3D Visualization and Interaction with Spatiotemporal X-ray Data to Minimize Radiation in Image-guided Surgery

Foteini Ioakeimidou[1] Alex Olwal[1] Axel Nordberg[2] Hans von Holst[2,3]

[1] *Computer Science and Communication, KTH Stockholm, Sweden*

[2] *Neuronic Engineering KTH Stockholm, Sweden*

[3] *Neurosurgery Karolinska University Hospital Stockholm, Sweden*

foteinii@kth.se, alx@kth.se, axeln@kth.se, hans.vonholst@karolinska.se

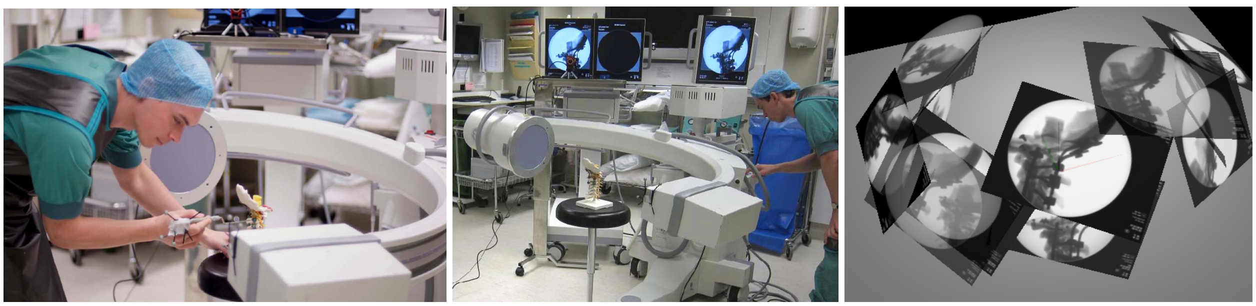

Figure 1. (Left and center) Our prototype setup in a surgical room for image-guided surgery where an intraoperational fluoroscope is used for X-ray imaging. (Right) Our system exposes the spatial and temporal relationships of the acquired X-rays in an interactive 3D visualization.

Abstract

Image-guided surgery (IGS) often depends on X-ray imaging, since pre-operative MRI, CT and PET scans do not provide an up-to-date internal patient view during the operation. X-rays introduce hazardous radiation, but long exposures for monitoring are often necessary to increase accuracy in critical situations. Surgeons often also take multiple X-rays from different angles, as X-rays only provide a distorted 2D perspective from the current viewpoint.

We introduce a prototype IGS system that augments 2D X-ray images with spatiotemporal information using a motion tracking system, such that the use of X-rays can be reduced. In addition, an interactive visualization allows exploring 2D X-rays in timeline views and 3D clouds where they are arranged according to the viewpoint at the time of acquisition. The system could be deployed and used without time-consuming calibration, and has the potential to improve surgeons' spatial awareness, while increasing efficiency and patient safety.

1. Introduction

Image-guided surgery (IGS) systems have drastically transformed modern medicine by exploiting medical imaging methods to expose internal views of the patient's anatomical structures. They enable safer, more accurate, and less invasive procedures, with the additional benefits of more accurate interventions and faster patient recovery [1].

The use of imaging technologies for diagnosis and localization before operations has, for example, resulted in substantial improvements of treatments and outcomes in neurosurgical procedures. A major concern today, however, is the lack of imaging technology for real-time guidance which, for example, could help surgeons to continuously assess how much of a tumor that is being removed during operation.

Positron Emission Tomography (PET), Computed Tomography (CT) and Magnetic Resonance Imaging (MRI) are established methods for 2D and 3D imaging, but high cost, large sizes, long scan times and complex physical configurations, currently make them only practical before surgical intervention. These factors prevent the widespread use of sophisticated real-time 2D and 3D scans in operating rooms.

Pre-operative scans can, however, often be complemented with simpler techniques, such as, ultrasound or X-rays, which can be continuously used during surgery and add temporal information [2].

