NAVIUS: Navigated Augmented Reality Visualization for Ureteroscopic Surgery

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Abstract. Ureteroscopy is the standard of care for diagnosing and treating kidney stones and tumors. However, current ureteroscopes have a limited field of view, requiring significant experience to adequately navigate the renal collecting system. This is evidenced by the fact that inexperienced surgeons have higher rates of missed stones. %22 of patients with residual stones require re-operation within 20 months. In order to aid surgeons to fully explore the kidney, this study presents the Navigated Augmented Reality Visualization for Ureteroscopic Surgery (NAVIUS) system. NAVIUS assists surgeons by providing 3D maps of the target anatomy, real-time scope positions, and preoperative imaging overlays. To enable real-time navigation and visualization, we integrate an electromagnetic tracker-based navigation pipeline with augmented reality (AR) visualizations. NAVIUS connects to 3D Slicer and Unity with OpenIGTLink, and uses HoloLens 2 as a holographic interface. We evaluate NAVIUS through a user study where surgeons conducted ureteroscopy on kidney phantoms with and without visual guidance. We observed that surgeons explored more areas within the collecting system with NAVIUS (average 23.73% increase), and experienced lower task load, as measured by NASA-TLX (up to 27.27% reduction). NAVIUS is a step towards intraoperative AR guidance for better surgical outcomes and surgeons' experience. The codebase for the system is available at: https://github.com/vu-maple-lab/NAVIUS.

Keywords: Endoscopy · Ureteroscopy · Kidney Stone Disease · Augmented Reality · Navigation

1 Introduction

Kidney stone disease is projected to affect 25% of the population in 30 years, decreasing a patient's quality of life and increasing the economical burden for healthcare and patients [24]. Endoscopy of the renal collecting system (i.e., ureteroscopy), is the gold standard for minimally invasive surgical treatment of kidney stones [30]. However, this surgery is challenging for urologists due to the limited field of view and complex 2D to 3D mapping negatively impacting navigation and kidney stone treatment [16]. To overcome these challenges, recent literature proposed the use of 3D printed models for preoperative planning [10], computer vision methods for anatomical navigation [22, 2], as well as virtual and augmented reality (VR/AR) systems [9].

In this work, we propose NAVIUS, an AR system that aids ureteroscopy by displaying a 3D virtual map created from a preoperative computed tomography (CT) scan. The system provides interactive annotations and visualizations for stones, spatial localization of the scope tip, CT scan overlays, and feedback for areas explored within the renal collecting system. To the best of our knowledge, our work is the first to demonstrate head-mounted AR visualization of real-time scope tip localization. NAVIUS can be used for preoperative planning and intraoperative navigation.

We evaluate the benefits of NAVIUS with user studies conducted in a mock operating room setup with renal collecting system phantoms. We analyze the effectiveness of NAVIUS through subjective surveys and objective evaluation of recorded scope trajectories. Additionally, we document our process to build realistic phantoms. We use anatomical models extracted from CT scans to ensure structural realism and colored silicone to create visual similarity. These phantoms can be used in surgical training or ex-vivo experiments.

Navigation Applications: Advancements in sensors and computer vision fields show promise to enhance ureteroscopy and other minimally invasive procedures. For example, Fu et al. developed a registration algorithm that uses structural similarities between endoscopy images and images rendered from preoperative scans to localize the endoscope [12]. Oliva Maza et al. used ORB-SLAM 3 [6] to provide a 3D map of the organ and pose of the ureteroscope [22]. Similarly, our previous work compared structure from motion algorithms to create a 3D map, and registered this to preoperative scans to assess visited areas [2].

Outside of vision, Yoshida et al. used the electromagnetic (EM) tracker for endoscope navigation and compared it with traditional fluoroscopy-based methods in several studies [31, 32]. Another study by Zhang et al. suggested the use of multiple sensors combined with a curve fitting algorithm to estimate accurate poses and bending angles [33]. These studies showed the feasibility and effectiveness of EM trackers in ureteroscopy; however, they were limited by surgical monitors as displays, causing a decrease in 3D perception.

