Interfacing Proprietary Hardware with the Image-Guided Surgery Toolkit (IGSTK): a Case for the OpenIGTLink Protocol

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ABSTRACT

One of the key technical challenges in developing an extensible image-guided navigation system is that of interfacing with external proprietary hardware. The technical challenges arise from the constraints placed on the navigation system's hardware and software. Extending a navigation system's functionality by interfacing with an external hardware device may require modifications to internal hardware components. In some cases, it would also require porting the complete code to a different operating system that is compatible with the manufacturer supplied application programming interface libraries and drivers. In this paper we describe our experience extending a multi-platform navigation system, implemented using the image-guided surgery toolkit IGSTK, to support real-time acquisition of 2-D ultrasound (US) images acquired with the Terason portable US system. We describe the required hardware and software modifications imposed by the proposed extension and how the OpenIGTLink network communication protocol enabled us to minimize the changes to the system's hardware and software. The resulting navigation system retains its platform independence with the added capability for real-time image acquisition independent of the image source.

Keywords: image-guided therapy, surgical guidance, hardware integration, software engineering, open source

1. INTRODUCTION

In this paper we describe our experience extending our CT-based navigation system for needle biopsies[1] to incorporate ultrasound (US) as a complementary real-time imaging modality, and to seamlessly support all tracking systems available in the Image-Guided Surgery Toolkit (IGSTK).[2] The original system was implemented using IGSTK, utilizing the Aurora electromagnetic tracking system (Northern Digital Inc.) and CT images. The only external hardware component on which the system depended was the tracking system. IGSTK currently provides platform independent support for tracking systems from Northern Digital Inc. (Waterloo, Ontario, Canada), Claron Technology Inc. (Toronto, Ontario, Canada), and Ascension Technology Corp. (Milton, Vermont, USA). It is thus possible to implement a platform independent navigation system that supports the most commonly used tracking systems.

The motivation for incorporating US imaging into our existing navigation system stems from the need for realtime imaging as a validation of the guidance information presented by the system. Intraoperatively, there are two modalities that provide realtime imaging, X-ray fluoroscopy and US. We chose to use US as it is nonionizing. It should be noted that, in our case, the required accuracy of the spatial positioning of the US image is lower than that required for guidance. The US image accurately depicts the underlying anatomical structures and its spatial positioning relative to the CT data is provided only as context. This is somewhat similar to the approach presented in.[3] In that work echocardiography is presented in the spatial context of preoperatively acquired data, improving the physicians ability to interpret the US images.

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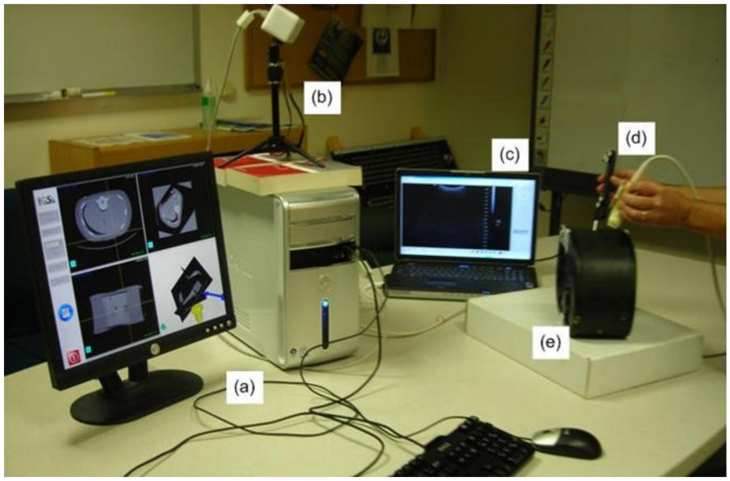


Figure 1. CT/US navigation system components: (a) navigation system computer; (b) MicronTracker2 optical tracking system; (c) Terason T2000 US system; (d) tracked tools (pointer and US probe); and (e) abdominal phantom.

