Development and Validation of an Open-Source Real-Time Freehand 3D Ultrasound Navigation System for Liver Surgery with GPGPU Acceleration

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Motivation

- Colorectal cancer is the second most common cause of death from cancer in the Western World [1]
  - up to 50 % of patients will develop liver metastases during the course of their disease [7]
- Over the last 30 years resection has been the “gold standard” treatment of malignant liver tumors [8]
- Accurate resection-limitations are essential for longterm survival after the resection
- Very often it is difficult to measure the distance from the surgical margin to the tumor [1]

Current Use of Ultrasound

- Many surgeons still rely solely on intraoperative ultrasonography and have not recognized the advantages of intraoperative navigation support [12]
  - → The surgeon combines pre-operative data 3D data with intraoperative information intuitively [2]
  - ⟹ Accuracy in liver surgery depends on the experience of the surgeon

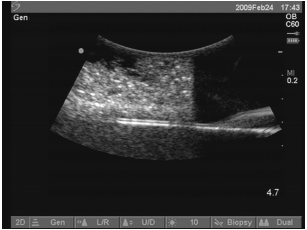


Figure: Ultrasound image

- Even in specialized centers rates of critical resections are high [9]
  - ⟹ Higher precision is needed [2]

Image Guided Surgery

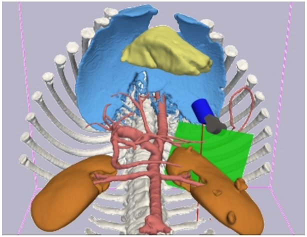


Figure: Image Guided Surgery

- Image guided surgery using navigation techniques is already an evolving procedure in neurosurgery, orthopaedic and otolaryngology surgery
  - $\longrightarrow$ Improved intraoperative orientation
  - $\Longrightarrow$ Increased accuracy of tumor localization and bone resection [11]
- Operative therapy of abdominal tumors is even more challenging because of
  - tissue deformation
  - breathing artifacts
  - absent / reduced anatomical landmarks

Current Operative Planning

- Current operative planing is based on [9]
  - Conventional computed tomography (CT)
  - Magnetic resonance imaging (MRI)
- Preoperative 3D simulation improves
  - Improves accuracy
  - Facilitates selection of the optimal surgical procedure
- Owing to organ shift and tissue deformation repeated re-registration of imaging data is required
  - Achieved with intraoperative CT or MRI [6]
- Disadvantages of intraoperative CT and MRI
  - Costs and need for specific devices and instruments
  - Specific logistical problems

Figure: 3T MRI from Philips

Intraoperative Imaging

- Intraoperative imaging avoids non-rigid registration during operation [5]
- Ultrasound based navigation for resection of liver metastases increased intraoperative orientation and confidence or the surgeon [2]
  - $\rightarrow$ Higher accuracy
  - $\rightarrow$ Surgery with more preserved parenchyma
  - $\Longrightarrow$ Makes surgery more reliable
- Delayed visualization have limited the use of 3D ultrasound to the use for diagnostics
  - $\Longrightarrow$ Real-time imaging techniques are necessary to adapt navigation techniques in clinical practice [2]

$\Longrightarrow$ We developed an open-source navigation system with GPGPU acceleration for real-time freehand 3D-Ultrasound using conventional hardware equipment

Imaging System

- **Manufacturer**: Dell Inc., Round Rock, TX, USA
- **Model**: Inspiron 5300
- **CPU**: Intel Core 2 Quad
  - Cores: 4
  - Operating frequency: 2.5 GHz
- **Memory**: 3.2 GB DDR3
- **Operating System**: Fedora Core 8

Graphics Card

Figure: nVIDIA Geforce 8800 GTX

- **Manufacturer**: nVIDIA Corporation, Santa Clara, CA, USA
- **Model**: Geforce 8800 GTX
- **GPU Operating Frequency**: 575 Mhz
- **Memory**: 768 MB DDR3
- **CUDA** Programmable

Video Capture Board

- **Manufacturer**: Hauppauge Computer Works, Inc. Hauppauge, NY, USA
- **Model**: Impact VCB Model 558
- **Chipset**: Braintree 878 compatible
- **Inputs**:
  - 3 Composite
  - 1 S–Video