Augmented Reality: Augmented reality technologies allowed improvements in visualization [4], planning [19], interaction, and communication [1] for minimally invasive surgeries [25, 9, 7]. Al Janabi et al. demonstrated the feasibility of Microsoft HoloLens (Microsoft Corporation, Redmond, WA, USA) devices in an operating room (OR) simulation setting as a visualization tool, and concluded that it can improve the procedure time and performance metrics [4]. Pose et al. created a real-time integration application between HoloLens 2 and 3D Slicer [11], and showed the feasibility of the system in a pedicle screw placement setup. The integration of AR systems to the OR opens up new possibilities to improve surgical outcomes.

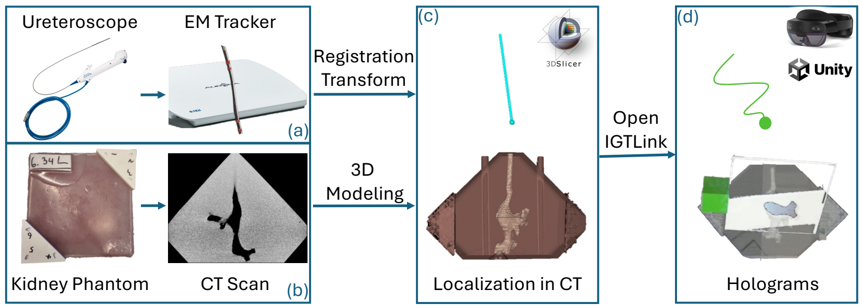

Fig. 1. Overall workflow of the system. We attach EM trackers to the ureteroscope tip and create 3D models from CT scans of phantoms. We register the scope tip positions to 3D models using 3D Slicer. Scope path, CT slices, and 3D model are visualized in HoloLens 2. Letters refer to sections in the methods.

2 Methods

NAVIUS integrates applications in 3D Slicer [11], Unity (Unity Technologies, San Francisco, USA), and HoloLens 2. Fig. 1 shows the overall system.

a. Ureteroscope Tracking. NAVIUS tracks the position and orientation of the scope tip using an EM tracker sensor (Aurora, Northern Digital Inc., Waterloo, Canada) attached rigidly to the tip, while preserving ureteroscope flexibility (Fig. 1a). 3D Slicer receives the tracking information real-time using OpenIGTLink [27] and PLUS toolkit [18].

b. Map Generation. We use patient CT scans to generate virtual 3D models of kidneys. We semi-automatically segment these scans using the 3D Slicer by manually guiding modules such as "level tracing" and "grow from seeds" (Fig. 1b). Stones detected in preoperative scans can be segmented using the same modules and added to the map as the initial estimation for stone positions. We export the segmentations as meshes in the OBJ format and import them into Unity.

c. Localization in CT. We create a Unity scene with 3D kidney models, a spherical game object to indicate the EM tracker position, and a user interface to control visualizations, tracking, and stone annotations. The AR application starts by establishing a connection between Unity and 3D Slicer on a remote computer. 3D Slicer sends the tracker position and 2D CT slice information as in [19] to Unity (Fig. 1c).

d. Holograms: In Unity, the 3D Slicer information and Mixed Reality Toolkit features are integrated to create holograms of CT overlays and tracker positions. Those holograms are displayed on the HoloLens 2 through holographic remoting (Fig. 1d). Using the HoloLens 2, users can place the holograms anywhere without disrupting their workflow and can see the targets from different viewpoints. A toggle between the complete anatomy visible in the CT field of view and the segmented collecting system allows surgeons to focus on the target area while retaining their spatial awareness (Fig. 2a-b). Whenever a stone is detected, they can annotate the area with a stone hologram and choose a different