Certain operational procedures, such as bone structure stabilization, require precise actions to avoid damage to surrounding structures. The acquisition of up-to-date imagery is thus essential to, for example, monitor bone drilling and screwing, or plate mounting for mechanical fixation. The number of images needed is, among other things, dependent on the location of the fracture, and the difficulty and severity of the injury. X-ray imagery's high spatial resolution and sensitivity to bone structure makes it superior compared to ultrasound as an imaging method for these procedures. New fracture stabilization techniques that rely on adhesion and minimally invasive methods [3], will be even more dependent on real-time imaging for successful guidance, to ensure that the surgeon can apply the treatment in the optimal area of the fracture.

The main drawback of X-ray-based guidance is the inevitable trade-off between radiation and temporal resolution, in addition to its inherent limitation of imaging on a 2D plane. For temporal continuity, a series of X-ray images can be acquired, but that generates high radiation doses. On the other hand, low dose acquisition only allows for single or few X-rays, which may limit the surgical accuracy. Radiation dose is often traded today for the need of temporal information during surgical intervention. The problem of these radiation issues has been demonstrated in comparisons between fluoroscopes and CT-based computer-assisted surgery [4].

In this paper, we present a prototype IGS system (See Figure 1 and 2) for bone fracture treatments with a user interface that combines real-time tracking, information visualization and interaction techniques to fully exploit each X-ray and its associated spatial and temporal information. The system has the potential to minimize radiation dosage by reducing the amount of needed X-ray imagery, and by augmenting the surgeon's spatial awareness and navigational skills.

2. Related Work

Peters [1] presents a survey of principles, techniques and existing systems for the registration of medical imagery with anatomical structures. It is complemented by Yaniv and Cleary's [2] categorization of IGS research according to their focus on Medical Imaging, Data Visualization, Segmentation, Registration, Human Computer Interaction (HCI) or Tracking Systems.

Foley et al. [5] describe how spatial information for the C-arm fluoroscope is used to overlay the real-time position of the surgical tools on the imagery. Hofstetter et al. [6] instead use optoelectronic markers on the surgical tools, the fluoroscope and the patient. Joskowcz et al. [7] use intraoperative X-rays to register preoperative CT scans with the patient during surgery.

While we also employ a motion tracking system, we do not only consider the IGS system as a means for registration (i.e., of scans, tools and patient), but also introduce the potential for interactive visualizations of spatial and temporal relations among a collection of X-rays, as shown in Figure 2.

In previous studies, 2D views are considered more suitable when users need to form precise associations, while 3D views are used to support qualitative overviews of the data [8][9]. Preim and Peitgen propose six "golden rules" [9] for the visualizations used in clinical applications with a discussion of the importance of integrated 2D and 3D visualizations, such as Tresens and Kuester's 2D/3D interface for biomedicine [10]. Tory et al.'s study shows that combined 2D/3D interfaces may be more precise and efficient compared to pure 2D or 3D visualizations [11]. Such combined interfaces may, however, require that users get training and experience in 2D/3D navigation. Zudilova et al.'s [12] study indicates that younger users with gaming experience perform better at 3D interaction with medical data. We may thus expect that these skills will become more common as the current generation of users gets increasingly more exposure to 3D environments and interfaces (e.g., through video games and desktop applications).

Our work does not only exploit the advantages of combined 2D and 3D visualizations, but we also add an information level through temporal relations between the data visualized.

