Towards portable image guidance and automatic patient registration using an RGB-D camera and video projector

Colton Barr[1], Andras Lasso[1], Mark Asselin[1], Steve Pieper[2], Faith C. Robertson[3],
William B. Gormley[3], Gabor Fichtinger[1, 4]

1. Laboratory for Percutaneous Surgery, Queen’s University, Kingston, Canada
2. Isomics, Inc., Cambridge, Massachusetts, USA
3. Department of Neurosurgery, Brigham and Women's Hospital, Harvard Medical School, Boston, Massachusetts, USA
4. Department of Surgery, School of Medicine, Queen’s University, Kingston, Canada

ABSTRACT

PURPOSE: Surgical navigation has remained a challenge in emergent procedures with mobile targets. Recent advances in RGB-Depth (RGB-D) camera technology have expanded the opportunities for adopting computer vision solutions in computer-assisted surgery. The purpose of this study was to demonstrate the capacity of an RGB-D camera rigidly fixed to a video projector to perform optical marker tracking, depth-based patient registration, and projected target visualization using open-source software.

METHODS: The accuracy of marker tracking and system calibration was tested by projecting points onto the corners of a geometrically patterned marker, which was imaged in several locations and orientations. The depth-based registration and practical projection accuracy of the system was evaluated by targeting specific locations on a simulated patient and measuring the distance of the projected points from their targets.

RESULTS: The average Euclidean distance between the marker corners and projected points was 5.34 mm (SD 2.93 mm), and the target projection error in the manikin trial following depth-based registration was 4.01 mm (SD 1.51 mm). On average, the distance of the captured point cloud from the manikin model after registration was 1.83 mm (SD 0.15 mm), while the fiducial registration error associated with registering a commercial tracking system to the manikin was 2.47 mm (SD 0.63 mm).

CONCLUSION: This study highlights the potential application of RGB-D cameras calibrated to portable video projectors as inexpensive, rapidly deployable navigation systems for use in a variety of procedures, and demonstrates that their accuracy in performing patient registration is suitable for many bedside interventions.

Keywords: image-guided procedure, frameless navigation, open-source, camera-projector system, automatic registration

1. PURPOSE

Image guidance plays a critical role in numerous surgical interventions, providing intraoperative insight into structures and tools being manipulated deep within the body that cannot be observed directly. While the additional time associated with setup and registration of surgical navigation systems is acceptable in most planned procedures, time sensitive emergency interventions require accuracy with minimal delay, a feature not currently available. In addition, surgical navigation systems are often expensive, bulky pieces of equipment integrated directly into an operating room and typically require specialized instrumentation, making them unavailable and impractical for use in an emergency bedside procedure. Rigid fixation of the target anatomy is also necessary in many image-guided systems, an invasive process that increases preoperative setup time and may interfere with existing surgical workflows. As a result there is a subset of critical surgical interventions that are performed at the bedside with minimal technological assistance, relying almost exclusively on physician experience and training.

There are numerous potential applications for a low cost, portable navigation system capable of providing intraoperative tracking and data visualization with a reasonable level of accuracy. One example of a procedure that could benefit from image based navigation is ventriculostomy, a common neurosurgical procedure that involves the insertion of a catheter through the skull and brain parenchyma into a fluid-filled ventricle. Today, this intervention is typically an emergent one, performed freehand at the bedside without navigation and relying on anatomical landmarks for entry at a heuristically selected point. Unfortunately, the morbidity associated with this procedure is relatively high, with an average of 1.5 attempts per successful freehand placement and reported rates of cortical vessel injury between 10%-20% [1, 2]. Computational analysis of preoperative images has been shown to yield optimal insertion points and trajectories for ventriculostomy, however without a means of visualizing this information intraoperatively it cannot be effectively applied [3].

While the use of a frameless image-guided system to achieve optimal catheter placement has been shown to reduce proximal failures [4], the standard of care for ventriculostomy is still the freehand approach. A 2008 survey of US neurosurgeons found that only 1% of clinicians regularly use image guidance, while 92% reported exclusively using a freehand technique [5]. The same study found that 94% of practitioners would not use an image-guided navigation system that guaranteed optimal catheter placement if it added more than 10 minutes to the procedure. This highlights the importance of time in the deployment and use of navigation tools in emergency procedures. In contrast to planned surgical procedures, in which high accuracy at the expense of long setup and calibration times is an acceptable tradeoff, the primary design constraint in emergency procedure navigation is related to portability and ease of operation. Therefore an image guidance system for ventriculostomy would represent an improvement on the current standard of care only if it could guarantee more consistent catheter placement than the freehand technique, and achieve this without significantly increasing the duration of the procedure.

