Improving AR Guidance for Motor Surgical Tasks: Visualizing Uncertainty

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Abstract

Augmented Reality (AR) has the potential to transform surgical procedures by offering surgeons real-time guidance during the operation. However, tracking and registration errors remain unavoidable challenges, often leading to misalignment of virtual overlays and compromising surgical accuracy. While previous studies have focused on reducing these errors through enhanced tracking techniques, little attention has been paid to visualizing the resulting uncertainty. We assume that, whatever progress is made in tracking systems, a certain degree of uncertainty will remain in the resulting guidance system. In this ongoing work, we propose to investigate whether visualizing uncertainty can improve surgeons' performance and confidence during motor surgery tasks. This paper introduces our research topic and outlines our preliminary approach, with the aim of sparking discussion and collaboration at the workshop.

CCS Concepts

• **Human-centered computing** → *Visualization design and evaluation methods.*

Keywords

Augmented reality, Surgery, Uncertainty, Guidance, Tracking errors

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1 Introduction

Augmented Reality (AR) has emerged as a promising tool in the surgical domain, aiming to enhance precision, reduce complications, and improve patient outcomes [1]. By applying AR technology to surgery, target anatomy, complex surroundings, and navigation information can be displayed directly in the surgical area [10]. Unlike traditional imaging technologies, AR enables real-time, intuitive visualization of internal structures and surgical pathways, reducing the cognitive load associated with interpreting separate imaging screens [9].

However, registration, tracking, and display errors remain significant problems in ensuring precise alignment of AR overlays with the physical environment. Ma et al. [10] reviewed registration and tracking techniques used in AR surgical navigation systems. They observed that tracking errors are unavoidable when using Head Mounted Displays (HMDs) in current AR surgical systems. To address these limitations, researchers have explored external optical and electromagnetic tracking techniques to enhance accuracy[11]. However, these techniques often disrupt surgical workflows, require additional hardware, and involve considerable calibration time [10]. We believe that uncertainties will persist in tracking systems in the future because reaching perfect accuracy is difficult. Even if future tracking systems achieve near-perfect accuracy, new tasks may need precision at tiny scales, like micromillimeters, which could still be challenging. In such cases, showing uncertainty visually might help people better understand the limitations. Furthermore, perfect tracking systems will likely need more resources, making them unsustainable or difficult to maintain for complex surgical tasks. Therefore, rather than focusing solely on developing new tracking techniques, we propose to investigate whether visualizing the uncertainty caused by tracking errors can improve performance in motor surgical tasks.

2 Visualizing the Uncertainty

We assume that whatever progress is made in tracking systems using HMD, a certain degree of uncertainty will remain in the resulting AR guidance system. We propose to investigate whether visualizing this uncertainty can improve performance in motor surgery tasks. This work is inspired by previous research on visualizing uncertainty in data science and analysis [6]. For instance, in the context of autonomous vehicles (AV), Doula et al. [3] have shown that visualizing uncertainty enhances driver engagement and confidence in the automated vehicle, while maintaining an acceptable mental load for the driver. Some studies on spatial prediction, such as locating downed aircraft or forecasting hurricane trajectories, have shown that visualizing uncertainty improves prediction accuracy [14]. Other studies have shown that adding uncertainty visualization to displays improves human performance in

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Table 1: Categories of observable uncertainties and their underlying errors

Category	Description	Cause
Offset	Virtual objects are consistently displaced from their real-world counterparts.	-Tracker alignment error -Virtual objects alignment error -Tracking error -Camera extrinsic calibration errors
Jitter	Virtual objects appear shaky or unstable, oscillating rapidly.	-Tracking error
Drift	Virtual objects gradually move away from their intended position over time.	-Tracking error -Tracker alignement error
Latency	A delay between real-world actions and corresponding virtual updates.	-Tracking error -Rendering errors -Display errors
Distortion	Virtual objects appear distorted due to incorrect internal camera parameters like focal length, optical center, and distortion coefficients.	-Camera intrinsic calibration error
Occlusion and depth issues	Virtual objects may appear partially occluded, disappear, or fail to be rendered in the correct depth order.	-Rendering errors
Blurred or Low-Resolution Visuals	Small virtual details or objects appear blurry or poorly registered due to limited resolution, lens distortion, or hardware limitations in the HMD.	-Display errors

decision-making, judgment and estimation tasks, and can help users better understand the associated data and act accordingly [8, 16].