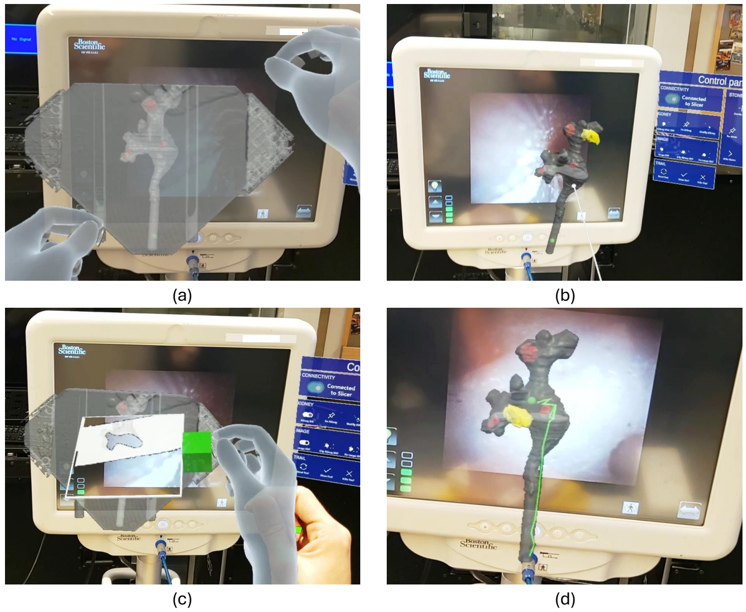

Fig. 2. Application features (a) Anatomy model that can be moved and scaled. (b) Segmented collecting system with stones or other pathologies annotated with different colors. (c) Overlay of preoperative scans matched to the hologram. (d) Scope tip position and tracked trajectory as a green marker and path.

color for each annotation (Fig. 2b). Furthermore, they can visualize the 2D slices of CT scans as an overlay or as a 2D image in user interface by freely moving the image plane over the 3D model (Fig. 2c) [19]. Finally, the application displays the scope position within the renal collecting system in real-time and creates a path of the movement. This allows surgeons to localize the scope within the collecting system with ease and keep track of the explored areas (Fig. 2d).

Phantom Production. We design our experiments with anatomically accurate phantoms to evaluate the system. To create the phantoms, we follow a similar methodology to Adams et al. [3], while eliminating the need for wax-compatible 3D printing. A detailed video explanation of the process can be found here: https://youtu.be/Ei3HvCMJSOw.

We use renal collecting system meshes segmented from patient CT scans and print with a Bambu Lab X1C 3D printer (Bambulab USA Inc., Austin, USA) (Fig. 3a). Using a cylindrical container, we mix 500 g each of Ecoflex 00-20 silicone rubber (Smooth-On, Inc., Macungie, USA) parts A and B, degas, and submerge the model, ensuring central positioning. A weighted plate keeps it submerged during solidification at room temperature for four hours.

After curing, we remove the Ecoflex mold and cut it into equal halves. This Ecoflex mold serves as the outer cast for the wax inner mold (Fig. 3b). We melt paraffin wax at 70°C and pour it into the Ecoflex cast via the ureter inlet. We

Fig. 3. (a) 3D printed collecting system. (b) Negative mold created with Ecoflex. (c) Wax model. (d) Outer mold filling. (e) Boiling to remove wax model and create calyces. (f) Final phantom.

carefully extract the wax mold after it solidifies at room temperature within an hour (Fig. 3c).

To create the external mold, we place the wax inner mold in a square container, mix 250 g each of Ecoflex parts A and B with one tablespoon of red food coloring, degas for 1 minute, and pour the Ecoflex mixture over the mold while ensuring central positioning. As the wax mold partially floats, we allow initial curing for two hours before adding another Ecoflex layer (Fig. 3d). After four hours, we remove the extender piece and submerge the phantom in 70°C isopropyl ethanol to dissolve the wax (Fig. 3e). Finally, we rinse, dry, and perform an endoscopic evaluation to confirm complete dissolution of wax. For our validation study, we use two phantoms that are evaluated as having similar exploration difficulty by a urologist.

3 Experiments

To evaluate the effectiveness of the proposed application, we conducted a user study with surgeons using kidney phantom models. We designed an experiment to simulate a real operating workflow, where six participants explore the renal collecting system with and without the NAVIUS system.

During the experiments, we attached an EM tracker to a Boston Scientific (Boston Scientific Corporation, Marlborough, MA, USA) single-use flexible ureteroscope using circular heat shrinks (Fig. 4a). This allows a rigid attachment to the tip without restraining the scope movement or significantly increasing the diameter. We fixed the phantoms rigidly on a tabletop field generator using double sided tapes. For the calibration, we 3D printed pieces with three scope tip slots and attached two of those rigidly to the phantoms (Fig. 4b). At the beginning of the experiments, we collected six data points by moving the scope to 3D printed reference slots, and using the "Fiducial Registration Wizard" within the SlicerIGT module [28], registered the tracker and CT scan coordinate planes. This module uses VTK [26] implementation of Horn's method [14], applying a closed-form solution to the least-squares problem for point pairs.

