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

- **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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The outcome of the surgical resection depends on accurate delineation of the surgical margin to the tumor edge [1]
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 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].

\[ \Rightarrow \text{10,000s of patients continue to be exposed to unnecessary risks} \]
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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


- Increased intraoperative orientation
- Increased accuracy
- Increased confidence of the surgeon
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Figure: Image Guided Surgery
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
Intraoperative Imaging using 3D Ultrasound

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Hardware Design

Figure: Hardware Design
Software Design

2 distinct Components:

1. a) Data Acquisition
   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](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/](http://www.kitware.com/))
- Cross-Platform: Linux, Windows, Mac and Unix
Software Design

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Figure: Software System Design
Data Acquisition

Figure: Activity Diagram: Data Acquisition

- VideoGrabbing: Video4Linux2
Software Design

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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
Software Design

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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)

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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:

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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

**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
Freehand Tracked Ultrasound

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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$_2$O

**Figure:** Study Tank with Phantom
Accuracy Study

Extension deviation of reconstructed volume

Location deviation of tracked instrument
- Average instrument dislocation
  $6.3 \pm 0.71 \, \text{mm}$

Figure: Extension deviation between phantom and reconstructed volume

Figure: Location deviation of tracked instrument
Accuracy Study

**Extension deviation of reconstructed volume**

**Location deviation of tracked instrument**
- Average instrument dislocation
  \[ 6.3 \pm 0.71 \text{ mm} \]

**Figure:** Extension deviation between phantom and reconstructed volume

**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

- Very high accuracy
  - 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
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
E. A. Bakalakos, J. A. Kim, D. C. Young, and E. W. Martin. Determinants of survival following hepatic resection for metastatic colorectal cancer. 


M. Kleemann, P. Hildebrand, M. Birth, and H. P. Bruch. Laparoscopic ultrasound navigation in liver surgery: technical aspects and accuracy.