One of our key concerns when incorporating the US machine into our navigation system was its physical footprint. When introducing additional equipment into the clinical environment we desire to keep the system's physical obtrusiveness to a minimum, as the clinical environment is already cramped. We chose the Terason T2000 portable US system (Teratech Corp., Burlington MA, USA) as our US system, as this system has a minimal physical footprint. Ideally, we would have incorporated the US image acquisition directly into our navigation system's code. Unfortunately, the application programming interface provided by the Terason system is an ActiveX control, limiting its use to the windows platform. As a result, our navigation system would become platform dependent, limited to the windows operating system.

Interfacing with proprietary hardware has been identified as one of the key challenges in the design of image-guided navigation systems.[4] The challenge stems from the requirements placed on the system's internal hardware and, in some cases, on the use of a specific operating system that is compatible with the external device's application programming interface libraries and drivers. In the extreme, these requirements can preclude the use of a given hardware component if it leads to major changes in existing software or hardware.

An elegant solution to this challenge is the recently proposed OpenIGTLink communication protocol.[5] Instead of incorporating the image acquisition code directly into our navigation system we use a client-server architecture utilizing OpenIGTLink communication messages. The end result is a navigation system that runs as two processes, either on the same computer under the windows OS, or on two separate computers connected via an intranet with US acquisition performed on a computer running the windows OS.

We next describe in detail our system's design and our experience with US calibration using two possible tracker configurations, one using an electromagnetic tracking system and the other using an optical tracking system.

2. MATERIALS AND METHODS

We have extended our CT-based navigation system to incorporate the Terason T2000 system as a complementary real-time imaging modality, and to seamlessly support all tracking systems available in the Image-Guided Surgery Toolkit.

In the work presented in this paper we use our system in two configurations, one with the Aurora electromagnetic tracking system from Northern Digital Inc. and the other with the MicronTracker2 H40 optical tracking system from Claron Technology Inc. A dynamic reference frame (DRF) is attached to the US probe and the US image is displayed in its correct spatial location relative to the tracked probe. In addition, the corresponding reformatted plane is extracted from the CT volume and displayed. Figure 1 shows our system's hardware components when configured with the optical tracking system.

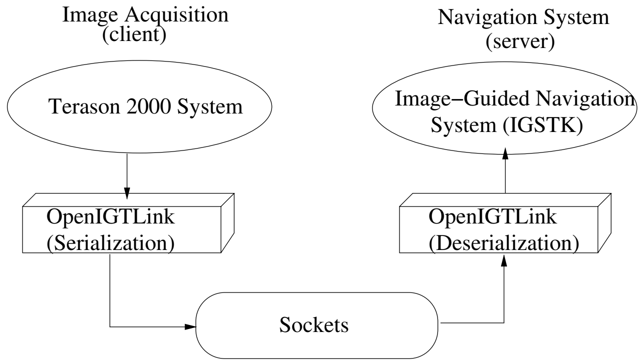


Figure 2. CT/US navigation system's client-server based architecture.

When configured with the MicronTracker2 system we encountered an additional challenge. Both the MicronTracker2 and the Terason system use the IEEE 1394 interface for communication. The computer used by our original navigation system had a single bus with multiple connections. The MicronTracker2 currently uses the full bandwidth of the bus, requiring us to add an additional bus to our system in order to concurrently run the Terason system. This further motivated us to pursue a client-server architecture for our navigation system, as this architecture would require minimal changes to the existing software and hardware.

In our case we would run the Terason system on a windows based laptop and send the acquired images via a network connection to our navigation system. This required the development of only one additional software component which receives a stream of images through a network connection, and some minor modifications of the original system's software. Figure 2 illustrates our navigation system's architecture.

To stream the US images via a socket connection we used the recently introduced OpenIGTLink communication protocol. Finally, to correctly position the US image relative to the tracked US probe we require the transformation between the probe's DRF and the image plane. This is obtained using a phantomless calibration procedure.

2.1 OpenIGTLink Communication Protocol

OpenIGTLink is a new, open, network communication protocol for the Image-Guided Therapy (IGT) environment. It describes a standardized data format for information that is frequently utilized by IGT systems. This includes two and three dimensional images, affine and rigid transformations, and query messages with regard to a sender's status and the set of messages a receiver can interpret.[5] In addition the protocol is easily extended to support user-defined messages.

