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

Jan Gumprecht

Brigham and Women's Hospital
and
Harvard Medical School

and

University of Mannheim

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Motivation

- **Liver cancer** is estimated the 6th most common cause of death from cancer in the USA in 2008 [3]
  - leading to **18,410 deaths** (12,570 men and 5,840 women).
- 5 year relative survival rate: 11 %
- Over the last 30 years surgical resection has been the "gold standard" treatment of malignant liver tumors [7]
- The outcome of the surgical resection depends on accurate delineation of the surgical margin to the tumor edge [1]

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Current Use of Ultrasound

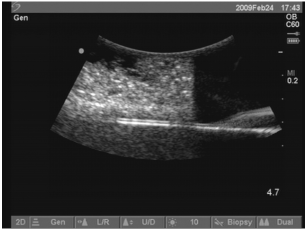

Figure: 2D Ultrasound image

- Many surgeons still rely solely on intraoperative 2D ultrasonography (US) and have not recognized the advantages of intraoperative navigation support [10]
  - → The surgeon combines pre-operative data 3D data with intraoperative information intuitively [2]
  - ⟹ Accuracy in liver surgery depends on the experience of the surgeon
- Even in specialized centers rates of critical resections are high [8]

⟹ 10,000s of patients continue to be exposed to unnecssary risks

Current Use of Ultrasound

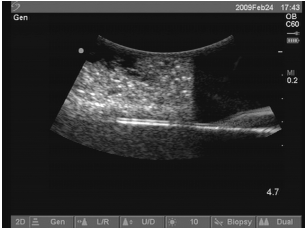

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Image Guided Surgery

- Navigation support for liver surgery using pre-operative imaging has been introduced to overcome this problem [6].
  - → Improves intra-operative orientation
  - → Facilitates increased accuracy of tumor localization and resection
- Pre-operative image guidance in soft tissue organs, including liver, continues to be challenging [4] because of
  - tissue deformation
  - breathing artifacts
  - absent or reduced anatomical landmarks

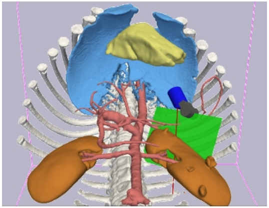

Figure: Image Guided Surgery

Alternative: Intra-operative 3D US based navigation [5]

- Increased intraoperative orientation
- Increased accuracy
- Increased confidence of the surgeon

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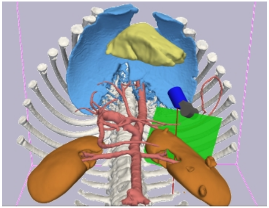

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Intraoperative Imaging using 3D Ultrasound

Problem: 3D US imaging has too slow update rates.

⟹ Application is limited to diagnostics

Solution

Based on this need I developed an open-source
Navigation System
with general purpose graphics unit (GPGPU) acceleration for
Real-Time Freehand 3D-US
using conventional hardware equipment.

⟹ Especially well suited for liver surgery

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Hardware Design

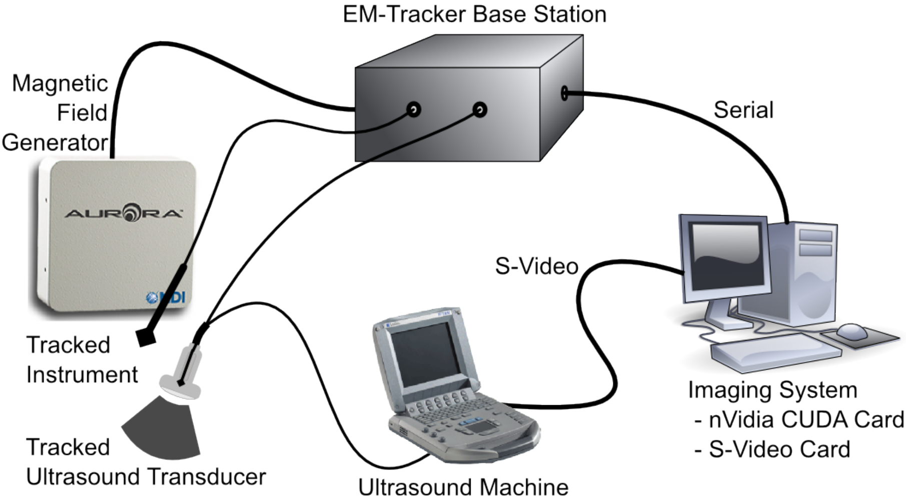

Figure: Hardware Design

Software Design

2 distinct Components:

