Optical Surgical Navigation: A Promising Low-cost Alternative*

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***Abstract*— State-of-the-art computer-assisted surgery relies on expensive infrared-based systems for precise positional measurements. Recently, low-cost optical tracking with cameras has emerged as an alternative to determine the locations of medical instruments. However, inconsistencies may arise between procedures due to differences in operating room conditions and patient anatomy. Therefore, it is crucial to identify and evaluate individual factors that may influence a procedure. In this study, we assess variables that affect marker tracking in the operating room: warping, line-of-sight obstruction, and operating room lighting. We evaluate fiducial ArUco markers as a low-cost alternative to traditional markers. We develop a ground-truth model in an XYZ environment to assess the real-time differential between the real and predicted positions. Each variable was isolated and simplified to quantifiable modifications to the physical marker and XYZ platform environment. We find that our navigation system is a promising approach for use in computer-navigated surgery. Future work will implement image processing techniques to increase the accuracy of optical marker tracking.**

I. INTRODUCTION

Surgical operations have increasingly turned to optical tracking to conduct difficult procedures where precision is required [1]. Optical tracking serves to identify regions of interest relative to the position of surgical tools. From here, guiding systems can help surgeons plan trajectories that mitigate unwanted anatomical damage [2].

Modern optical navigation setups typically utilize stereoscopic cameras. The camera observes 3D objects such as reflective marker spheres using infrared light which enable real-time tracking [3]. Stereoscopic cameras achieve depth perception by utilizing a two-camera system. Positional information is inferred based on the difference between the two images captured [4]. However, the cost of implementing these camera systems can be expensive for small healthcare centers, independent practices, and training purposes [5].

Recent improvements to consumer-grade camera systems have opened the door for more affordable camera systems to be used in surgical operations. For example, an iPhone-based augmented reality navigation setup has been successfully used for brain lesion localization [6]. However, optical tracking systems are unable to utilize reflective markers without the assistance of infrared or laser-receiving camera systems [3]. On the other hand, pose tracking with 2D markers has the potential of being usable with a low-cost camera system. However, before implementing low-cost camera systems, it is necessary to determine the effects of different operating room environments and patient-specific variables on marker tracking. In this paper, we aim to design a low-cost optical marker tracking system that can be utilized in different surgical settings. To achieve this, we conduct quantitative tests on a proof-of-concept marker system that replicates diverse operating room scenarios and patient anatomies.

II. METHODS

A. Ground Truth Platform

To test the factors that affect marker tracking, a ground-truth testing platform is necessary. We accomplish this by designing an X-Y platform that allows us to validate our position tracking algorithm. Our setup is shown below in Fig. 1. The platform spans 500 mm by 500 mm in the X and Y directions. The moving marker is shuttled around the X-Y platform at fixed distances and speeds. Our study performs marker tracking experiments in the X-Y plane. In a future publication, we will integrate additional markers into our setup as well as validate in the Z direction using stereoscopic vision.

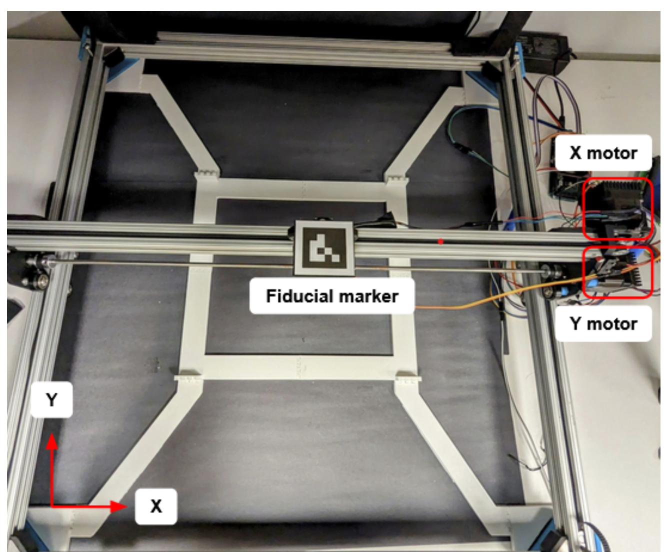

Fig. 1. Constructed X-Y Platform. The platform spans 500 mm by 500 mm. The marker is able to move in the X and Y directions.

B. Marker Tracking

Our marker tracking implementation makes use of ArUco markers. ArUco markers belong to an open-source fiducial

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marker library dedicated to positional tracking in real-time [7]. We perform tracking by following the center pixel coordinate of the marker as it moves.