Data is transmitted over a network using peer-to-peer socket communication. This approach is simple, supporting messages sent by a variety of external sources, using a common message format. In addition, it lends itself in a natural manner to the separation between the main body of an IGT application and new, untested, research components. This is similar to the proprietary research interfaces available for the IGT systems from BrainLab[6] and Medtronic. These provide bidirectional data exchange methods between clinical IGT systems and research software.

The OpenIGTLink message consists of a header and body, with a fixed header structure used by all message types. The header is comprised of the following fields (all numerical values are in big endian byte order):

- Version number - Version of OpenIGTLink protocol (unsigned short, 2 bytes).
- Data type - A string denoting the message data type, in our case "IMAGE" (char[12], 12 bytes).
- Device name - A string denoting the unique name of data source (char[20], 20 bytes).
- Time stamp - The time when the data was generated (unsigned int, 8 bytes).

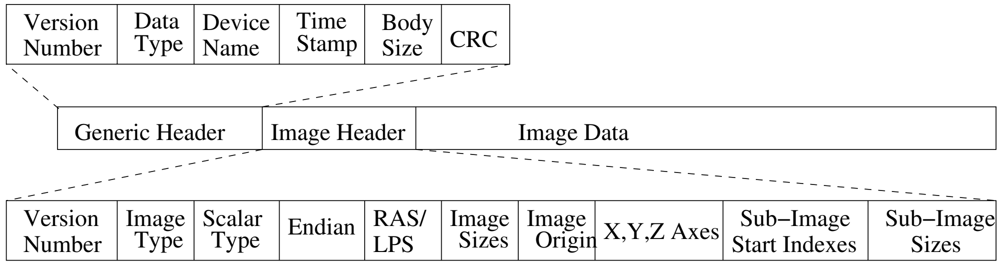


Figure 3. OpenIGTLink "IMAGE" message structure.

- Body size - The size of the message body. This allows an application that receives an unexpected message type to discard the information from the data stream (unsigned int, 8 bytes).
- Cyclic redundancy check (CRC) - A CRC for the message body, used for verifying its integrity (unsigned int 8 bytes).

In our application we utilize the "IMAGE" message type which also has its own fixed header structure, followed by the image data. The header is comprised of the following fields:

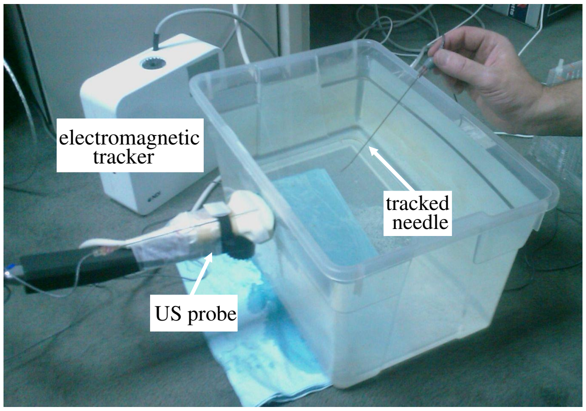
- Version number - Version of image message (unsigned short, 2 bytes).
- Image type - Single channel, scalar, or multi-channel, vector, image (unsigned int, 1 byte).
- Scalar type - Basic data type of pixel/voxel (unsigned int, 1 byte).
- Endian - Data is in big/little endian (unsigned int, 1 byte).
- Coordinate system type - Which medical coordinate system, RAS or LPS (unsigned int, 1 byte).
- Image size - Number of pixels in each direction x, y, z (3x unsigned int, 6 bytes).
- Image origin - Image origin coordinates x, y, z (3x float, 12 bytes).
- x axis - direction of "x" axis with length being the pixel spacing in this direction (3x float, 12 bytes).
- y axis - direction of "y" axis with length being the pixel spacing in this direction (3x float, 12 bytes).
- z axis - direction of "z" axis with length being the pixel spacing in this direction (3x float, 12 bytes).
- Sub-image start indexes - Starting index of sub-image (3x unsigned int, 6 bytes).
- Sub-image size - Number of pixels in each direction x, y, z (unsigned int, 6 bytes).

Figure 3 illustrates the "IMAGE" message structure. Note that this message structure enables the transmission of complete images or partial, rectangular, sub-images which can be used for partial image update.