3. Maximizing the benefit of X-rays

Imaging techniques in the surgery room are often limited to X-ray imaging, in which an X-Ray "snapshot" reveals the current internal view of the patient. The problem is that every change of state that deforms the tissue (e.g., when cutting or moving the surgical instrument) requires a new X-ray image, and procedures that can't be visually monitored (especially in minimally invasive surgery) force surgeons to "work in blindness" in-between acquired X-rays. The hazardous radiation from X-rays prohibits the surgeon from continuously taking new X-rays and it is always

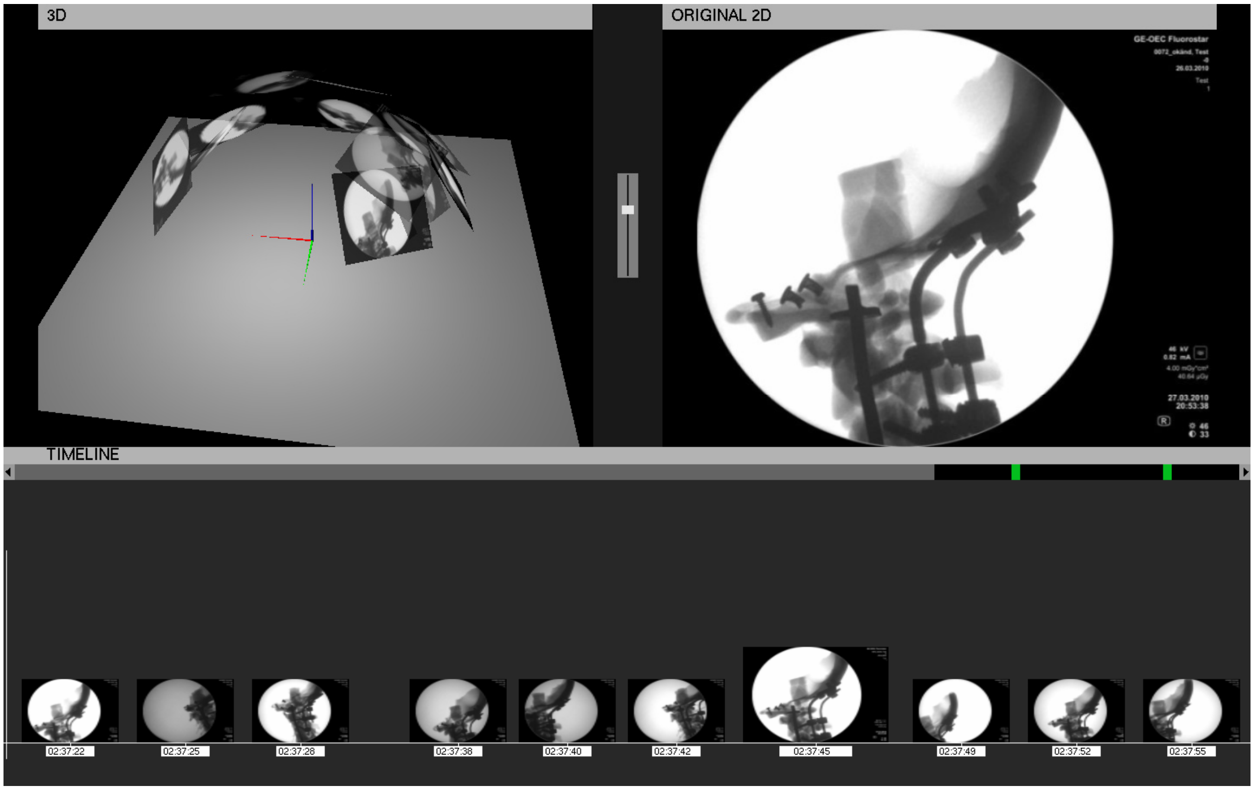

Figure 2. The user interface provides three views of the acquired X-ray imagery. 3D view (top left): A 3D cloud where each X-ray is positioned and oriented based on the fluoroscope's alignment at the acquisition time. The user can change the perspective through rotation, pan and zoom. Original 2D view (top right): A full-resolution view of an X-ray that has been activated from the 3D or Timeline view. Timeline view (bottom): The acquired X-rays are arranged in an interactive timeline. Green markers on scrollbar indicate locations with additional images that are outside the current view (grey part of scrollbar).

desirable to minimize exposure. Besides the limited temporal updates, X-rays also do not inherently provide 3D information. Therefore, surgeons still take an excessive amount of images, not only over time, but also from different angles. Currently, surgeons rarely take advantage of the spatial and temporal information that is associated with a specific X-ray image. It is, however, important to note that each X-ray acquisition is a 2D image taken at a specific time, from a specific position and orientation. Its relationship to other X-rays in space and over time places it in a context that may be advantageous to exploit.

