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Development and pilot validation of laser path anchor (LPA): A novel tool for augmented reality surgical navigation

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Abstract: Augmented reality navigation (ARN) enhances localization and operation by overlaying virtual guides onto real-world surgical fields. The study introduces a laser path anchor (LPA), a novel tool for ARN in surgery aimed at mitigating depth perception challenges. The LPA anchors the virtual planned path onto the physical laser beam, ensuring accurate puncture from any perspective. The tool consists of a rack, a primary laser emitter, an indicating laser emitter, and an AR marker with intrinsic and extrinsic properties validated through calibration and testing. Intrinsic validation involved measuring the parallelism between the indicating and primary laser using Cartesian graph screens. Extrinsic validation assessed the alignment and shortest distance between the virtual path and primary lasers. Results showed an angle deviation of 0.08° between the indicating and primary laser and 1.44° ± 0.47° between the virtual path and primary lasers, with a shortest distance of 7.60 mm ± 2.50 mm. The usability test demonstrated the LPA's effectiveness in guiding needle insertions without altering the perspective or distracting the surgeon. Despite some limitations, the LPA enhances the user's perception of linear objects and eliminates the need for perspective adjustments during puncture, warranting further development.

Keywords: Augmented reality, navigation, surgery, laser

1 Introduction

Augmented reality (AR) technology can overlay virtual images or information onto the surgical field, providing intraoperative guidance for surgeons. Immersive AR offers a more realistic, engaging user experience, showing greater promise and appeal. Consequently, immersive AR navigation (ARN) for surgery is being extensively developed, tested, and applied.

Visual information about the planned puncture path to physicians is a crucial application of immersive ARNs. However, depth perception poses a significant challenge (see Figure 1A and 1B). The user may not accurately perceive depth along the line of sight, making it difficult to ensure no inadvertent deviation from a single perspective. Additionally, obtaining multiple perspectives requires the user to move around the holograms, leading to holographic drift and user distraction.

To address this issue, the concept of a laser path anchor (LPA) was proposed (see Figure 1C). The LPA aims to "lock" the virtual planned path in physical space and provide feedback to the user, observing from different perspectives and ensuring the real-time alignment of the actual puncture with the planned path.

2 Materials and Methods

This section provides an in-depth description of LPA's design and principles, followed by an explanation of the intrinsic and extrinsic properties and their calibration verification methods. It concludes with an experimental design for assessing the LPA's proof-of-concept usability.

2.1 The LPA and AR platform

The LPA consists of a rack, two laser emitters, and an AR marker (Figure 2A and 2B). The rack has a self-locking flexible holder and two limit rings, allowing the user to adjust its position and orientation in space (See Figure 2A). The primary laser emitter, the crosshair laser (wavelength: 532 nm, power: 30 mW), is mounted on the rack via a limit ring and projects a crosshair forward using a custom lens. The indicating laser emitter (wavelength: 650 nm, power: 12 mW), is also mounted on the rack, projecting parallel to the crosshair laser's centerline with an optical axis separation of approximately 34 mm (See Figure 2B). The AR marker consists of a polylactic acid panel (dimensions: 6 cm × 6 cm) printed with a visually recognizable target image. Rigidly connected to the rack, it anchors

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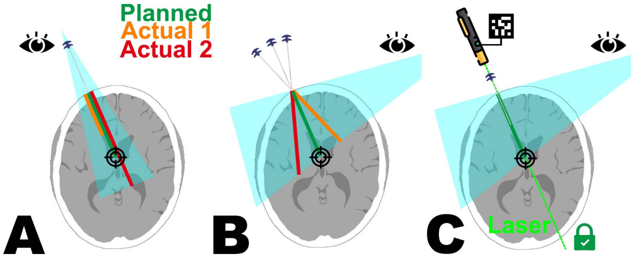

Fig. 1: Perceiving line segment positions is challenging due to depth perception issues since the actual path may deviate from the planned path, whether using an axial (**A**) or lateral view (**B**). Employing the proposed laser path anchor (LPA) can "lock" the path from the axial direction(**C**).