Building on these findings, we aim to explore the role of uncertainty visualization in AR-assisted surgery. Specifically, we want to answer the following question: Can visualization of uncertainty improve the surgeon's performance and confidence during a motor surgical task despite tracking and registration errors? To answer this question, our approach comprises three phases: (1) establishing a taxonomy of tracking errors, (2) designing uncertainty visualizations for a motor surgical task, and (3) conducting a user study to evaluate the effectiveness of these visualizations.

3 Taxonomy of Tracking Errors

Yang and Zhang [17] identified multiple sources of tracking and registration errors in HMDs, including tracker alignment errors, virtual object alignment errors, camera calibration errors (intrinsic and extrinsic), rendering errors, and display errors (see Figure 1). Although this taxonomy comprehensively addresses the technical origins of tracking errors, it offers limited interpretability for end-users like surgeons, who need to understand how these errors manifest (e.g., jitter or latency) during surgical procedures.

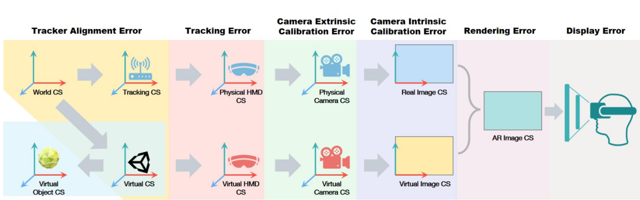

Figure 1: Sources of tracking and registration errors (Figure from [17])

Moreover, Zheng et al. [18] categorized errors into two main types: Dynamic and Static. Dynamic errors arise from system delays and appear only when the user's viewpoint or the augmented object moves, causing temporal misregistration. Static errors result from calibration, tracking, and modeling processes, leading to spatial misregistration even in the absence of movement. Common symptoms of static errors include constant offsets, jitter due to unstable tracking, and drift caused by error accumulation.

Building on these foundations, our work seeks to bridge the gap between technical error sources and their practical impact on the surgical workflow. More specifically; we extend Yang and Zhang's [17] taxonomy by identifying how each technical error translates into observable. Table 1 describes the observable uncertainty for each type of error.

The resulting taxonomy proposed in Table 1 guides our subsequent design of uncertainty visualizations tailored to surgical contexts.

4 Uncertainty Visualization Techniques

Several approaches, frameworks, and taxonomies have been proposed to represent uncertainty in data visualization [6]. The design of uncertainty visualizations has been particularly studied in the fields of data science and analytics [6]. For example, Maceachren et al. [12] proposed several techniques that use visual features, such as color, hue, brightness, and saturation, to effectively indicate uncertainty (see Figure 2).

Another approach is to display areas of uncertainty, as on Google Maps, where a transparent circle around a location point represents the uncertainty of the position [7].

Finally, Pang et al. [13] have studied and classified data presentation techniques with their associated uncertainty. The techniques include adding glyphs, adding geometry, modifying geometry, modifying attributes, animation, and sonification.

Despite the availability of numerous works on visualizing data uncertainty such as those mentioned above, we are not aware of

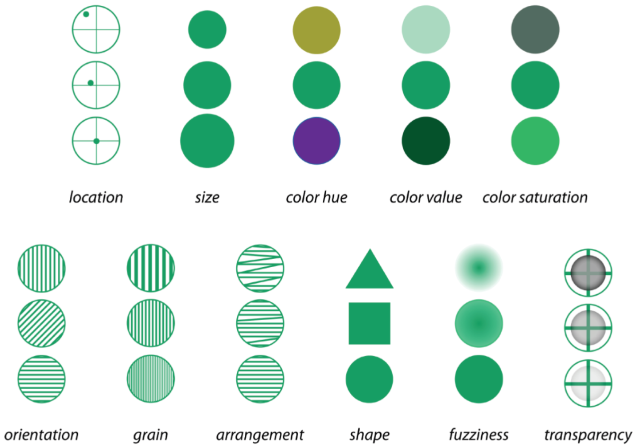

Figure 2: Uncertainty visualization techniques (Figure from [12])

any empirical research examining its effects on AR-assisted surgical tasks. This work aims to fill this gap by comparing different uncertainty visualization techniques applied to AR guidance techniques.