Recent advances in RGB-Depth (RGB-D) camera technology and an increase in the availability of consumer grade 3D depth cameras have expanded the opportunities for adopting computer vision solutions in computer-assisted surgery. To provide the patient registration and tracking accuracy necessary for most mobile surgical navigation applications, an RGB-D camera could be used instead of an optical tracker at a fraction of the cost and size. Rigid fixation of the patient is typically not feasible in emergency procedures, therefore patient movement relative to the RGB-D camera could be monitored by temporary fixation of an optical marker to the patient. Coupling a depth camera with a portable video projector, hereafter referred to as an RGB-D camera-projector system, would facilitate direct visualization of navigation information in the surgical field. This approach allows clinicians to focus solely on the operative site without requiring them to shift their gaze to an external monitor. Numerous open-source tools exist that would complement an RGB-D camera-projector system, including toolkits for webcam-based optical marker tracking, software packages for projector-camera calibration, and medical imaging platforms for conveying information of interest using the projector. The purpose of this study was to develop and evaluate an open-source RGB-D camera-projector system capable of optical marker tracking, depth-based patient registration and projected target visualization.

2. METHODS

2.1 Requirements

The primary design requirements in developing an image guidance system for emergency procedures were related to time and convenience. Unlike most conventional navigation solutions, this system had to be portable enough to be brought to the patient's bedside and intuitive enough to calibrate and register on site. This meant that overall size and form factor were fundamental design constraints, along with ensuring sufficient hardware was on board to streamline calibration and registration tasks. Another important consideration was the method used to convey navigation information to the clinician. A truly convenient system would integrate seamlessly into existing surgical workflows, while augmenting a user's ability to plan and perform the standard procedure. The convenience of the system would also be increased by minimizing its cost, which would enable hospitals to purchase and maintain multiple units. Finally, the accuracy of the system had to be sufficient to provide useful spatial information in real time.

2.2 Hardware Platform

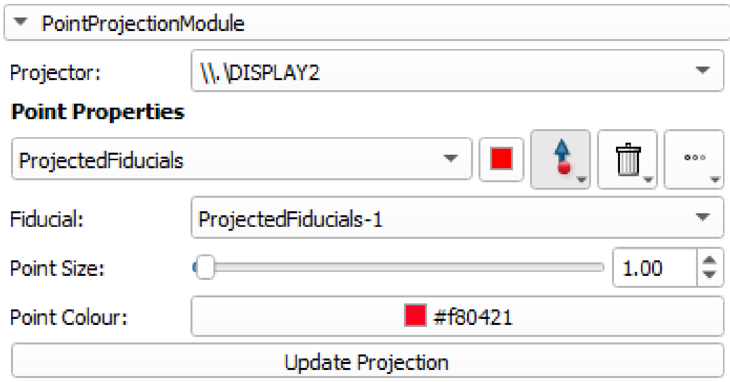
To explore options for making a camera-projector system with an appropriate balance of portability, affordability and overall accuracy, we selected the AAXA Pico M6 projector (AAXA, Irvine, CA, USA). This 1080p projector is capable of battery operation for up to one hour at 500 Lumens for effective visualization in a variety of ambient light conditions, and is relatively inexpensive ($599 USD). The M6 projector was combined with the Intel RealSense D435 (Intel, Santa Clara, CA, USA) since it is readily available at a low price point ($179 USD) and has a small form factor, all features that are desirable in a lightweight, portable navigation system. The projector and RGB-D camera were rigidly fixed to one another using a metal bracket and mounted on a standard camera tripod for portability (Figure 1).

Figure 1. Front view [left] and side view [right] of the Pico M6 projector rigidly fixed to the Intel RealSense.

2.3 Software Platform

The software for both implementing and testing this proof of concept system was built primarily using 3D Slicer and PLUS (Public Library for Ultrasound toolkit). 3D Slicer is an open-source medical image computing and visualization platform with powerful built-in tools for 3D visualization, volume registration and data analysis. It is particularly well suited for rapid system prototyping using Python, which is also host to numerous computer vision and image processing packages. RGB and depth images were streamed from the RealSense to 3D Slicer using PLUS, an open-source software library built by Lasso *et al.* for processing and streaming of real-time data from a number of different sensors and tracking systems [6]. A custom 3D Slicer extension was developed to facilitate intuitive 3D interaction with the system (Figure 2) and visualize the projected information on a virtual model (Figure 3).