Since neither more sensitive X-ray equipment nor better radiation tubes can address these problems, a reasonable solution is to combine multiple techniques. In order to significantly increase the temporal resolution, without increasing the radiation dose, a visualization tool combined with X-ray imaging is proposed. The goal is to combine high spatial resolution from an X-ray image with high temporal resolution from real-time motion tracking, in order to minimize the needed radiation dosage, while improving the surgeon's overall understanding of the situation.

3.1. A 3D Cloud of 2D X-rays: Visualizing Spatial Relationships

The extracted position and orientation of the fluoroscope at the moment that an X-ray image was acquired allows the creation of a 3D model to visualize spatial relationships. The X-rays are shown as oriented 2D slices in the 3D space based on their calculated transformation matrices (See Figure 2 and 3), inspired by recent 3D visualizations of photo collections [13]. Our approach is also similar to the ExoVis, out-of-place, visualization method, which is used to allow the manipulation of cutting planes on a medical 3D model

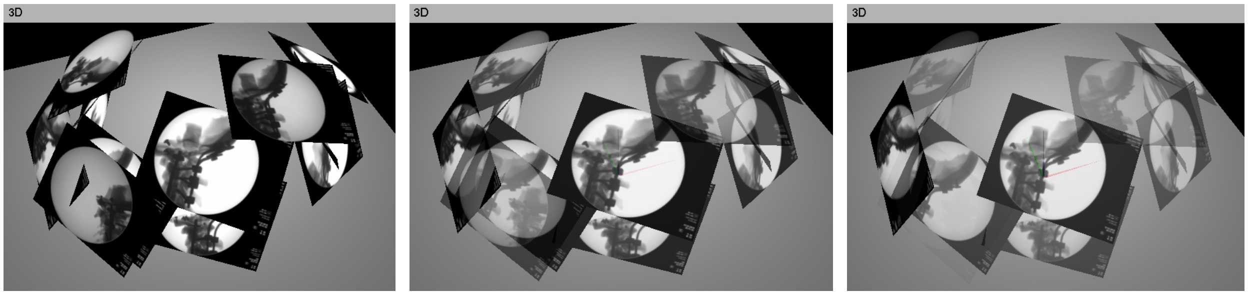

Figure 3. The spatial 3D arrangement also provides temporal cues with transparency mapping. The user can interactively control the mapping through a slider to make all X-rays fully opaque (left), or fade out older ones (right).

from multiple viewpoints. This, however, is not possible with traditional in-plane clipping methods, which were also shown to perform worse than ExoVis in empirical studies [8].

The user (e.g., a doctor or a nurse) can also freely change the view in the scene through basic 3D navigation (rotation, pan and zoom). We currently provide a mouse-based interface, where horizontal dragging with the left button rotates the scene, the scroll wheel controls zoom level, and vertical dragging with the right button pans the view. An X-ray slice becomes active in the 3D view when clicked, which presents a full screen view of the X-ray image in the traditional 2D perspective. Therefore, the X-ray slice in the 3D cloud acts as an "orientation icon" and the high-resolution version in the 2D view provides a means for precise examination and interaction for the user. While it may be interesting to in the future explore the combination of our techniques with 3D reconstructions [10] of the medical data, we first choose to focus on providing meaningful detailed visualizations of the spatial and temporal relations between the X-rays, with support for clustering and manipulation of the images.