5 Envisioned User Study

We are considering a within-subject experimental design to assess the potential benefits of uncertainty visualization on surgical performance. In our proposed study, we will compare three conditions:

(1) Guidance without Tracking Errors.
(2) Guidance with Tracking Errors.
(3) Guidance with Tracking Errors + Uncertainty Visualization.

Condition (1) serves as an ideal, error-free benchmark representative of a future scenario where errors may be eliminated, while Condition (2) introduces realistic challenges that affect performance. Condition (3) then tests whether visualizing these errors can mitigate their negative impact. Comparing Conditions (2) and (3) specifically helps us understand if adding error visualization improves performance under error conditions. We compare Conditions (1) and (3) to investigate whether, in an error-free scenario, visualizing errors might affect surgeons similarly to the ideal state.

5.1 Task

The envisioned experiment focuses on a drilling task, as it is a precision-demanding task in many surgeries such as orthopedics and dentistry.

5.2 Selection of AR guidance techniques

Many AR guidance techniques were proposed to guide motor surgical tasks. For example, to guide a drilling task in surgery, these techniques include displaying the patient's anatomy [2], or 2D guidance information on how to position, orient, and insert the surgical tool [4], or 3D planned landmarks such as the planned incisions or drilling positions [15].

Building on prior work in AR guidance for drilling tasks [5], we selected two guidance techniques to investigate the role of uncertainty visualization: a 2D crosshair and a 3D trajectory. The 2D crosshair visualization employs a small point that represents the surgical tool's orientation and must be aligned with the crosshair's center. While the 3D trajectory guidance displays an extrapolated path of the surgical tool that needs to be aligned with a target point. These techniques have consistently demonstrated higher precision and faster execution times compared to other AR guidance techniques [5].

5.3 Independent variables

The independent variables will be guidance techniques (2D crosshair, 3D trajectory) and uncertainty visualization techniques (size, color, shape, transparency). In Condition (2), we will introduce tracking errors; since there are several types of errors (such as jitter, offset, and latency, detailed in section 3), we will initially focus only on jitter for the first experiment. We will then compare how different uncertainty visualization techniques affect users' performance when jitter is present. To fully address our research question, it is important to explore various visualization designs, as these could significantly influence the outcomes in Condition (3), where uncertainty is presented to the user. However, the design is still under discussion, as multiple parameters need to be considered.

For example, see Figure 3 for an illustration of the size gradient (an uncertainty visualization technique [12]) applied to the 2D crosshair and 3D trajectory guidance techniques.

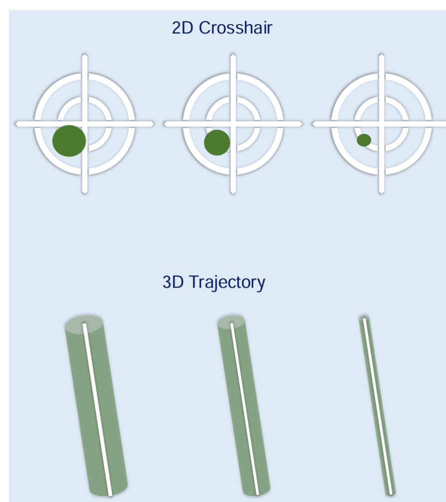

Figure 3: Integration of uncertainty visualization (size gradient) with two AR surgical guidance techniques: 2D crosshair and a 3D trajectory

5.4 Measures

We plan to measure task completion time, target error to assess the surgeons' drilling performance, as well as subjective feedback on confidence and trust on the system. Together, these measures offer a comprehensive assessment of whether uncertainty visualization can enhance overall surgical performance.

This is a draft design of the experiment. This experiment is a first step in determining whether visualizing tracking uncertainty can improve surgeon accuracy and confidence in AR-assisted surgical tasks.

6 Conclusion

This paper presents work in progress on the study of uncertainty visualization in AR-guided surgery, with a focus on improving guidance during critical tasks such as drilling. The experimental study we propose, although still under development, aims to assess the impact of uncertainty visualization on task performance and surgeon confidence. This research raises several other key questions:

- What is the impact of visualizing uncertainty in AR-guided surgery that is most relevant to study?
- Should the different sources of uncertainty be made explicit to the user?
- Should uncertainty be displayed as an additional visualization alongside the guidance display, or should it be integrated into a single hybrid visualization?

Answering these questions will be essential in future studies to refine AR guidance systems and, ultimately, improve the accuracy and safety of surgical interventions.

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