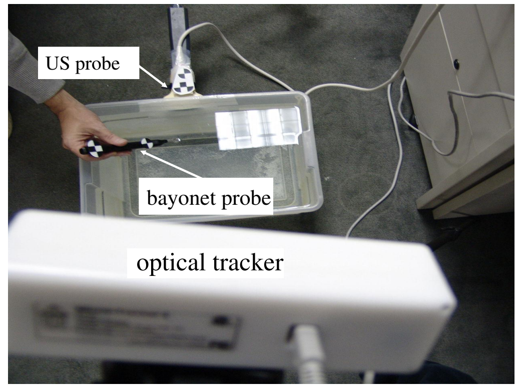
2.2 US calibration

We use a phantomless calibration procedure[7] to estimate the image scale factors and the rigid transformation between the DRF attached to the US probe and the US image plane. This is similar to the approach described in.[8] For completeness we provide a brief description of the method.

The US probe is positioned next to a water bath with a window in its side through which images are acquired. A pointer tool is then moved so that its tip intersects the US imaging plane. When using the optical tracking system we use a tracked bayonet probe, and when using the electromagnetic system we use a tracked needle. Both instruments are calibrated so that the tip position is known with respect to the instruments DRF. Figure 4 illustrates the calibration setup.



(a)



(b)

Figure 4. US calibration setup with (a) Aurora electromagnetic tracking system, and (b) MicronTracker2 optical tracking system.

The calibration transformation relates pixel locations to their spatial locations relative to the DRF attached to the US probe. To perform the calibration we observe the relationship between the coordinate systems, relating the pointer tool's tip location to its pixel location in the the US image (see Figure 5). The following quantities are known:

- $\mathbf{P}^{pointerDRF}$ - The pointer tool's tip location relative to its DRF.
- ${}_{pointerDRF}T^{tracker}$ - The transformation from the tracker to the pointer tool DRF.
- ${}_{USDRF}T^{tracker}$ - The transformation from the tracker to the US DRF.
- $\mathbf{p}^{USImage}$ - The pixel location at which the pointer tool's tip intersected the US image plane.

As we assume the pointer tool's tip intersects the US image plane we have:

$$ {}_{pointerDRF}T^{tracker}\ \mathbf{P}^{pointerDRF} = {}_{USDRF}\ T^{tracker}\ {}_{USImage}T^{USDRF}\ \mathbf{p}^{USImage} $$

where ${}_{USImage}T^{USDRF}$ is the unknown calibration transformation, a homogenous matrix of the form:

$$ {}_{USImage}T^{USDRF} = \begin{bmatrix} | & | & | & | \\ s_x\mathbf{r1} & s_y\mathbf{r2} & \mathbf{r3} & \mathbf{t} \\ | & | & | & | \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

Each point pair contributes three linear equations with nine unknowns $s_x\mathbf{r1}$, $s_y\mathbf{r2}$, and $\mathbf{t}$. Where $[\mathbf{r1}; \mathbf{r2}; \mathbf{r3}]$ is a rotation matrix, $\mathbf{t}$ a translation vector, and s_x, s_y scale factors relating pixel and metric measurements in the image plane. The estimation is then formulated as a linear least squares problem which is solved using the Moore-Penrose pseudoinverse.

To evaluate the calibration we performed the following experiment. Three data sets were acquired, each consisting of 30 measurements. Each measurement includes the spatial position of the pointer tip in the tracker's coordinate system, its image location in pixels and the pose of the US DRF in the tracker's coordinate system. From each of the data sets we estimate the calibration transformation. We then evaluate it using the two remaining data sets. For each data element, we take the image point and transfer it to its spatial location in the tracker's coordinate system via the calibration transformation. The distance between the known pointer tip position and the estimated one is our error measure. The experiment was performed using the electromagnetic tracking system and the optical one.