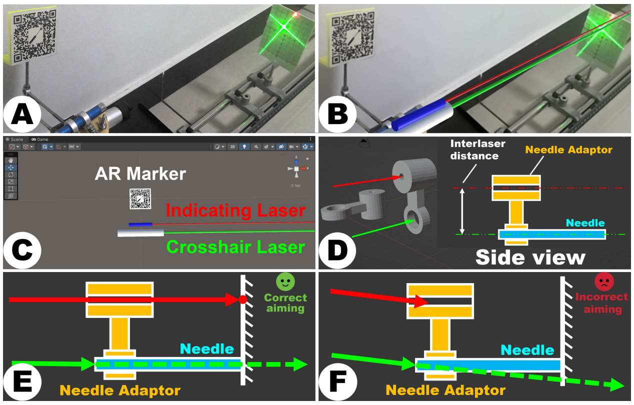

Fig. 2: The LPA and needle adaptor's structure and function. The LPA emits parallel lasers (**A**) with virtual path anchored (**B** and **C**). The needle adapter acts as a collimator (**D**), assisting users in determining whether the puncture needle is coaxial with the crosshair laser (**E** and **F**).

the dual laser system to the virtual path. Once the target image is detected and recognized by the AR device, the anchoring relationship is visualized for the user (See Figure 2C). This process used the Vuforia Software Development Kit (SDK) (Version 10.14, PTC, Inc., Boston, MA, USA).

The AR Marker and the laser pair define its extrinsic and intrinsic properties. The transformation from the AR marker to the primary laser, an extrinsic property, reflects the LPA's fundamental purpose of ensuring the physical laser path aligns with the planned path in space (See Figure 3A). Moreover, the transformation from the primary laser to the indicating laser, an intrinsic property, represents the spatial information transfer within the dual laser system (See Figure 3A). This intrinsic relationship is necessary because the primary laser projecting directly onto the puncture needle and surgical field would obstruct the surgeon's view. Instead, the indicating laser projected nearby better aligns with mental ergonomics.

To achieve this, an adapter was designed to be fixed to the needle's tail end, featuring a deep hole parallel to the needle (See Figure 2D—2F and Figure3A). This adapter is akin to a "front sight" on a rifle. It consists of two cylindrical components of different lengths, connected side by side, with their central axes spaced equally to the interlaser distance in the LPA (See Figure 2D). Each cylindrical component has a hole along its central axis. The shorter cylinder has a larger hole to hold and fix the needle, aligning its central axis with the puncture path. The longer cylinder has a smaller hole to indicate the laser, functioning as a collimator. The indicating laser can pass through this hole only if it is perfectly aligned with the central axis of the longer cylinder (See Figure 2E and 2F). The indicating laser passing through the hole indicates that the needle's direction is parallel to the laser direction. To ensure the LPA's reliability, extrinsic and intrinsic calibrations must be verified regularly. Extrinsic calibration focuses on aligning the virtual path with the primary laser to achieve coaxial positioning, while intrinsic calibration ensures the parallelism between the indicating laser and the primary laser.

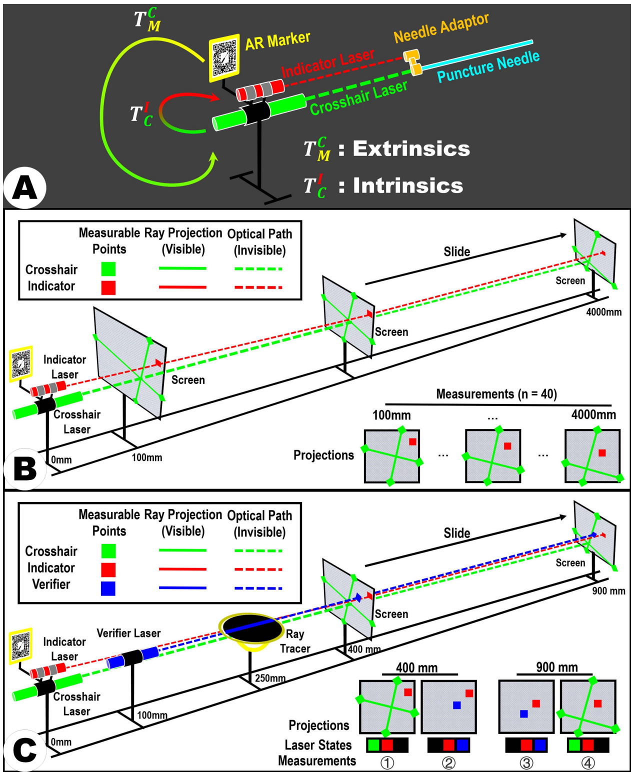

Fig. 3: LPA's intrinsic and extrinsic properties (**A**) and experimental principle for intrinsic (**B**) and extrinsic validation (**C**).

Since the LPA is theoretically compatible with all marker-based AR software and hardware platforms, platform selection is not critical for this proof-of-concept study. Therefore, a minimal functionality AR platform was developed using Unity (version 2021.3.4f1, Unity, San Francisco, CA, USA) to simplify testing. The project files were packaged as a Universal

Windows Platform (UWP) application and deployed to the HoloLens-2 (Microsoft, Redmond, WA, USA). The platform's sole function is displaying the virtual path upon detecting and recognizing the AR marker (See Figure 2C).

