Abstract

The increasing integration of digital technologies into surgical workflows is reshaping the landscape of computer-assisted interventions, with a growing focus on enhancing precision, efficiency, and adaptability in complex procedures.

This evolution reflects a broader movement toward human-centered technological ecosystems in healthcare, where digital tools support clinicians in improving surgical performance, reducing errors, and facilitating more effective communication between medical teams and patients.

In this context, Augmented Reality (AR) emerges as a key enabler of Augmented Surgery, an approach in which real-time visual guidance and spatial overlays enhance the surgeon's situational awareness. Rather than automating surgical acts, AR supports intraoperative decision-making by improving the alignment between digital planning and physical execution.

Central to this transformation is the concept of tracking: the ability to localize tools and anatomical structures in space with high accuracy and consistency.

The reliability of tracking performance is a key factor for the clinical adoption of AR in the operating room, as it directly determines the surgeon's confidence in digital guidance.

Rigorous evaluation methods and robust tracking accuracy build trust in the technology, fostering its integration into routine surgical practice and enabling the broader diffusion of AR-based solutions. This research explores how AR-based tracking systems and interactive guidance processes can improve surgical precision, enable flexible device design, and promote more adaptive intraoperative behaviors. The focus gradually shifts from static, patient-specific hardware to adjustable, feedback-driven systems supported by visual computing and real-time control.

Chapter 1 introduces the overall research framework and outlines the rationale of the study.

It provides a background on the technological and clinical context, followed by the motivation that frames the relevance of augmented reality in surgical guidance.

The chapter then defines the research objectives and presents the methodological approach adopted to address them.

Furthermore, the main research questions are formulated, serving as the guiding thread for the subsequent chapters.

Chapter 2 provides the theoretical background, covering the fundamentals of augmented reality, optical tracking principles, marker typologies, and surgical cutting guides.

Chapter 3 presents a systematic analysis of AR applications in osteotomies, highlighting clinical benefits and persistent technical limitations such as calibration requirements, tracking reliability, and device ergonomics.

Chapter 4 defines and validates a methodology for dimensional and mechanical evaluation of surgical guides, quantifying deviations introduced across design and fabrication steps.

Chapter 5 proposes a metrological procedure to benchmark AR-based tooltip tracking, while Chapter 6 introduces a dedicated platform for comparative assessment of optical tracking systems, with performance analyzed in terms of accuracy, jitter, and trajectory control.

Chapter 7 introduces MOTT, a Modular Optical Tool Tracking software architecture that standardizes the implementation and benchmarking of optical tracking algorithms.

Finally, Chapter 8 presents and validates a hybrid surgical guide that combines a general-purpose anchoring system with AR-based visual feedback for intraoperative adjustment of the cutting plane.

The system is tested on 3D-printed mandibular mockups, confirming the effectiveness of real-time feedback in improving alignment accuracy.

The findings of this thesis highlight the potential of AR-driven, human-centered solutions to improve surgical accuracy, reduce intraoperative variability, and support flexible planning execution. Although the proposed methodologies are designed to be adaptable to different medical contexts, their development and validation were conducted within the specific framework of maxillofacial surgery. By bridging physical tools and virtual guidance, these approaches pave the way toward more adaptive and responsive technologies in surgical practice.