1. a) Data Acquistion
   b) Volume Reconstruction
   c) Data Forwarding

2. Surgical Navigation and Visualization

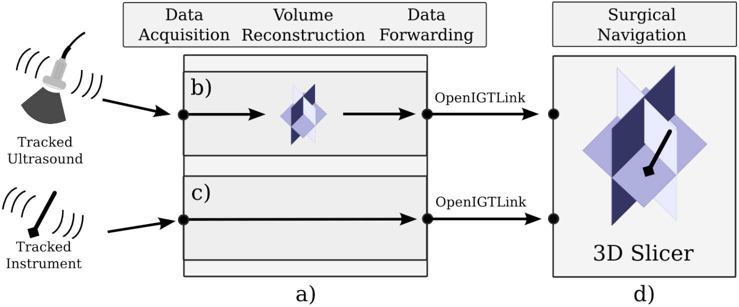

Figure: Software System Design

Software 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 interface 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 - Visualization Toolkit

- 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

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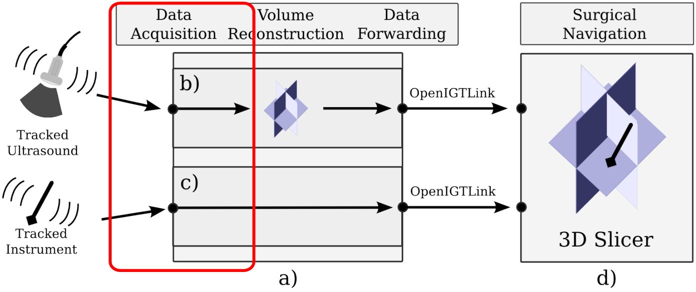

Figure: Software System Design

Data Acquisition

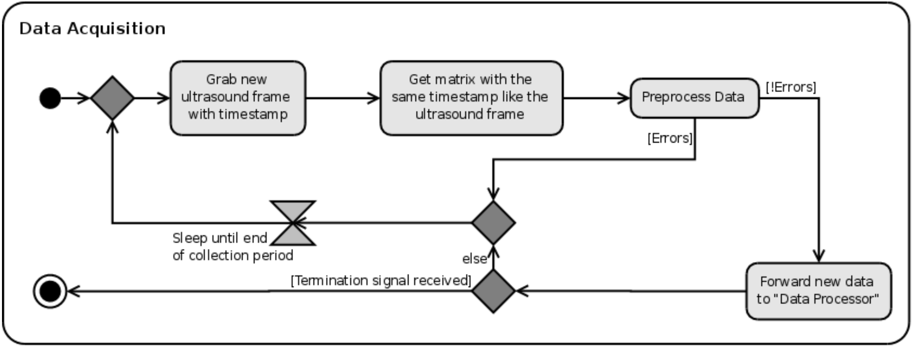

Figure: Activity Diagram: Data Acquisition

- VideoGrabbing: Video4Linux2

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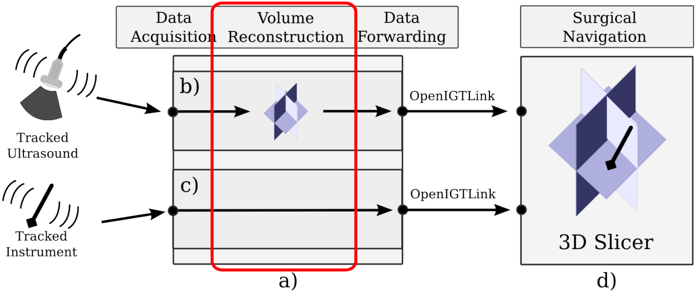
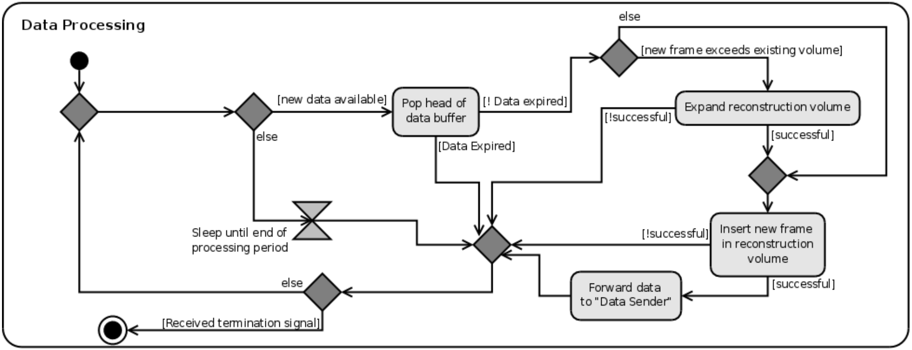


Figure: Software System Design

Data Processing - Volume Reconstruction



- Reconstruction Technique:
  - Pixel-based with interpolation kernel
- Alternatives:
  - Voxel-based
  - Function-based