One surgeon and five surgical trainees with different levels of experience with HoloLens 2 and ureteroscopy explored the renal collecting systems. Each

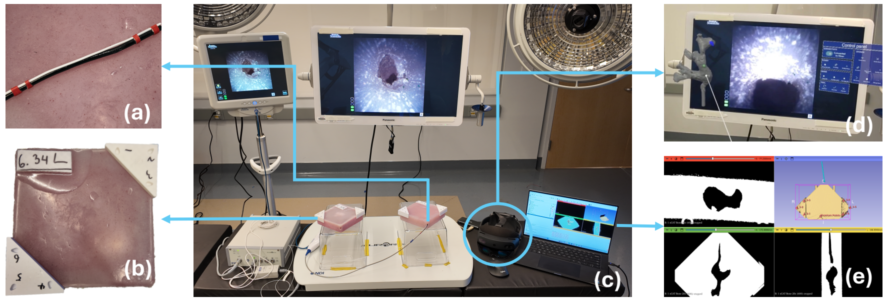

Fig. 4. Experimental setup (a) EM tracker attachment to scope. (b) Phantoms with registration fiducials. (c) Mock OR experimental setup. (d) HoloLens 2 field of view. (e) 3D Slicer view with registered scope positions and preoperative scans.

participant conducted two trials in two different conditions in different phantoms: with application (WA) and no application (NA). All participants reviewed the preoperative CT scans of the phantom before starting each procedure. In the WA condition, participants used the AR system with HoloLens 2, with a 3D model of the phantom and real-time localization. In the NA condition, they followed the standard workflow of relying on their spatial memory from the initial CT review. We randomized the order of phantoms and the availability of the AR application to minimize the learning effects at each trial. Participants completed the NASA Task Load Index (NASA-TLX) [13] to assess subjective workload and the System Usability Scale (SUS) [5] to evaluate the AR application. We recorded the real-time tracking data and quantitatively evaluated the explored area and distance traversed with the scope. All experiments were approved by Vanderbilt University Medical Center Institutional Review Board (#231997).

4 Results

NASA-TLX Results. To measure the cognitive load and participants' experience with the application, participants were asked to complete NASA TLX survey after each trial, rating 6 different categories from 1 to 20 (Table 1).

SUS Results: We asked participants to fill out a questionnaire with 10 questions by ranking the statements from 1 (strongly disagree) to 5 (strongly agree) and calculated the SUS score [5]. Both the baseline NA scenario and the WA scenario had the same final SUS score of 67.08 on the average of 6 users. The standard deviation was 9.14 for the case without the application and 7.65 with the application. In our results, only two questions had >1 difference in average responses for the two scenarios while the other metrics had less than 0.5 difference. Question 4 on the need for support (negative effect on the score) was rated 1.83 for NA and 3.83 for WA. Question 7 on ease of learning (positive effect) was rated 2.67 for NA and 4.17 for WA.

Quantitative Results. To evaluate the performance quantitatively, we analyzed the EM tracker data recorded with Perk Tutor Transform Recorder module

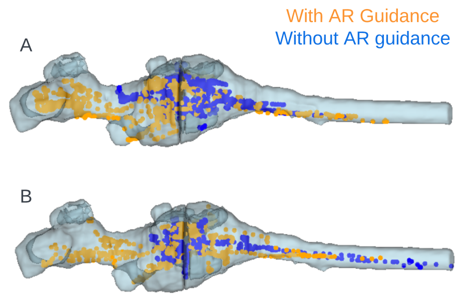

Fig. 5. Trajectories resulting from AR guidance (in orange) show in-depth exploration of the kidney phantom as opposed to without AR guidance (in blue). (A) and (B) shows trajectories created by four users exploring the kidney phantoms; 2 with AR guidance and 2 without.

for 3D Slicer [29]. We applied an outlier removal to the trajectories to discard unrelated points created during the retraction. We used a Mahalanobis distance [21] threshold determined by trial and error based on trajectory visualizations. With a threshold of 3.0, 3.57% of points were considered outliers. For volume coverage analysis, we fit a convex hull over the trajectories (Table 2).

