virtual anatomical and functional human
- High fidelity virtual surgical simulation:
  - Minimally invasive surgeries
  - Vascular interventional radiology surgeries

Long term R&D in virtual medicine



- Virtual Anatomy
  - Virtual Skeletal Anatomy
  - Virtual Cardiovascular Anatomy, etc.
- Virtual Ultrasound Intervention
  - Regional Anaesthesia
  - US-guided breast biopsy, liver biopsy, etc.
- Vascular & Interventional Simulation
  - Organ-based Intervention
  - Cardiac vascular Intervention, etc

Summary

- There are many exciting applications to be further developed in virtual medicine and computer assisted medicine.

- Virtual reality, visualization and imaging will play an important role in future medical education, diagnosis, as well as surgical planning and training.

- Deep collaborations among medical and engineering colleagues are essential in order to achieve breakthrough advancement.