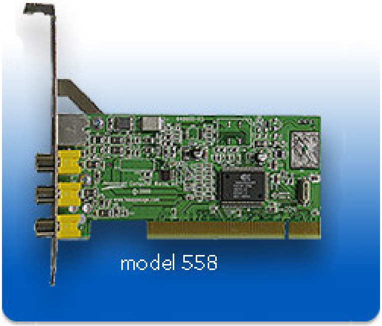


Figure: Hauppauge Impact VCB Capture Card

Ultrasound System

Figure: SonoSite Titan Ultrasound System

- **Manufacturer**: SonoSite Inc., Bothell, WA, USA
- **Model**: Titan
- **Imaging Probe**:
  - 2D abdominal transducer
  - 60 mm curved array of piezoelectric crystal elements
  - Operating bandwidth 2 - 5 Mhz

Tracking System

- **Manufacturer**: Northern Digital, Waterloo, ON, Canada
- **Model**: Aurora
- **Measurement Technology**: Electromagnetic
- **Number of Probes**: 2
- **Sensor**: 6 DOF (Degrees of Freedom)
- **Accuracy**: 1.1 mm
- **Measurement Rate**: up to 40 Hz
- **Interace**: RS232

Figure: NDI Aurora Tracking System

Tracking System continued

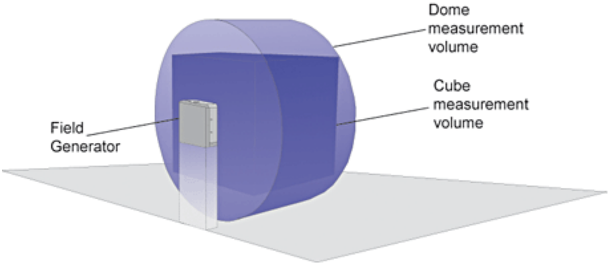


Figure: NDI Aurora Measurement Volume

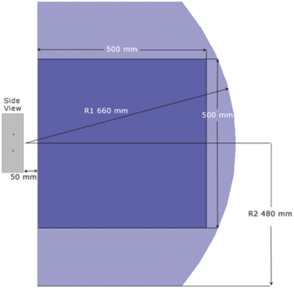


Figure: NDI Aurora Measurement Volume Sectional Drawing

Freehand Tracked Ultrasound

Figure: Ultrasound transducer and tracker probe

Figure: Ultrasound probe with attached tracking sensor

Phantom Study

- **Tank**:
  - Dimensions: 50 cm x 30 cm x 20 cm (WxHxD)
  - Material: Polypropylene
- **Phantom**: Cleaning Sponge
  - Dimensions: 8,9 cm x 4,8 cm x 1,8 cm (WxHxD)
- **Imaging Medium**: H_2O

Figure: Study Tank with Phantom

Software System Design

2 distinct Components:

1. a) Data Acquistion
   b) Volume Reconstruction
   c) Data Forwarding
2. Surgical Navigation and Visualization

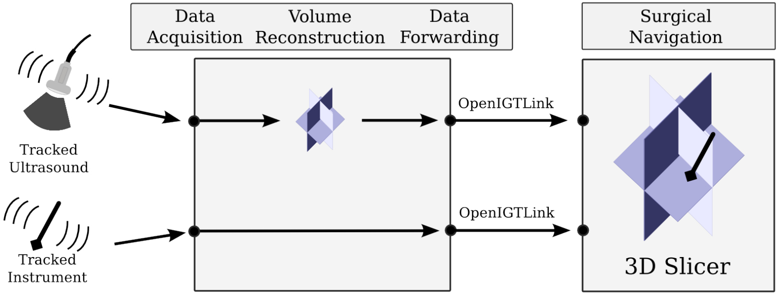


Figure: Software System Design

Software System Design continued

- **Massive Parallelization**: Independent tasks executed in different threads
- **Data Rates**: up to 200 $\frac{MB}{second}$
- **Real-Time performance**: limited to 30 $\frac{frame}{second}$
- Special **high performance** implementations
- Data recording and processing in the **background**
- Graphical user interace operates smoothly in the **foreground**
- Well suited for implementations on **parallel architectures**

Algorithms

- **Programming Language**: C++
- **Class Library**: VTK (http://www.vtk.org)
- **Synchronization**: Mutex Locks

