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Augmented Reality in Robotic Surgery: A Case Study on Precision and Workflow Integration From Real to Virtual Environment

Tanazzah Rehman Khan [1], Sheraz Saudagar [2], Zainab Fatima [3], M. Hassan Tanveer [4*], Shehnila Zardari [5], Razvan C. Voicu [6], Hazry Desa [7]
[1,5] Software Engineering Department, NED University of Engineering, Karachi, Pakistan
[2, 3, 4, 6] Department of Robotics and Mechatronics Engineering, Kennesaw State University, Marietta, GA, USA
[7] Centre of Excellence for Unmanned Aerial Systems, Universiti Malaysia Perlis, 01000 Kangar, Perlis, Malaysia
Email: [1] rehman4302338@cloud.neduet.edu.pk, [2] ssaudaga@students.kennesaw.edu, [3] zfatima@kennesaw.edu, [4] mtanveer@kennesaw.edu, [5] shehnilaz@cloud.neduet.edu.pk, [6] rvoicu@kennesaw.edu, [7] hazry@unimap.edu.my
*Corresponding Author

Abstract—**Augmented Reality (AR) offers the transformative capability to integrate digital data directly into the surgical field, significantly enhancing intraoperative guidance during robotic-assisted oncological procedures. Since its early adoption in the 1990s, AR in surgery has evolved with advancements in head-mounted displays, computer vision, and sensor fusion technologies. In this case study, AR was applied to robotic interventions in prostate, kidney, and head-and-neck cancers, resulting in a 30% reduction in resection errors during radical prostatectomy and a 20% decrease in operative time for transoral robotic surgeries (TORS). Integration of AI-driven haptic feedback and real-time fluorescence spectroscopy further improved tumor localization accuracy from 47.3% to 70.0%. Despite its promise, the widespread implementation of AR faces challenges such as high setup costs, steep learning curves, and limitations in depth perception and real-time image registration. Emerging technologies like 5G-enabled AR streaming and dynamic deformable models present new pathways for remote surgical mentorship and improved anatomical fidelity. This paper highlights the role of AR in improving precision, reducing complications, and redefining surgical training, emphasizing its potential to reshape clinical practice across diverse oncological applications.**

Keywords*—Augmented Reality; Robotic-Assisted Surgery; Intraoperative Guidance; Transoral Robotic Surgery; Prostatectomy; Sensor Fusion; Haptic Feedback; Real-Time Imaging; Partial Nephrectomy; AR Surgical Training.

I. Introduction

Robotic-assisted surgery has redefined precision and control in modern operating rooms, yet it remains limited by the surgeon's ability to interpret and respond to complex, often obscured anatomical data in real time. Augmented Reality (AR), a technology that overlays computer-generated content onto the real surgical field, offers a powerful solution by improving intraoperative visualization, improving surgical precision, and reducing procedural errors. This is especially relevant in oncological surgery, where accurate delineation of tumor margins and real-time anatomical guidance are critical for successful outcomes.

At the forefront of these developments, interdisciplinary research across engineering, computer science, and design has been instrumental in creating systems that overlay digital information onto real-world scenes. This integration transforms not only routine activities but also specialized professional processes, facilitating significant improvements in productivity and effectiveness. Extensive research efforts have enabled seamless fusion between the digital and natural realms, with innovations in sensor technology, mobile computing, adaptive interfaces, and advanced image processing laying the foundation for sophisticated and highly interactive augmented experiences.

A. Augmented Reality

Augmented Reality (AR) is a technology capable of enhancing real-world environments by integrating computer-generated information with natural settings [1]. By seamlessly merging visual, auditory, and sensory digital elements with physical reality, AR provides an enriched sensory experience beyond traditional interactions. Instead of substituting the real environment, AR augments it with informative digital overlays, offering additional context and deeper insights. Fig. 1 illustrates the reality-virtuality continuum, showcasing the progressive spectrum ranging from purely physical reality through various degrees of digital augmentation, leading ultimately to fully virtual environments.

The concept of augmented reality took shape with the pioneering introduction of a head-mounted display (HMD) in 1992, designed initially for aircraft manufacturing [3]. This groundbreaking application catalyzed further advancements, fueling diverse innovations and the development of practical, specialized hardware such as Google Glass, Microsoft

HoloLens, Epson Moverio BT-300, and Magic Leap. Progress in mobile computing technology, sensor integration, and AR-specific hardware, along with improvements in computer vision and image processing, have significantly expanded AR's scope and functionality [4].

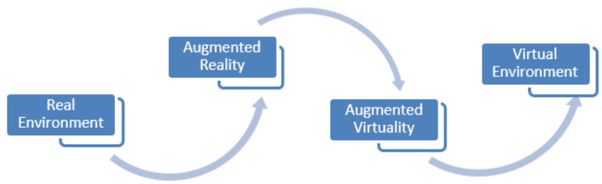

Fig. 1. Reality-Virtuality Continuum

Current research continues refining AR technology, focusing on improving tracking accuracy, stability of digital overlays, and the natural integration of virtual elements within physical environments. Enhanced computational capacities and innovative display technologies further enable more realistic and interactive AR experiences. These advancements are driving AR adoption in sectors like entertainment, advertising, education, navigation, and maintenance, redefining user engagement and offering intuitive, real-time access to critical information with gesture recognition and touchless UI.

