

Current Limitations and Opportunities for Surgical Navigation

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Introduction

Optical tracking systems (OTS) have been used for medical imaging during surgery long before even the term biophotonics had been coined. Biophotonics is the science of using light photons for imaging biological materials to acquire surface contours and underlying anatomical features. The term biophotonics was probably coined after the beginning of OTS in neurosurgery. As a subset of image-guided navigation, the idea in using an external device to project onto an anatomical location and guide a tool to that location first appeared in literature in 1908.^{1,3} This external device was the stereotactic frame and it allowed precise guidance coordinates to the anatomical region of interest. Neurosurgery was the original clinical application for the stereotactic frame^{3,4} since brain tissue is highly sensitive to surgical trauma and would therefore require precise guidance to the target location. Another possibility for early adoption into neurosurgery is that bony anatomy such as the spine and cranium provided well defined and rigid-body landmarks. Limitations to frame-based stereotaxy include patient discomfort, limited view of the surgical field and no awareness to complications such as rupturing a vessel.³ To overcome some of these limitations, frameless stereotaxy was introduced in the 1990s by David Roberts^{3,5} and gave way to what we see today in surgical navigation.

Why OTS?

Today, complications encountered in neurosurgical treatment of brain tumors, spinal fractures, and deformities continue to have significant impact on the lives of people in Canada. Nearly all neurosurgical procedures require some bone cutting, typically craniotomy, and bone drilling in order to gain access to the target lesion. The danger in this procedure is accidental plunging of the drill into the dura and underlying brain, spinal cord, or nerve roots. Therefore, the surgeon is required to make accurate incisions towards the site with-

out collateral damage.⁶ In spinal fusion surgery, the accuracy with which screws are inserted has a direct surgical impact to the patient. Improperly placed screws to the vertebral body could place potential danger to nearby neural and vascular structures,⁷ leading to complications which may require revision surgery,⁸ with individual patient and also societal health care cost implications.

A Brief Overview of OTS

To aid targeting and to minimize intraoperative navigation pitfalls, neurosurgical navigation systems and specifically optical tracking systems, were developed to help improve surgical accuracy by combining pre-operative imaging modalities such as magnetic resonance imaging (MRI) and computed tomography (CT) images with a GPS-like tracking system. Similar to how a car's location is mapped onto the roadways in Google Maps in real-time, the OTS maps the tool's (car) position in relation to the body (roadways) via the CT or MRI (Google Maps) images. The current standard for surgical navigation inside the operating room (OR) is based on an infrared (IR) sensor array in conjunction with a charge-coupled device (CCD) camera that locks onto passive (reflective markers) or active light-emitting diode (LED) markers.⁹ The typical workflow that one may observe in an OR using an OTS would consist of the following: (1) Place fiducial on patient (2) Acquire preoperative CT or MRI (3) Enable OTS tracking (4) Identify fiducial markers on patient (5) Complete registration process (6) Enable CT or MRI image overlay (7) Verify registration accuracy for error tolerance (8) Confirm with imaging (9) Proceed with surgery.

Most commercial optical tracking systems will use preoperative imaging data such as CT or MRI scans but there is now an increasing interest in using intraoperative imaging for navigation. Commercial companies like Philips and Siemens have introduced cone beam intraoperative imaging systems for the OR but these units required a dedicated facility.¹ On the other hand, Medtronic Inc. originally pioneered mobile intraoperative imaging, with the O-Arm system. This consisted of a cone beam CT imaging and associated hardware and software. Such trend is continuing with additional devices becoming available through Health Canada (e.g. BrainLab).

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What are the Advantages and Disadvantages?

Potential advantages in using optical tracking systems include cost-effectiveness and training. Manbachi et al.⁷ demonstrated cost-savings of \$70,000 when a group used a navigation system for pedicle screw insertion for 100 cases and obtained a decreased revision rate. For medical training, intraoperative optical tracking guidance can benefit medical students by having a staff surgeon monitor them in real-time and directing corrective measures when required.

Other benefits include increased accuracy during complex surgery, minimizing radiation exposure, performing higher volume of surgeries and its use in performing Minimally Invasive Surgeries (MIS). Despite these benefits that one can see when using optical tracking systems, Hartl et al.¹⁰ conducted a global survey and found that only 11% of surgeons in North America and Europe used navigation despite its widespread availability. However, non-users cited disadvantages which include high acquisition cost, lack of adequate training, equipment problems and disruption of OR workflow. A typical computer-assisted surgical system can cost around \$500,000 for spinal fusion procedures. Registration times are long⁷ and are significant towards overhead operating costs since surgery cannot proceed until registration is complete.^{7, 11, 12} Registration is essential in spatially aligning the two coordinate systems (patient plus CT/MRI imaging data) together.¹³ Paired-point registration is the process that fuses this data together and its accuracy is dependant on matching of the corresponding surface points in the preoperative image data. In general, the more paired-points the better registration accuracy. The time between the pre-operative scans to the time of the procedure leads to navigation errors due to reference frame shifting, fiducial marker shifting (skin movement), brain-shift, and from internal changes inside the brain. These pre-operative scans can be as old as a few days to a few months and during this time, the original positioning of the fiducial markers (via bony landmarks) may have shifted.¹ Other OTS potential sources of error include imaging errors, surface model generation errors (point-to-point selection), tracking device positioning error and registration errors. During the operation, additional navigation errors arise since many of the current systems cannot account for breathing compensation, brain-shifting, and unwanted patient shifting due to bedside bumps during the procedure.¹⁴ If this happens, re-registration is required, further increasing the operating time. In a separate study by Kolvukangas et al.,¹⁸ they found 200 hazardous situations documented in the 2012 MAUDE database that used computer navigation devices for neurosurgical procedures. It was possible that a number of these incidents could have been prevented if the accuracies of those devices were assessed preoperatively. Another limitation of current optical tracking systems is OR lighting. The infrared cameras of OTS units require an optimal distance away from the surgical field. This minimizes obstruction of the reflective IR lighting back to the camera