VTK

- Open-Source
- Software system for:
  - 3D computer graphics
  - Image processing
  - Visualization
- Used by thousands of researchers and developers worldwide
- Professional support and products provided by Kitware, Inc. (http://www.kitware.com/)
- Cross-Platform: Linux, Windows, Mac and Unix

Data Acquisition

2 threads run simultaneously

A. Tracking Data

1. Receives tracking information from the 2 tracker probes
2. Converts tracking information to 4x4 matrices
3. Stores matrices on 2 separate stacks along with a timestamp

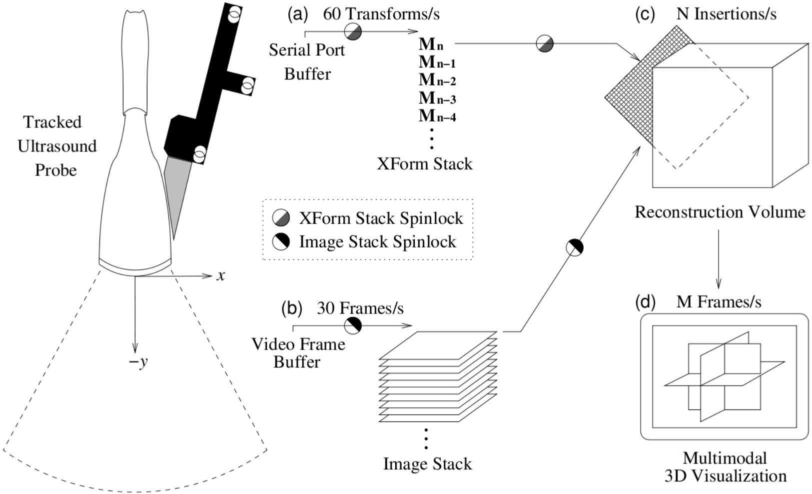
B. Ultrasound Frames

1. Grabs ultrasound frames from video capture board
2. Resizes ultrasound frames
3. Stores images on a stack along with a timestamp and the concurrently recorded matrix

- **Capture rate**: up to 30 $\frac{frames}{second}$
- **Kernel interface for video capturing**: Video for Linux two

Volume Reconstruction

We extended the volume reconstruction algorithm of Gobbi and Peters [4]



Data Forwarding

- **Threads**: 2
  1. Prepare and send reconstructed volume
  2. Prepare and send tracking information of tracked instrument
- **Transfer Protocol**: OpenIGTLink Protocol (http://www.na-mic.org/Wiki/index.php/OpenIGTLink)

OpenIGTLink Protocol

- Open-Source
- Simple but extensible data format to transfer data between software and devices
- Designed to work on the application layer of TCP/IP

Visualization and Navigation

We use 3D Slicer (`www.slicer.org`) as surgical navigation software

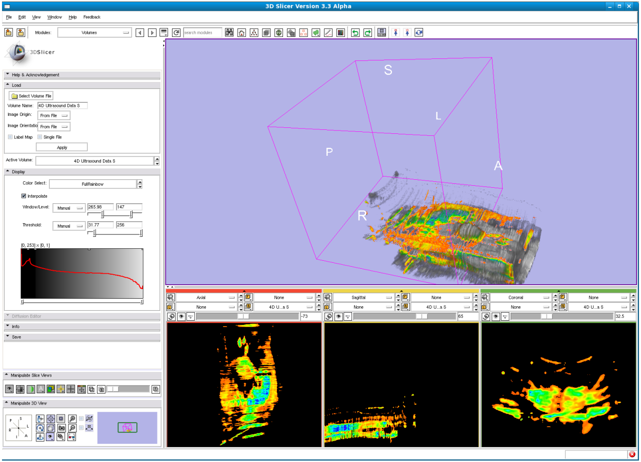


Figure: 3D Slicer displaying the scanned phantom

Visualization and Navigation continued

3D Slicer

- Open-Source
- Cross-Platform: Linux, Mac, Windows and Unix
- Designed to visualize and analyze medical image data
- OpenIGTLink interface
- Newly developed extension for volume rendering
  - Performs all calculation on the graphics card
  - Uses nVIDIA CUDA
  - Reduces extensively the workload of the CPU

Validation Study

Accuracy study

- Compare extensions of phantom with reconstructed volume
- Measure location deviations of tracked instrument