3.2. Timelines + Transparency: Exposing Temporal Context

Temporal relationships for the X-rays are visualized both through opacities in the 3D visualization and in a separate timeline view. (See Figure 2)

The opacities of the 2D slices in the 3D view depend on how recently the X-ray was acquired. The more recent, the more opaque, while older X-rays gradually fade, as shown in Figure 3. The user can interactively control the transparency mapping through a slider, which makes it possible to make all X-rays fully opaque, or gradually fade out the older ones by dragging the slider downwards.

The timeline uses a roll-over fisheye effect to enlarge the X-ray thumbnail under the cursor for quick inspection (Figure 4), while a mouse-click, brings it up in the high-resolution 2D view, as shown in Figure 2.

Figure 4. The timeline uses a roll-over fisheye effect to enlarge the thumbnail under the cursor for quick inspection.

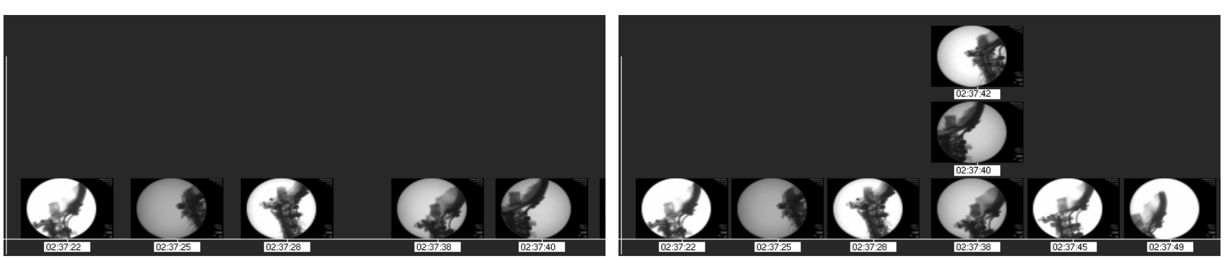

Figure 5. An automatic grouping algorithm uses the intervals of the X-rays' acquisition times, to minimize clutter in the timeline.

The timeline also has an automatic grouping algorithm, based on the intervals of the X-rays' acquisition times (shown in labels below thumbnails), to minimize clutter, as shown in Figure 5. The clustering intervals can be increased or decreased with the keyboard (+/–). Users' navigation in the timeline is additionally aided by colored markers in the scrollbar space, to indicate the position of image groups. (See Figure 2).

3.3. Synchronized Tracking of Tool, Fluoroscope and X-rays

Previous work have shown how a motion tracking system can allow the surgeon to view continuous movement of the live-tracked tool in a previously taken X-ray, without having to consider a series of new X-rays, as long as internal structures are assumed to not have changed.

Besides this, our system also has the capabilities to provide continuous feedback for the movement of surgical equipment inside the 3D space. This may, in particular, be interesting, as it would allow surgeons to preview the usefulness of new images from a particular perspective, given the ease with which one can identify spatial and temporal overlap with another image.

It should also be emphasized that the system requires no calibration (beyond that of the motion tracking system), as all tracked components (e.g., surgical instrument and fluoroscope) are in the same coordinate system, which is an important advantage over many traditional systems [1].

4. Implementation

We found it important to develop a system that could be easily deployed in existing operating rooms. We have therefore specifically focused on leveraging already existing medical equipment and an unobtrusive, low-cost commercial tracking system that requires minimal modification to current surgery rooms.

The software is implemented in C++ and OpenGL and runs under Windows XP on a 2.33 GHz Intel Core 2 Duo with 2 GB RAM. For X-ray acquisition we use an unmodified GE Healthcare Fluoroscope 7900 [14], shown in Figure 1. A 3D tracking system (NaturalPoint OptiTrack) provides position and orientation (6DOF) with unique identification for multiple passive, retroreflective markers in the space [15]. (See Figure 6). The system uses a standard motion tracking approach, both for the X-ray device and the operational tools. Multiple cameras with infrared lights illuminate