In order to integrate optical position tracking in our surgical navigation system, it is important to determine all potential factors that can affect the accuracy of ArUco code tracking. Using the XYZ platform as our ground-truth model, we have conducted numerous marker tracking experiments. The factors that we tested for were warping, line-of-sight obstruction, and operating room lighting.

In all experiments, the moving marker was shuttled around the platform in the X and Y directions in a square pattern, as shown in Fig. 2. A tracking camera was placed directly above the starting position of the moving marker at a height of 500 mm. The camera was placed parallel to the X-Y plane to ensure only 2D motion was recorded.

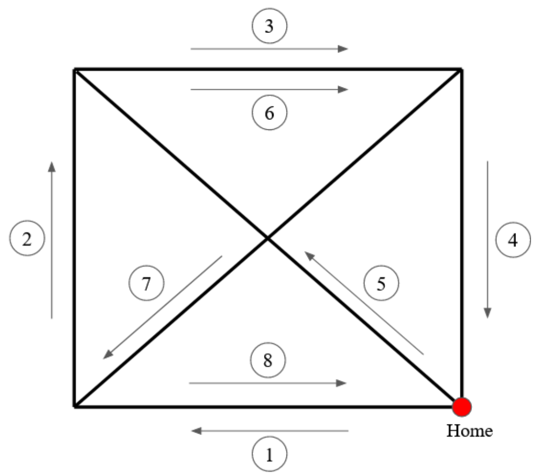

Fig. 2. Marker movement pattern. Numbers one through eight correspond to the order of travel.

Table I displays the default parameters used in testing. Upon capturing a video of the moving marker, the video was transferred into Python. At each frame, the marker ID and pixel coordinates of the marker center were captured with the aid of OpenCV and ArUco packages [7]. To determine the real-life distance that the marker moves, we have converted the pixel position of the markers to real length values by dividing the real width of the marker by the Euclidean space of the marker width in pixels.

After computing the position of the marker in millimeters, the data was imported into MATLAB for analysis. At each frame, the position of the marker given by the camera was compared against the ideal position of the marker. The ideal position of the marker was obtained by computing the expected distance traveled at each frame based on the known motor specifications. The error of the moving marker was recorded as the marker moved through space for three trials.

C. Marker Warping

Marker warping can arise from a variety of factors in surgical operations. In practice, patients may be required to reorient themselves depending on the needs of the physician.

TABLE I
DEFAULT PARAMETERS USED IN MARKER EXPERIMENTS

Parameters	Settings
Marker platform speed	10 mm/s
Pixel density	4x4 pixels
Marker width	40 mm
Camera resolution	1080p
Frames per second	60 fps

Skin markers can also be placed on curved surfaces, such as when markers need to be placed along the spinal region.

We categorize marker warping into four general categories: concave, convex, stretch, and compression warping. In concave and convex warping, we designed 3D printed marker platforms with a 1 cm focal length, as shown in Fig. 3. To simulate 2D deformation, we stretched and compressed ArUco markers by a factor of 25%.

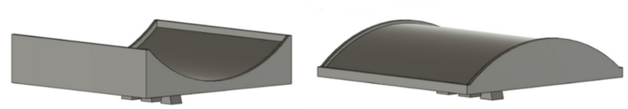

Fig. 3. Computer-aided Design (CAD) models of the concave and convex marker platforms used.

D. Line-of-sight Obstruction

One of the biggest challenges of implementing optical tracking systems is line-of-sight obstruction. We define line-of-sight obstructions to be either partial or total covering of the marker from the tracking camera's perspective.

To study line-of-sight obstructions, we covered markers with a thick stripe along the right-hand side, as shown in Fig. 4. The thickness of the strips was varied to be 0, 0.5, 1, or 1.5-bits thick, respectively. A bit is defined as the black and white squares that make up the ArUco marker.

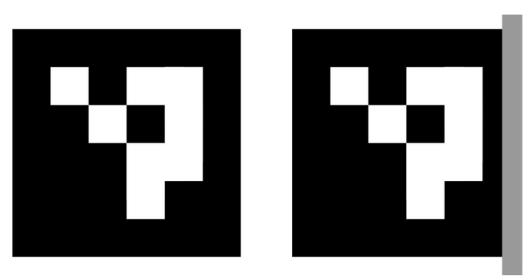

Fig. 4. Example ArUco code in the line-of-sight obstruction experiments. The left code shows the unaltered marker. The right code shows the marker covered with a 0.5-bit thick strip.