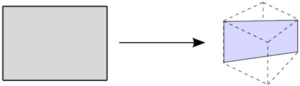


Figure: Volume reconstruction

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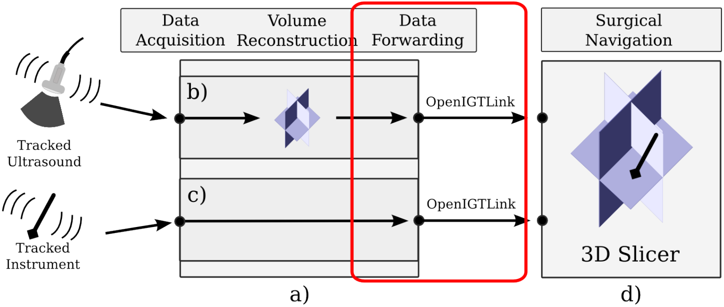

Figure: Software System Design

Data Forwarding

- **1 Thread:**
  - Prepare and send reconstructed volume
- **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

Instrument Tracking

2 distinct Components:

1. a) Data Acquistion
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2. Surgical Navigation and Visualization

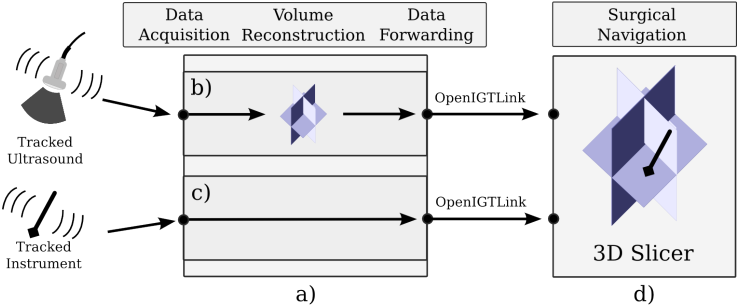

Figure: Software System Design

Visualization and Navigation

3D Slicer (`www.slicer.org`) was used as surgical navigation software

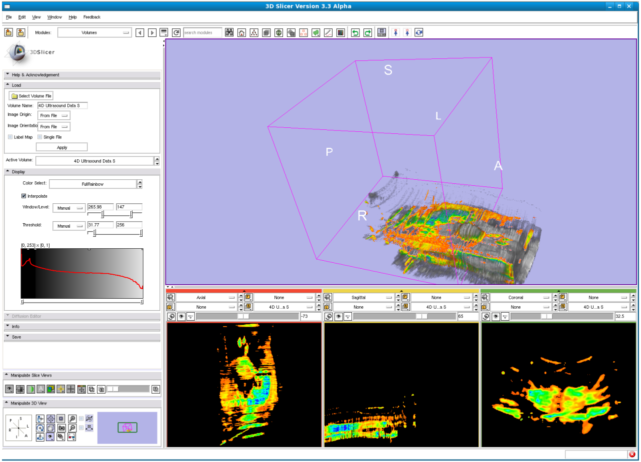

Figure: 3D Slicer displaying the scanned phantom

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
- GPGPU Acceleration: Newly developed extension for volume rendering
  - Performs all calculations on the graphics card
  - Uses nVIDIA CUDA
  - Reduces extensively the workload of the CPU

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Imaging System

Computer: Dell Inspiron 5300

- CPU: Intel Core 2 Quad
  - 4 Cores operating @ 2.5 GHz
- Memory: 3.2 GB DDR3
- Graphics Board: nVidia Geforce 8800 GTX
  - 768 MB DDR3 RAM
  - 128 Streamprocessors @ 575 MHz
  - CUDA compatible
- Video Capture Board: Hauppauge Impact
  - Brooktree 878 Chip

Figure: SonoSite Titan Ultrasound System

Ultrasound System: SonoSite Titan

- 2D transducer operating @ 5 MHz

Tracking System: NDI Aurora

- Technique: Electro-Magnetic
- Accuracy: Up to 1.1 mm

Freehand Tracked Ultrasound

Figure: Ultrasound transducer and tracker probe

Figure: Ultrasound probe with attached tracking sensor

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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

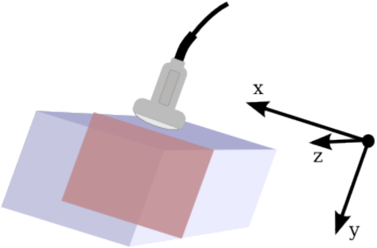


Figure: Scan movements were only performed along the z-axis to assess specific reconstruction properties