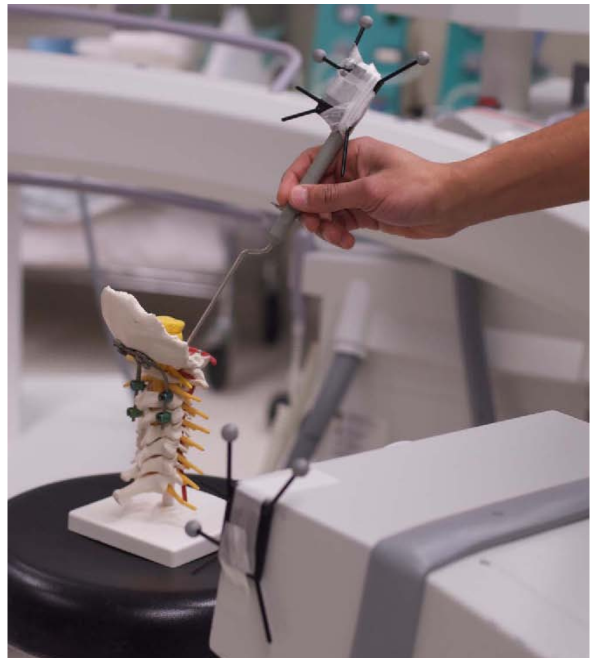

Figure 6. Surgical pointer and part of fluoroscope with attached 3D marker structures (three retro-reflective balls in rigid arrangement).

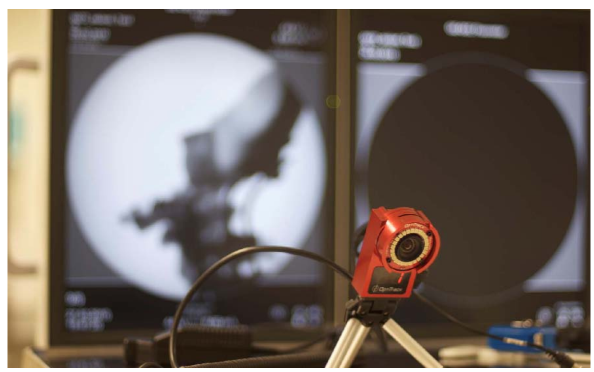

Figure 7: One of three infrared cameras with built-in infrared illuminators and on-board image processing for point tracking.

the space (See Figure 7), and the light is brightly reflected back into the camera only by the retroreflective material on the markers. The system fuses each marker's detected 2D location in the different camera views to recover 3D position. Rigid structures with three or more markers allow us to recover unique identification of tracked objects, as well as orientation, which we use for the surgical tool and fluoroscope (see Figure 6). The tracking system is interfaced using NaturalPoint's Tracking Tools [15].

5. Conclusions

This paper describes a novel approach for maximizing the potential of IGS systems by augmenting current surgical procedures with real-time tracking data and interactive visualization. We developed a prototype where a motion tracking system is used to associate each X-ray from a fluoroscope with the spatial position of the machine at the time of exposure. Our contribution lies in a user interface that exposes the associated temporal and spatial relationships for these multiple 2D X-rays in the 3D surgery space. The interaction techniques aim to help surgeons make fast, yet highly informed, decisions before each use of harmful X-rays. We hope that these techniques will help make operations safer and more effective for the patient through reduced radiation, and by giving the surgeons additional tools that further empower their specialized skills.

6. Future Work

While designed and developed in collaboration with neurosurgeons and experts in medical technology, we are planning to conduct more extensive tests and evaluations with a larger group of doctors. We have also started to explore gesture-based techniques as an alternative to the current keyboard/mouse interface (not appropriate for a sterile surgical environment), and refinements to the 2D/3D visualizations and the associated interactions. Including and combining our techniques with preoperative medical data, such as CT and MRI, can further expand the potential of the system. Finally, we find it interesting to also continue developing the information visualization notion of uncertainty in our images, such as adaptive image fading, and generalize the concepts that we started to explore in this work. Interactive techniques in combination with semi-automatic reasoning could allow us to increase the understanding of the X-ray imagery, for the full potential of this powerful, yet harmful radiation.