2.2 Experimental design

To verify the intrinsic, i.e., the parallelism between the indicating laser and the primary laser, a Cartesian graph screen (10 cm × 10 cm, 1 mm grid) was placed at 40 equidistant positions in front of the primary laser lens (ranging from 100 mm to 4000 mm, in 100 mm increments), with placements parallel to each other (see Figure 3B). With LPA's two lasers activated, the laser projection patterns on the screen were recorded at each position (see Figure 4A). Extrinsic validation was performed after that. The LPA was positioned at the "0" site on a sliding rail, while another Cartesian graph screen (8 cm × 10 cm, 1 mm grid) was placed at 400 mm and 900 mm along the rail (see Figure 3C and 4B). A third laser (the verifier laser at 100 mm) with a light tracer made of foam (at 250 mm) was used to align the verifier laser path with the perceived virtual path (see Figure 4C). The verifier laser and the crosshair laser were alternately activated, producing four projection patterns on the screen from the two measurement positions, which were recorded (see Figure 4B and 4C). This process was repeated three times by the same individual (Z.Q.).

Each projection pattern recorded above extracted the coordinates of the measurement points, including the geometric centers of the indicating laser and verifier laser's spots and the crosshair laser's four intersection points with the Cartesian graph's edges. The 40 projection patterns were registered and stacked for intrinsic validation, followed by a coordinate transformation using the crosshair laser as the reference. In the new coordinate system, a linear fitting was conducted on the indicating laser's scatter spots. The angle deviation between the two laser beams was calculated from the regression coefficients, representing the parallelism quality of the laser system. For extrinsic validation, the angle deviation and shortest distance between the verifier laser and the crosshair laser (defined as the length of the common perpendicular segment of skew lines) were calculated to evaluate their coincidence.

Finally, as an LPA usability test, the surgeon (Z.Q.) inserted a needle into a head model simulating a puncture procedure. Assuming the planned path has been prepared, the surgeon deployed the LPA, initially verifying the alignment of the planned path with the primary laser path (see Figure 5A). Next, with the primary laser deactivated and only the indicating laser activated (see Figure 5B), the surgeon inserted the needle along the planned path, ensuring the indicating laser passed through the hole in the adaptor until reaching the target. The operator's subjective experience and comments were recorded for qualitative assessment.

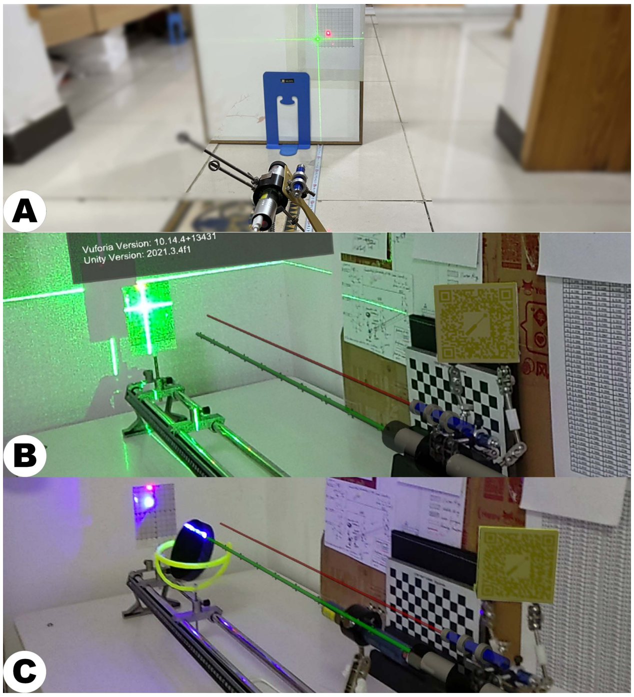

Fig. 4: Experimental procedure of LPA's intrinsic (**A**) and extrinsic properties (**B** and **C**).

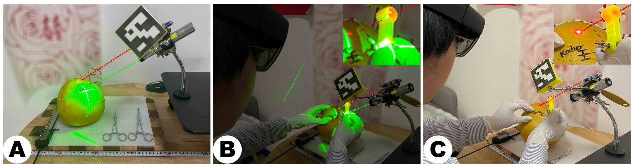

Fig. 5: The LPA-assisted puncture process involves the following steps. First, the operator anchored the virtual path (**A** and **B**). Then, the crosshair laser was turned off, and the puncture was performed from a lateral perspective with axial locking (**C**).