Accuracy Study

Figure: Photo of phantom with track instrument

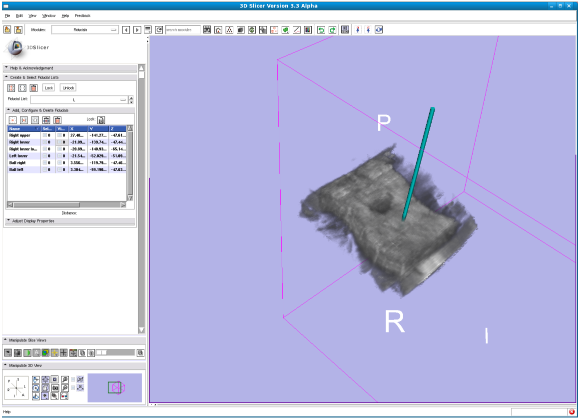


Figure: Reconstructed phantom and locator of the tracked instrument

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

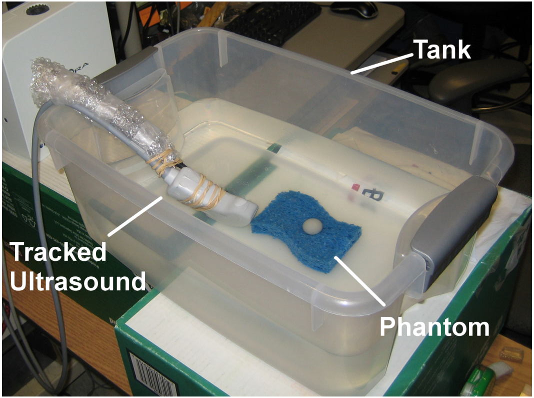


Figure: Study Tank with Phantom

Accuracy Study

Extension deviation of reconstructed volume

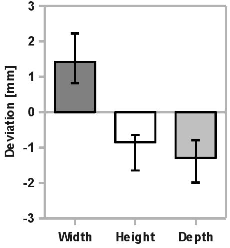


Figure: Extension deviation between phantom and reconstructed volume

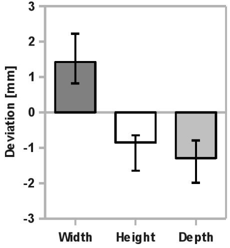
Location deviation of tracked instrument

- Average instrument dislocation 6.3 ± 0.71 mm

Figure: Location deviation of tracked instrument

Accuracy Study

Extension deviation of reconstructed volume



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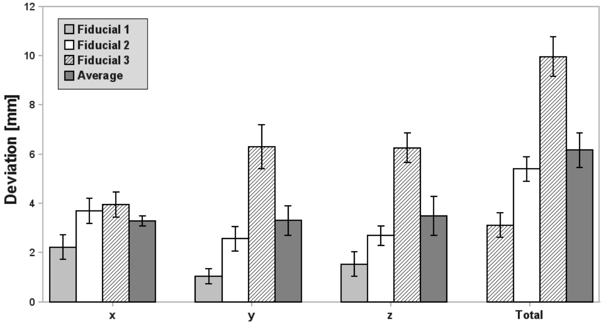

Figure: Location deviation of tracked instrument

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

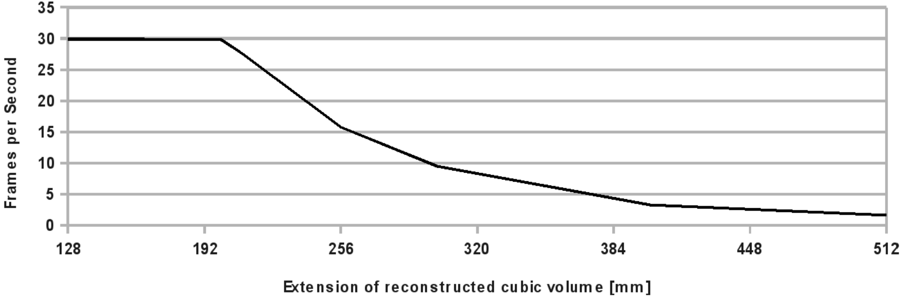

Figure: System performance

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Discussion

- Very high accuracy

  $\rightarrow$ Better control of ideal resection margin

  $\Longrightarrow$ **More reliable Resection**

- Immediate reacquisition of US images during and after tissue resection

  $\Longrightarrow$ **Increased accuracy of surgery**

- Modular open-source approach

  $\Longrightarrow$ **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

    $\rightarrow$ More computational power for reconstruction

    $\Longrightarrow$ **Increased overall system performance**

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Conclusion

Real-time Ultrasound has been around for almost 20 year [9] but the system is the first to demonstrate:

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

In conclusion the system has the potential to

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

Thank you
for
your
Attention

I am looking forward to your questions

and

I hope you will give me the opportunity

to share my enthusiasm with you

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