For our optical marker tracking system we decided to use the ArUco marker library, a well-established, OpenCV-based pose estimation toolkit with robust error correction and additional support within the PLUS toolkit. Using PLUS enabled us to stream marker pose information to 3D Slicer in real time, which we then used to compute the location of the marker relative to the projector and generate the appropriate output image. Rapid calibration of the system was achieved using the ProCamCalib tool developed by Audet *et al.* [7], which facilitates calibration of an arbitrary number of cameras and projectors to one another simultaneously.



Projector: \\.\DISPLAY2
ProjectedFiducials
Fiducial: ProjectedFiducials-1
Point Size: 1.00
Point Colour: #f80421

Figure 2. The custom extension UI for point projection.

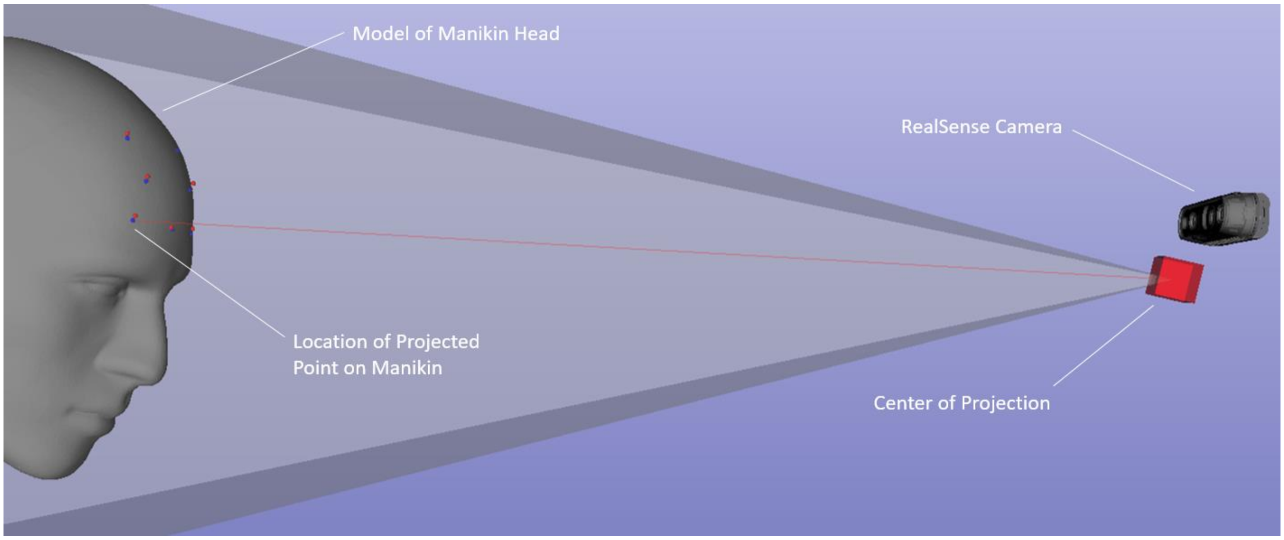


Figure 3. The interactive model of the system implemented in 3D Slicer. Each fiducial can be dragged to a different location on the model, and the specific fiducial to visualize via projection can be selected.

2.4 Workflow

To assess the concept of using a camera-projector system as a navigation tool for emergency procedures, a basic workflow was proposed to simulate its potential application to frameless bedside neurosurgical interventions (Figure 4.). The face provides unique geometry well suited to automatic surface-based registration, making emergency neurosurgical procedures an ideal use case for this type of system. The workflow was broken down into four separate steps: segmentation, calibration, registration and navigation. Each of the first three steps generated important system information that was applied during navigation. In the proof of concept system calibration and registration were automated, while the segmentation step and transitions between steps required manual input. The final system would ideally automate the transitions between steps as well, requiring minimal user input beyond manipulation of a calibration board and temporarily moving surgical drapes.

The first step in our proposed workflow was segmentation, which involved generating a model of the patient's skin. Since preoperative imaging is typically captured to plan treatment, this imaging data could be segmented to generate a model of the patient's superficial soft tissue. The optimal entry point for a procedure like ventriculostomy could then be determined on the model, either automatically in software or by manually placing virtual fiducials in a 3D Slicer interface. A structured light scan of a manikin head was used to simulate the segmented imaging data, with entry points selected manually in the custom 3D Slicer extension. The second step was calibrating the system, which would be performed automatically at the bedside before each procedure to ensure that any changes to the geometry of the system are captured. The open-source ProCamCalib tool was used to demonstrate automatic calibration in the proof of concept system, and took less than 30 seconds to complete the calibration process.