3 Results

The angle deviation between the indicating and crosshair laser was 0.08° (see Figure 6A—6C). The angle deviation between the verifier laser and the crosshair laser was 1.44° ± 0.47°, with the shortest distance of 7.60 mm ± 2.50 mm (see Figure 6D and Table 1). In the usability test, the surgeon could consistently observe the needle insertion from a lateral perspective and monitor the relationship between the indicating laser and the adapter without adjusting the viewpoint. The surgeon reported the puncture process as easy and confident and did not experience any distractions.

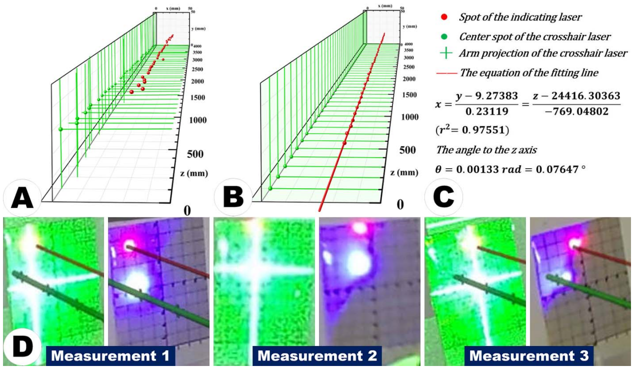

Fig. 6: Intrinsic and extrinsic validation results. Projection measurements of the original stack (**A**) and the stack after the coordinate transformation (**B**), showing promising parallelism (**C**). (**D**) shows extrinsic measurements at 900 mm for the indicator (red), crosshair (green), and verifier laser projections (purple).

Tab. 1: Validation results for LPA's extrinsic property

Measurement session	#1	#2	#3	Mean ± SD
Angular deviation [°]	1.01	1.38	1.95	1.44 ± 0.47
Shortest distance [mm]	5.31	7.24	10.27	7.60 ± 2.50

4 Discussion

This study introduces the concept, design, properties, and validation of the LPA, a new ARN tool that addresses common depth perception challenges, particularly for linear objects. The LPA ensures accurate axial punctures from any perspective by anchoring the planned path to the physical laser. The promising validation and usability results established a foundation for future improvements and clinical applications.

It is well known that ARN systems can easily overlay any pre-planned trajectory onto a surgeon's field of view. However, accurate perception of the intra-operative needle position remains critical and challenging. For accurate puncture, surgeons need to continuously observe the actual position of the needle and compare it with the pre-planned trajectory, correcting any potential deviations. Grunert et al.[1] mounted AR markers on the puncture instrument to achieve real-time visualization. This instrument helps to confirm the final position of the cannula tip in real time, providing the maximum possible feedback. However, they acknowledged that the system's performance limitations could lead to unstable or interrupted tracking of the AR markers, significantly impacting the procedure. Connecting and calibrating the needle with the sterile AR markers is an additional operational step. In this study, the LPA provides a stable physical reference, making the surgeon's perception of puncture alignment independent of real-time AR visualization. Even if AR marker tracking fails, the surgeon can still complete the puncture procedure guided by the indicating laser. Another advantage is that the LPA can be deployed outside the sterile field and does not require calibration during the surgery, offering greater convenience.

From an ergonomic perspective, one of the LPA's significant advantages is the reduction in the frequent viewpoint changes needed to enhance depth perception. A concern is whether the indicating laser spot might be invisible from a lateral perspective, i.e., viewing orthogonally to the laser beams. Although this situation did not occur in the study, the next logical system upgrade would be redesigning the needle adapter to provide physical cues indicating the needle's alignment with the anchored trajectory, visible from a lateral viewpoint.

Nonetheless, the LPA has some limitations. Firstly, as reported by Grunert et al., using a planar target image as the AR marker, while simple, still depends on the user's perspective, affecting extrinsic property stability[1]. Secondly, the LPA has to be deployed at least 30 cm away from the surgical area to maintain sterility, amplifying the impact of angular deviations: A 1.0° angular deviation may theoretically cause a 5.2 mm radial error. This limitation of the parallel dual-laser system could be mitigated by integrating a vertical dual-laser system , as demonstrated in the laser crosshair simulator (LCS) . Finally, as one of the study-specific limitations, there is currently no data on the accuracy and clinical feasibility of LPA-assisted punctures, which future research should explore.

Despite these limitations, the LPA enhances user perception of linear objects and eliminates the need for perspective adjustments during puncture, warranting further development.

5 Conclusion

The LPA shows encouraging results in efficiency and comfort in ARN systems. Its potential to enhance user perception positions this tool as promising for improving surgical intervention.

Author Statement

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References

[1] Grunert R, Winkler D, Wach J, Kropla F, Scholz S, et al. IMAGINER: improving accuracy with a mixed reality navigation system during placement of external ventricular drains. A feasibility study. Neurosurgical Focus 2024;56(1):E8.