E. Operating Room Lighting

Depending on the location and financial situation, hospitals and operating rooms may vary significantly. One direct result of this is the quality of different lighting environments, such as light temperature and intensity.

To study the effect of different lighting conditions on marker tracking, we tested the following color temperatures:

white (6000K), warm-white (4500K), and warm (3000K). In addition, we also varied the light intensities to 1000, 700, 500, and 250 lux, respectively.

III. Results

A. Marker Warping Performance

Table II reports the detection error associated with the marker warping experiments. Three trials containing no warping were also reported as a baseline measurement.

TABLE II
DETECTION ERROR RESULTS (IN MM) IN THE MARKER WARPING EXPERIMENTS.

Parameters	Trial 1 (mm)	Trial 2 (mm)	Trial 3 (mm)
No Warping	0.97 ± 0.41	0.98 ± 0.41	0.95 ± 0.35
Concave	1.73 ± 0.66	1.71 ± 0.63	1.61 ± 0.61
Convex	1.45 ± 0.57	1.70 ± 0.65	1.62 ± 0.66
Stretch	0.98 ± 0.41	0.94 ± 0.35	0.82 ± 0.34
Compression	1.03 ± 0.42	0.94 ± 0.35	0.81 ± 0.32

Fig. 5 displays the error heatmaps associated with each warping parameter. Each heatmap displays the error averaged over the three trials.

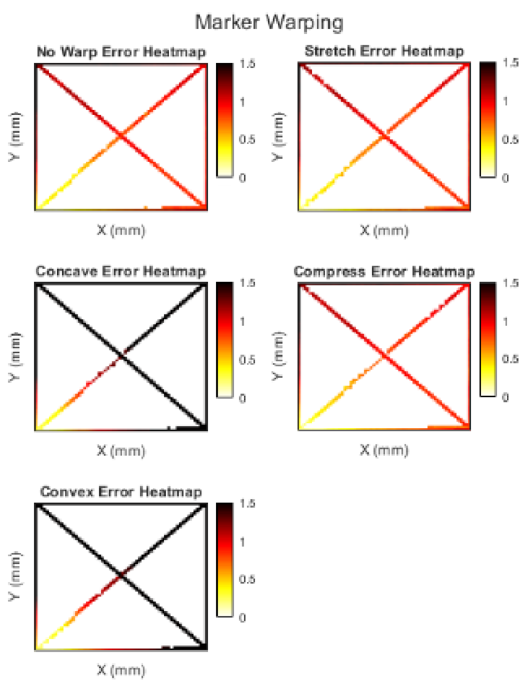

Fig. 5. Error heatmaps in marker warping experiments. The average of the three trials was taken.

B. Line-of-sight Performance

To study line-of-sight performance, we report the successful detection rate percentage rather than the error per trial. As the amount of obstruction increased, the marker tracking algorithm "struggled" to properly detect the moving marker. Table III reports the successful detection rate percentage associated with marker obstruction.

TABLE III
DETECTION RATE PERCENTAGES IN MARKER OBSTRUCTION EXPERIMENTS.

Bit Thickness	Detection Rate
0	100%
0.5	12.5%
1	0%
1.5	0%

C. Operation Room Lighting Performance

Table IV reports the detection error associated with the light temperature experiments. Additionally, Table V reports the detection error associated with the light intensity experiments.

TABLE IV
DETECTION ERROR RESULTS (IN MM) IN THE LIGHT TEMPERATURE EXPERIMENTS.

Temperature (K)	Trial 1 (mm)	Trial 2 (mm)	Trial 3 (mm)
6000	0.76 ± 0.34	0.97 ± 0.43	0.78 ± 0.30
4500	0.98 ± 0.40	0.79 ± 0.31	0.88 ± 0.42
3000	0.93 ± 0.48	0.85 ± 0.40	0.93 ± 0.35

TABLE V
DETECTION ERROR RESULTS (IN MM) IN THE LIGHT INTENSITY EXPERIMENTS.

Intensity (lx)	Trial 1 (mm)	Trial 2 (mm)	Trial 3 (mm)
1000	0.75 ± 0.31	0.96 ± 0.43	0.78 ± 0.43
700	0.88 ± 0.37	1.05 ± 0.46	1.07 ± 0.36
500	0.97 ± 0.38	0.86 ± 0.30	0.92 ± 0.38
200	1.13 ± 0.47	1.07 ± 0.38	0.82 ± 0.31

Fig. 6 displays the error heatmaps associated with each lighting parameter. Each heatmap displays the error averaged over three trials.