The third step in the workflow was to perform patient registration without requiring user input. This concept was realized in the system using an RGB-D

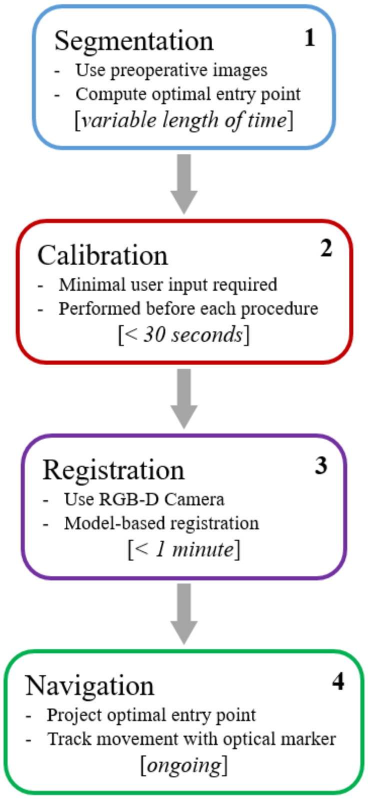


Figure 4. Proposed system workflow.

camera to perform depth-based registration. A point cloud was generated from the RealSense depth images and processed to isolate the facial geometry. The “Model Registration” module from SlicerIGT was then used to compute the final registration transform [8], which yielded the pose of the patient relative to the camera. Once the registration transform was determined, the selected point on the manikin model projected directly onto the manikin to emulate the navigation step of the procedure. While the simulated patient was static relative to the camera-projector setup in the system that was implemented, the proposed workflow would use an optical marker rigidly fixed to the patient’s skull to maintain registration in a frameless procedure. The accuracy of optical marker tracking combined with camera-projector calibration was tested separately in this study to assess the feasibility of this approach.

To examine the performance and practicality of this workflow, the fundamental components were implemented and experimentally tested. Optical marker tracking was evaluated in combination with system calibration by projecting points onto a tracked marker, while automatic registration and point projection accuracy were determined using a manikin patient model.

2.5 Evaluating optical marker tracking

To test the concept of using ArUco markers to track intraoperative movement of the patient in a frameless procedure, we evaluated the ability of our system to correctly determine the location of a marker relative to the projector. We designed software in 3D Slicer to track the location of an ArUco marker using the RealSense camera and project a dot at each of the marker’s 4 corners. The custom ArUco marker was designed with concentric circles of a known diameter around its corners to help visually measure the distance of the projected point from the true marker corner (Figure 5). The 8 cm^2 marker was fixed to a flat plane, and images were captured with the plane held steady at various angles and locations within the camera’s field of view, between 30 cm and 90 cm from the camera. The distance of the projected points from the corners of the marker were then determined visually in each image based on the diameter of the ring within which the majority of the point was contained.

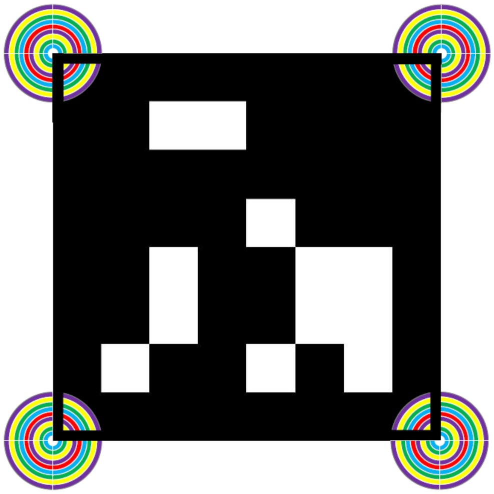


Figure 5. The modified ArUco marker with concentric 1 mm rings for visually measuring point projection error.