5 Discussion and Conclusion

Using NAVIUS resulted in improvements in the four NASA-TLX metrics, with greatest differences in increased performance (27.27%) and reduced frustration (26.56%) (Table 1). We observe increases in physical and temporal demand metrics, but these changes are less significant compared to improved metrics. These limitations may be caused by the surgeons' unfamiliarity with the system and the added stimulation from the application.

Furthermore, when users are asked if they have additional comments, without prompting, 3 out of 6 surgeons stated that NAVIUS would boost their confidence in exploring the kidney. Quantitative results support this, as surgeons covered 23.73% more volume on average without significantly increasing the scope travel

Table 1. NASA-TLX metric average (standard deviation) assessments of 6 users. Lower is better. Best values are indicated in bold.

	No Application	**With Application**	**% Change**
Mental Demand	13.33 (4.03)	**11.00 (4.98)**	-17.50
Physical Demand	**9.83 (4.83)**	10.17 (4.45)	3.39
Temporal Demand	**7.00 (5.29)**	7.50 (4.89)	7.14
Performance	9.17 (3.06)	**6.67 (5.43)**	-27.27
Effort	13.00 (4.34)	**10.17 (5.56)**	-21.79
Frustration	10.67 (2.16)	**7.83 (4.96)**	-26.56

Table 2. Quantitative results acquired by endoscopy trajectory. Averages (standard deviation) of 4 users with complete trajectory recordings during the exploration.

	No App.	**With App.**	**% Change**
Convex Hull Volume mm^3 (↑)	10603.42 (5377.97)	13119.28 (3543.74)	23.73
Total Distance Traveled mm	747.50 (372.54)	757.25 (242.70)	1.30

distance (Table 2, Figure 5). We report results from four users since the trajectory collection on two users was incomplete. This increase in volume coverage indicates that the surgeons went into more calyces with the help of NAVIUS. Thus, NAVIUS helps surgeons do a more thorough exploration and avoid missed areas or stones.

NAVIUS scored 67.08 (±7.65) in the SUS evaluation, which is around the general average and accepted benchmark of 68 (±12.5) [15]. The same average SUS scores for the procedure with and without the proposed AR application shows that the application does not introduce significant additional challenges to usability. User responses to SUS question 4 on the need for technical support indicate the limited familiarity of surgeons with the headset. The performance of surgeons may improve on all metrics as they become more familiar with HoloLens 2 and NAVIUS. In question 7 of the SUS, participants claimed that this application is easier to learn compared to ureteroscopy without visual guidance, which shows the potential for increased proficiency in the short term.

Integration of the system to the OR can be affected by factors such as decreased EM tracker performance due to interference by other devices and the need to attach the sensor to the scope. However, usability can be improved with additional calibration procedures [20], and specialized tracker attachments using medical-grade heat shrinks. Alternatively, trackers can be placed in the working channel of the endoscopes. Furthermore, previous studies show the usability of EM trackers in operating rooms [23]. Based on the experimental results reported by Lugez et al. [20] and Poulin et al. [23], we consider the performance of EM trackers acceptable for a surgeon-in-the-loop visualization system.

In addition, registration of preoperative data to intraoperative workflow can be more challenging in a live OR setting, with factors such as deformation or limited calibration. Nonetheless, in the clinical scenario, fluoroscopy can be integrated to improve the registration. Additionally, methods Kuntz et al. proved with in-vivo experiments, such as sensorized fiducials or driving the endoscope to collect data points, can be used [17]. Since the current attachment and registration solutions suffice for our phantom studies, we left the modifications to these components for future work. Our experiments in this study evaluate the core idea of navigated AR visualizations and their technical feasibility. This step is necessary to power future in vivo and clinical studies with more surgeons for improved statistical analysis. Our future work includes the integration of vision-based navigation and registration pipelines that would improve the clinical feasibility of the system.

To conclude, we introduce NAVIUS, an AR application to aid surgeons during kidney stone surgeries. In the phantom studies, we observe improvements in both NASA-TLX metrics and the volume covered within the collecting system. This system can be extended to other surgical areas, and can be integrated with robotic systems using interfaces such as SlicerROS2 [8]. Future work can focus on introducing additional functionalities such as collaborative virtual environments and integration of endoscopic segmentations. Overall, this application can improve the operational outcomes for the patient and the surgeons' experience in the OR. NAVIUS demonstrates the feasibility of navigation and AR integration to transform ureteroscopy workflow.

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