7. Acknowledgments

We thank Yngve Sundblad for coordination of the project and the Karolinska University Hospital for access to surgery rooms and medical equipment. This project was funded by The Swedish Knowledge Foundation and supported by the KTH SimVisInt project.

References

[1] M.T. Peters, “Image-guided surgery: From X-rays to virtual reality”, *Computer Methods in Biomechanics and Biomedical Engineering*, vol. 4, no.1, pp. 27-57, 2000.

[2] Z. Yaniv, and K. Cleary, “Image-guided procedures: A review”, Computer Aided Interventions and Medical Robotics Division, Image Science and Information Systems Center, Georgetown University, Tech. Rep. CAIMR TR-2006-3, 2006.

[3] A. Nordberg, P. Antoni, M. I. Montanez, A. Hult, H. von Holst, and M. Malkoch, “Highly Adhesive Phenolic Compounds as Interfacial Primers for Bone Fracture Fixations", *ACS Applied Materials and Interfaces*, vol 2, no. 3, pp. 654-657, 2010.

[4] F.T. Gebhard, M.D. Kraus, E. Schneider, U.C. Liener, L. Kinzl, M. Arand, “Does Computer-Assisted Spine Surgery Reduce Intraoperative Radiation Doses?”, *Spine*, vol. 31, no. 17, pp. 2024-7, 2006, discussion 2028.

[5] K.T. Foley, D.A. Simon, Y.R. Rampersaud, “Virtual Fluoroscopy”, *Operative Techniques in Orthopaedics*, vol. 10, no. 1, pp. 77–81, 2000.

[6] R. Hofstetter, M. Slomczykowski, M. Sati, and L.P. Nolte, “Fluoroscopy as an imaging means for computer-assisted surgical navigation”, *Computer-Aided Surgery*, vol. 4, no. 2, pp. 65-76, 1999.

[7] L. Joskowcz, C. Milgrom, A. Simkin, L. Tockus, and Z. Yaniv, “FRACAS: A system for computer-aided image-guided long bone fracture surgery”, *Journal of Computer-Aided Surgery*, vol. 3, no. 6, pp. 271-278, 1999.

[8] M. Tory, E.A. Kirkpatrick, M.S. Atkins, and T. Möller, “Visualization task performance with 2D, 3D, and combination displays”, *IEEE Transactions on Visualization and Computer Graphics*, vol. 12, no. 1, pp. 2-13, 2006..

[9] B. Preim and H-O. Peitgen, “Smart 3D Vizualizations in Clinical Applications”, in *Proc. Smart Graphics Symposium*, Springer, July 2003, pp. 343-352.

[10] M.A. Tresens, “Hybrid-Reality: Collaborative Environment for Biomedical Data Exploration Exploiting 2-D and 3-D Correspondence”, in *Proc. NSF Lake Tahoe.* Oct. 2003, Workshop on Collaborative Virtual Reality and Visualization.

[11] M. Tory, “Mental registration of 2D and 3D visualizations (an empirical study)”, in *Proc. IEEE Visualization,* Oct. 2003, pp. 371-378,

[12] E.V. Zudilova-Seinstra, B. W. van Schooten, A. Suinesiaputra, R.J. van der Geest, B. van Dijk, J.H.C. Reiber, P.M.A. Sloot, Virtual Reality, vol. 14, no. 2, pp. 105-118, 2010..

[13] N. Snavely, S.M. Seitz, R. and Szeliski, “Modeling the world from internet photo collections”, *Computer Vision*, vol. 80, no. 2, pp. 189-210, 2008.

[14] GE HealthCare (2011, June 12). *OEC Fluorostar 7900*, [Online]. Available: http://www.gehealthcare.com/euen/surgery/products/oec-fluorostar

[15] NaturalPoint (2011, June 12). *OptiTrack and Tracking Tools* [Online]. Available: http://www.naturalpoint.com/optitrack