due to direct lighting in the surgical light heads. Another optical limitation is line-of-sight during tool tracking. Line-of-sight is crucial for continuous real-time connection between the tracking tool and OTS. This is not always convenient as other surgical instruments and multiple surgeons may block the anatomical interest. Because of this, operating room set-up prior to the surgery must take into account the physical footprint of these large and obtrusive OTS and intraoperative units or risk machine repositioning during the procedure, thereby disturbing the workflow and increasing operating times. The worst case would be canceled usage of the system midway in the procedure due to space constraints and rely back on surgeon experience and expertise. All of these errors have left surgeons with the impression that accuracy decreases during surgery.¹⁴ Stieglitz et al. completed a study and found that there is an ongoing loss of neuronavigation accuracy throughout the procedure. The authors used a BrainLab VectorVision2 (BrainLab, Feldkirchen, Germany) neuronavigation system and a Medtronic StealthStation (Medtronic) for their studies. The major factors that contributed to errors were surgical draping, attachment of skin retractors and duration of surgery. Early navigation systems reported tracking errors of 2-3mm¹⁵ and more recent systems using the BrainLab VectorVision2 and Medtronic StealthStation reported a mean error of 2.9 mm¹⁴ after the co-registration process.

Next Generation Applications

So where are we now in terms of state-of-the-art? With respect to surgical training, Rosser et al.¹⁶ found correlation between faster completion and reduced errors in laparoscopic surgeries when surgeons had a background in video games. Therefore, potential future neurosurgical training may benefit in gaming and simulation engines that incorporate the physical and virtual world. Current commercial visualization in OTS systems consists of three orthogonal 2D images and a 3D view. As technological leaps unfold in computational and gaming power, thereby catapulting 3D rendering and simulation software to push past the old polygon-like world into real-world high definition realism, it is only natural that augmented reality is finally becoming of age. Augmented reality overlays three-dimensional computer generated data onto the actual world that we see. What is the best way to represent this visualization data? This is still an understudied topic but future surgeons could potentially become better trained in neurosurgical procedures if optical tracking systems were to become economically feasible and ergonomically easy to use.

With respect to surgical robotics, there has been an active interest in automating neurosurgical procedures that can eliminate surgeon hand tremors, reduce human fatigue, and to be used for minimally invasive surgery. Robotic manipulator tracking in surgery have been widely explored but a fundamental problem remains – current commercial OR navigation systems are a bottleneck in providing accurate real-time

feedback information to the robot. They have measurement update rates much slower than the robot control cycle.^{12, 17}

Furthermore, the navigation system errors that were mentioned earlier have to be taken into consideration in neurosurgical robotics since these units will operate in anatomically tight confined spaces. Real-time tool position tracking would therefore be critical for robotic surgery. There is therefore opportunity for novel technology development to make the procedure safer, faster image acquisition speeds, lowering the surgical time and in improving surgical outcomes.

Evolution of OTS: Optical Surface Imaging

To address the limitations of current state-of-the art optical tracking systems, the optical surface imaging (OSI) design was developed in our research lab in hopes of minimizing surgical work flow interruption and making it more economically accessible. It is currently completing clinical trials for spinal fusion procedures and can provide guidance to surgeons inserting pedicle screws, with rapid set up time and fast registration, which is a step above other commercially available surgical navigation devices.

To address the issue of intraoperative procedures, current commercial systems are large and obtrusive in the operating room or are permanently fixed in its own dedicated room. Our navigation system using OSI is integrated with the operating room light, intuitive and non-obtrusive. To address the labor intensive and time consuming paired-point registration issue, the OSI technique instead uses biophotonics (the science of using light photons for imaging biological materials) to automatically detect the surface contours in the entire field of view. The anatomical roadmap is then projected onto computer screens in the operating room so that surgeons can view the images in real-time as they operate. The navigation system is mounted above the table as the operating room light, for which the positioning and repositioning of the device are similar to how surgeons would move current surgical lights. Workflow is not disturbed and requires minimal operational movements. The device is user friendly and requires minimal setup time. This translates to faster and cheaper operating costs. Current operating room costs are between \$100 to \$200 per minute in Canada and typical neurosurgical procedures average about six to eight hours, which could translate into significant cost savings or improving throughput. While the spinal surgery trial is ongoing with this device, additional trials in cranial surgeries is underway.

Conclusion

Studies have shown that surgical navigation systems have the potential to help reduce surgical time, reduce length of hospital stay, reduce hospital cost and complication rates. New advancement in biophotonics technology and machine vision may further improve the economics and ergonomics of surgical navigation systems and widen clinical adoption.

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