2.6 Evaluating depth registration and point projection

To test the use of depth images to perform patient registration and projectors to relay navigation information directly on the patient, an extension was written in 3D Slicer that simulated the geometry of the camera-projector system relative to a model manikin head. The real manikin head was rigidly attached to a table and the camera-projector system was oriented to capture the full face of the model. Once depth-based patient registration was performed and the corresponding transform between the camera and patient was determined, the extension facilitated the placement of virtual fiducials on the manikin model within Slicer. The position of each target point on the manikin's head was calculated and a point was projected onto the real manikin for visualization. In order to determine the true location of the projected points on the manikin relative to the virtual points in the software, a commercial optical navigation system (Optitrak, Corvallis, OR, USA) was also aligned with the manikin head and registered to it via fiducial registration. A calibrated pointer tracked by the Optitrak was then used to touch the projected point on the manikin, and the location of the pointer tip was recorded in Slicer. The absolute distance between the simulated point in Slicer and the projected point as determined using the Optitrak was then calculated for each pair of points.

3. RESULTS

3.1 Optical marker tracking

A camera-projector calibration was performed and custom software in 3D Slicer was executed to project points onto the corners of a tracked marker. The marker was captured at 5 distances from the camera and in 10 separate orientations at each distance, for a total of 50 positions within the tracked volume. The average absolute distance of the projected points from the corners of the marker was 5.3 mm, with a standard deviation of 2.9 mm. The magnitude of position error relative to the distance of the marker from the camera is shown in Figure 6.

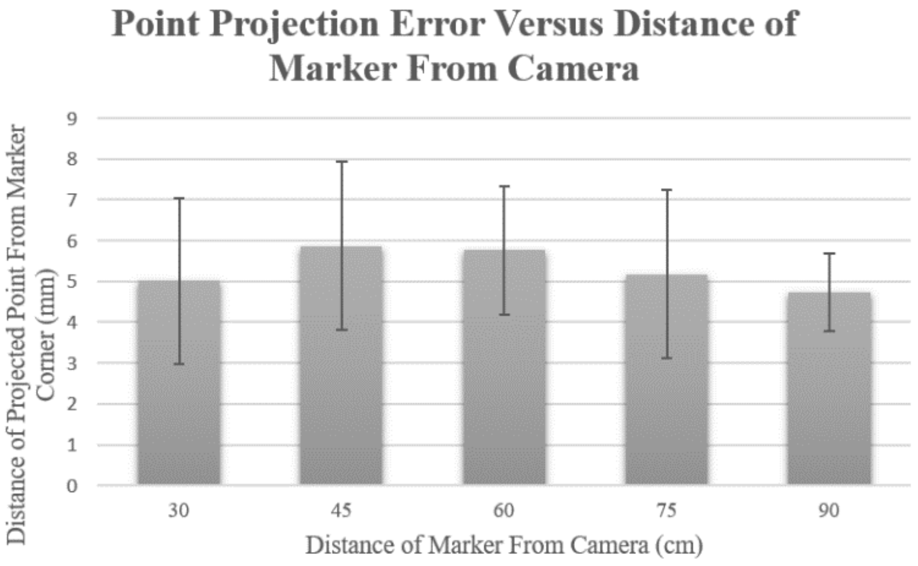


Figure 6. The point projection error relative to the distance of the marker from the camera.

3.2 Depth registration

A series of trials (n=3) were performed, with 20 pairs of points captured in each trial. The first 10 target points in each trial were the same set of points used to perform fiducial registration between the Optitrak and the manikin, in order to minimize the influence of the commercial tracker's registration error. The second set of 10 points in each trial was randomly placed on the forehead and top of the manikin's skull to simulate possible entry points for neurosurgical procedures. The average overall Euclidian distance of the projected points from the target points was 4.01 mm, with a standard deviation of 1.51 mm. The average distance for the first group of 10 projected points was 4.72 mm (SD 1.64 mm), while the average distance of the second set of points was 3.30 mm (SD 0.92 mm). The average distance of the captured depth point cloud from the manikin model after iterative closest point (ICP) registration was 1.83 mm (SD 0.15 mm), and the average fiducial registration error associated with registering the Optitrak to the manikin was 2.47 mm (SD 0.63 mm). The error associated with each pair of points in Trial 2 can be seen in Figure 7.