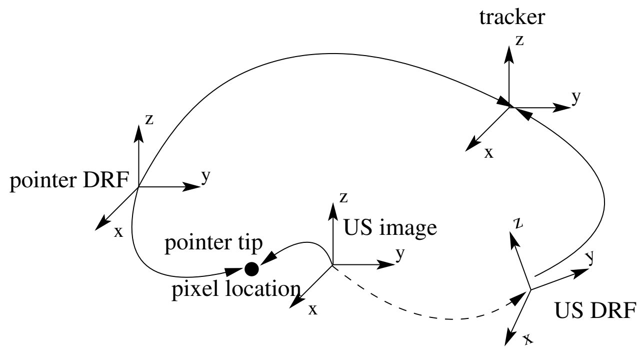


Figure 5. Relationship between the coordinate systems used for US calibration. Solid lines denote known quantities, dashed line denotes unknown calibration transformation (pixel scaling followed by a rigid transformation).

3. EXPERIMENTAL RESULTS

The use of the OpenIGTLink protocol allowed us to acquire images and tracking data using a platform independent application even though our US system provides an image acquisition interface that is specific to the windows operating system. In all of our experiments images were successfully acquired by our client program running on the windows machine and transferred to our main application, the server, which provided the navigation guidance using the tracking information and US images.

We evaluated the phantomless calibration algorithm using two system configurations. The first configuration utilized the Aurora electromagnetic tracking system and a tracked needle and the second configuration utilized the MicronTracker2 H40 and a bayonet probe as the pointer tool.

We have found that the line of sight constraint imposed by the optical system was challenging. Positioning the bayonet probe so that its tip intersected the US image plane while both the US DRF and bayonet DRF were visible to the tracking system required repeated data acquisition attempts. Data acquisition with the electromagnetic system was straightforward and did not require any effort on behalf of the operator.

Calibration accuracy for both configurations was on the order of several millimeters (3-6mm). Tables 1 and 2 summarize the results obtained when performing US calibration utilizing the electromagnetic and optical tracking systems respectively. It should be noted that localization accuracy of the specific tracking system has minimal effect on the calibration accuracy, even though the optical system is more accurate than the electromagnetic one. This is primarily due to the inaccuracies inherent to this phantomless calibration approach, modeling the US image as a mathematical plane and identifying the image location of the pointer tool with the tool's tip even though it can be a point on the shaft.

Based on these results we conclude that this calibration approach should only be used for qualitative purposes. That is, positioning the US data in the context of the CT image while the physician uses the realtime US image as the guiding modality. Overlaying target regions defined in the CT onto the US image is not sufficiently accurate.

4. DISCUSSION AND CONCLUSIONS

We have presented a client-server based approach to integrating a US system providing a windows based API with a platform independent image-guided navigation system. The end result is a system in which US images

data set	1	2	3
1	-	3.9 (0.87)	4.9 (1.2)
2	4.4 (0.65)	-	4.8 (1.3)
3	5.8 (0.7)	5.4 (1.4)	-

Table 1. Results from US calibration for system configured with the Aurora electromagnetic tracking system. Mean (std) are given for each data set, with the row entry being the data set used for estimating the calibration and the column entries the data sets on which it was assessed. All measurements are in millimeters.

data set	1	2	3
1	-	2.9 (1.7)	4.5 (2.4)
2	5.3 (1.5)	-	3.7 (1.5)
3	6.3 (3.1)	4.1 (1.9)	-

Table 2. Results from US calibration for system configured with the MicronTracker2 optical tracking system. Mean (std) are given for each data set, with the row entry being the data set used for estimating the calibration and the column entries the data sets on which it was assessed. All measurements are in millimeters.

are acquired on a windows machine and displayed on the navigation system that is either running on the same computer or on another computer with a different operating system. The software is based on the open source Image-Guided Surgery Toolkit[9] and the OpenIGTLink[5] message protocol.

To use the US images and place them within the context of the CT data used for navigation we need to perform spatial calibration of the US system. We evaluated our implementation of a phantomless US calibration algorithm using two system configurations, one with an electromagnetic tracking system and the other with an optical tracking system. We concluded that the type of tracking system had negligible effect on the calibration accuracy as compared to the inherent accuracy of the calibration approach. We have empirically determined that the accuracy obtained using this calibration approach is appropriate only for qualitative guidance. That is, the US image can be positioned in the context of the CT data, but quantitative transfer of information between the two modalities is inaccurate.

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