IV. Discussion

The findings of our study reveal that the use of fiducial markers for optical tracking in operating rooms can serve as a feasible and cost-effective alternative to advanced surgical navigation systems. Our methods involved adjusting a wide range of parameters that could potentially impact performance in the operating room environment, yet most of the tests yielded an error of less than 1 mm. However, our analysis revealed that marker obstruction significantly hindered tracking, where even a small obstruction can have a large effect on the correct identification of the marker. As seen in Table III, a 0.5-bit obstruction renders markers virtually unusable in surgical operations. Nevertheless, using a multi-camera system would increase the probability of correct detection and accurate readings. It is apparent that, given smart camera placement, this problem is trivial to overcome.

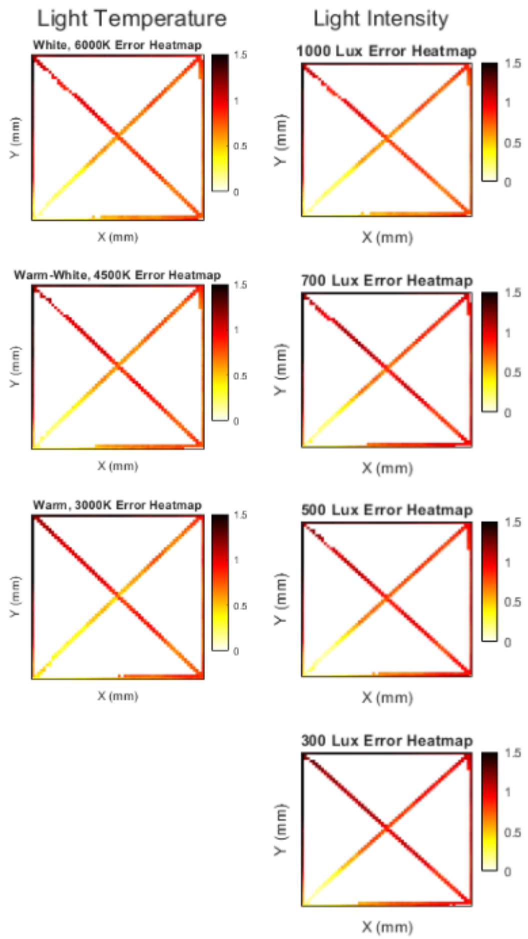

Fig. 6. Error heatmaps in operation room lighting experiments. The average of the three trials was taken.

Overall, the error per trial increased when working with concave and convex-warped markers compared to the baseline. Light temperature appeared to produce sub-millimeter error results in all conditions. Light intensity produced errors on the order of 1 mm as intensity decreased. Interestingly, stretching or compressing the marker had a small effect on tracking accuracy. One possible explanation could be that concave and convex-warping not only distort the marker in 2D, but they also distort the depth of the marker. Future optical tracking systems will need an appropriate way to measure such changes.

It is important to note that variables such as operating room conditions and marker warping may be more difficult to control in real-world scenarios. However, there are other patient-specific variables that fall into this category that have not yet been tested. These variables include skin movements, sweating, and wear and tear of the markers. All of these factors can result in inconsistencies in marker tracking if not accounted for correctly.

While the above results highlight some of the variables present in marker tracking, future work must involve optimizing image processing algorithms. In particular, the implementation of an extended Kalman filter or machine learning regression algorithms could temporarily estimate the location of markers experiencing line-of-sight obstruction. Additionally, we are exploring thresholding techniques to track marker IDs more accurately in various lighting conditions.

V. Conclusion

In this study, we have evaluated the potential of low-cost optical tracking in applications of minimally invasive surgery. We do this by constructing a ground-truth validation platform, used in tandem with ArUco markers to evaluate the accuracy of marker tracking software in various environments. We concluded that our proposed optical tracking system is a promising low-cost substitute for existing surgical navigation systems. Assessment of our tracking system yielded less than 1 mm error in various operating room environments. The main determinant of tracking quality was line-of-sight obstruction, which we aim to address by incorporating multiple cameras and various positions for consistent detection. Future work will include the integration of digital image processing, filtering techniques, and machine learning regression to increase the accuracy of our tracking system.

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