Performance study

- Execution with different volumes of fixed sizes

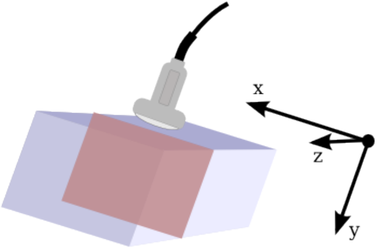


Figure: Scan movements were only performed along the z-axis to assess specific reconstruction properties

Accuracy Study

Figure: Photo of phantom with track instrument

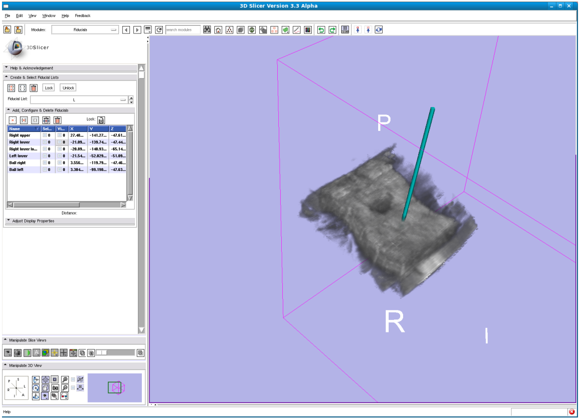


Figure: Reconstructed phantom and locator of the tracked instrument

Accuracy Study

Extension deviation of reconstructed volume

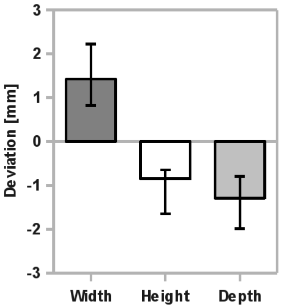


Figure: Extension deviation between phantom and reconstructed volume

Location deviation of tracked instrument

- Average instrument dislocation $6.3 \pm 0.71\,\text{mm}$

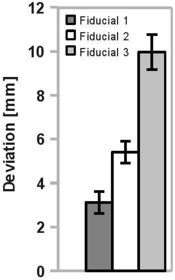


Figure: Location deviation of tracked instrument

Performance Study

- Real-Time performance for volumes with a size of up to 192 x 192 x 192 voxels
- At a voxel size of 1 mm volumes of up to 7 liters are processable in real-time

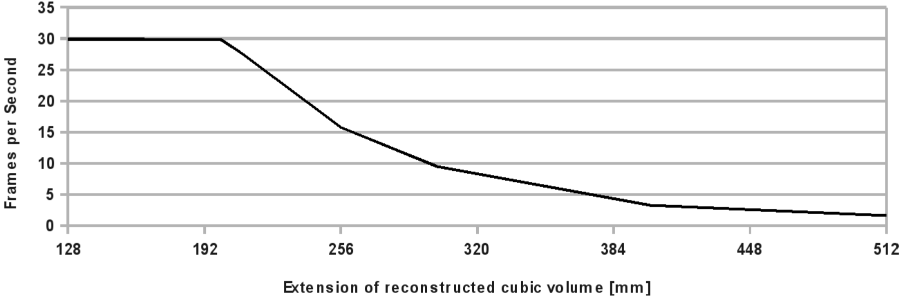


Figure: System performance

Discussion

- Average deviation of our system is 5.5 mm
  - Median accuracy of conventionell resection 42 mm [3]

  → Better control of ideal resection margin

  ⟹ **More reliable Resection**
- Immediate reacquisition of US images during and after tissue resection

  ⟹ **Increased accuracy of surgery**
- Modular open-source approach

  ⟹ **Simple adjustment to basically any appropriate hardware**
- 3D Slicer as surgical navigation front end
  - Instantaneous overlay of pre-operative 3D MRI data
  - Nonlinear registration of MRI to ultrasound
  - GPGPU rendering

    → More computational power for reconstruction

    ⟹ **Increased overall system performance**

Conclusion

Real-time Ultrasound has been around for almost 20 year [10] but our system is the first to demonstrate:

Freehand real-time 3D ultrasound with navigation for liver surgery

In conclusion our system has the potential to

- introduce substantial improvements in the field of liver surgery
- finally bring navigation technique to clinical practice in liver surgery

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