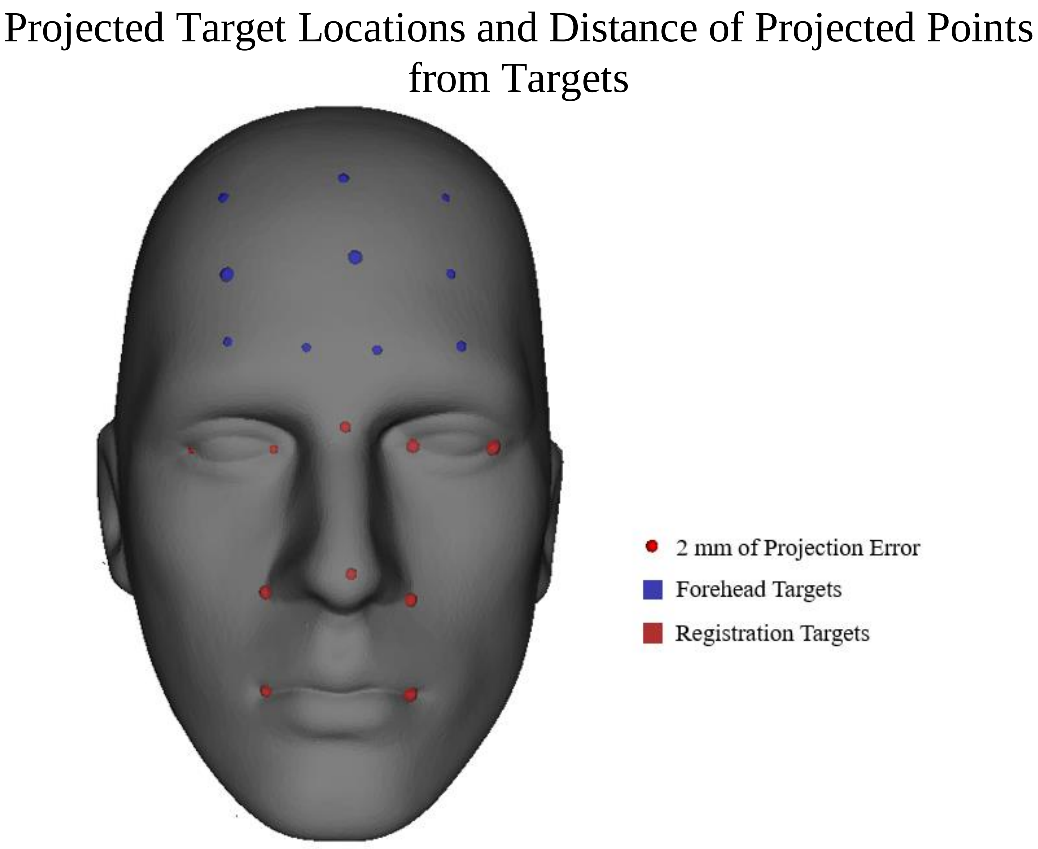


Figure 7. The locations of the target points used in Trial 2 on the manikin. The projection error is proportional to sphere size.

4. DISCUSSION

The results of the optical marker tracking experiment showed no correlation between the distance of the marker from the camera and the distance of the projected point from the marker's corners. The average projected point distance of 5.3 mm leaves significant room for improvement in terms of the accuracy of projecting a point onto a tracked target. This value needs to be minimized before the ArUco markers can be used to effectively track patient movement during frameless procedures. Future work to improve optical marker tracking using the RGB-D camera will focus on the integration of depth data to refine marker localization, an approach that has already been demonstrated to reduce depth-axis tracking error by up to 90% [9].

The comparable performance of ICP registration using a depth image point cloud to the gold standard of fiducial registration highlights the potential for RGB-D cameras to facilitate hand-free, automatic registration. There are a number of factors that may have contributed to the 1.42 mm decrease in average target projection error between the first and second sets of points, including the targets in the first group being further from the projector on average than those in the second group. The location within the tracked volume that the camera-projector calibration was performed may have also played a role, since the calibration board was rotated on the forehead of the manikin and the focal length of the projector was manually adjusted to this distance. The overall error observed in the system was likely influenced by a combination of sources, including the commercial tracker, the camera-projector calibration and the patient registration with both systems. Future work will involve the quantification of each source of error and investigation into possible means of minimizing these errors.

5. NEW OR BREAKTHROUGH WORK TO BE PRESENTED

This study highlights the potential application of RGB-D cameras calibrated to portable projectors as inexpensive, rapidly deployable navigation systems for use in a variety of procedures, and demonstrates that their accuracy in performing patient registration is suitable for many bedside interventions.

6. CONCLUSION

RGB-D camera-projector systems represent a new platform for intraoperative tracking and data visualization. They have the potential to provide sufficient accuracy for a variety of surgical applications in a lightweight, inexpensive and rapidly deployable package. This study proved that open-source software can be used to efficiently calibrate and register an RGB-D camera-projector system to a patient, and demonstrated the system's capacity to track optical markers and project target locations on a registered patient.

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