B. Application of AR in Healthcare

A comprehensive review of AR-focused literature using the Scopus database from 2010 onward highlights healthcare as a primary sector benefiting from augmented reality [6]. Healthcare-related studies represent 41 percent of identified publications, indicating substantial and growing interest in this domain. Fig. 2 illustrates the increasing trajectory of research activity specifically targeting medical and healthcare AR applications.

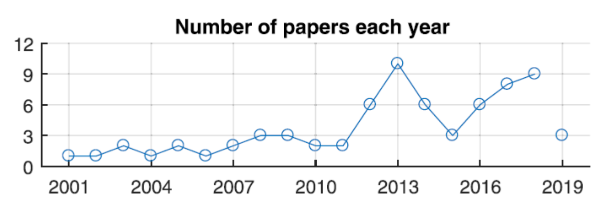

Fig. 2. Number of AR-related papers in Healthcare [6]

Innovative applications integrating computer vision, image segmentation, cloud computing, and robust wireless communications have significantly advanced healthcare capabilities. These technologies facilitate early diagnostics, real-time patient monitoring, and remote patient care. The utilization of AR in surgical planning, patient education, and remote consultations has further optimized medical procedures, providing healthcare professionals with real-time data and intuitive, interactive interfaces for improved clinical outcomes [7].

Despite the increasing adoption of robotic platforms such as the da Vinci Surgical System, challenges such as depth perception limitations, high equipment costs, complex learning curves, and image registration inaccuracies persist. These barriers prevent many institutions from realizing the full benefits of AR integration in surgical oncology. For instance, tissue deformation during manipulation can render static preoperative models unreliable, and traditional imaging systems often lack the spatial resolution or temporal synchronicity required for real-time decision-making.

Recent clinical studies have begun to quantify the benefits of AR-enhanced surgical procedures. In partial nephrectomy, AR reduced clamp time by 20% and improved tumor localization accuracy from 47.3% to 70.0% [7]. Furthermore, skill training platforms using AR have accelerated surgeon learning curves while enhancing spatial orientation and procedural confidence. These findings emphasize AR's potential not just for intraoperative guidance, but also for preoperative planning, supervised robotic motion, bedside assistance, and proctor-led skill transfer.

Yet, gaps remain in understanding how AR can be robustly integrated into surgical workflows, particularly across diverse cancer types and robotic modalities. A lack of standardized protocols, limited large-scale clinical trials, and inconsistent hardware/software interoperability still hinder AR's widespread adoption in high-stakes surgical environments.

The research contribution of this paper is a structured review and synthesis of recent advances in augmented reality for robotic-assisted oncology. We evaluate empirical case studies, technical innovations, and application frameworks focused on enhancing tumor resection precision, surgeon training, and real-time surgical decision-making. This paper also identifies current barriers to clinical deployment and outlines future directions for AR-based surgical systems, including 5G-enabled remote mentorship, real-time deformable modeling, and integrated AI-driven guidance. Section 2 details the foundational technologies critical for AR implementation, emphasizing sensor integration, image processing techniques, and user interface design. Section 3 provides a comprehensive review of practical implementations and case studies across diverse sectors, including healthcare, manufacturing, and education. Section 4 explores existing challenges and limitations in augmented reality deployments, while Section 5 discusses future trends and potential advancements. Finally, Section 6 concludes the paper with recommendations for future research directions.

II. Literature Review

A comprehensive review of augmented reality (AR) applications in surgical environments reveals extensive research addressing measurement accuracy, system performance constraints, and the integration of innovative technologies [1], [2]. The literature encompasses review articles, feasibility studies, and comparative analyses of both simulated and real intraoperative scenarios, collectively providing insights into existing challenges and future potential [3], [4]. This extensive body of work highlights the technological advancements required for accurately integrating digital overlays with actual anatomical structures, emphasizing the significant potential of AR to enhance visualization, advance surgical training methods, and improve precision in surgical interventions [5].

Initial research primarily addressed foundational limitations encountered when applying AR in surgical procedures [6]. For example, an influential review titled "Intraoperative Clinical Application of Augmented Reality in Neurosurgery" by William Omar (2019) pinpointed critical gaps, such as the absence of reliable tools for measuring three-dimensional overlay errors and the limitations of existing camera technologies in generating realistic 3D models [7], [8]. The comprehensive analysis proposed novel techniques for evaluating the various stages and inherent drawbacks of intraoperative AR systems, emphasizing the necessity of developing advanced sensor technologies, robust computational frameworks, and standardized accuracy metrics to enable precise and dependable AR overlays during surgery [9], [10].

Further studies expanded upon these initial observations by exploring the computational requirements and procedural disruptions associated with AR technology [11], [12]. A review titled "Recent Development of Augmented Reality in Surgery" detailed the need for complex, computationally intensive algorithms and highlighted the risk of inattention blindness—an issue where crucial unexpected visual elements may be unintentionally overlooked—as well as prolonged preparation times necessary for AR system deployment [13]–[15]. Researchers examined the application of technologies such as head-mounted displays (HMDs), gesture recognition interfaces, and fluoroscopic dual-laser-based systems designed to enhance image reconstruction and overlay precision [16], [17]. These insights illustrate surgeons' growing interest in leveraging AR to bolster procedural safety and effectiveness, while simultaneously identifying a clear need for continued improvements in computational efficiency and streamlined integration into surgical workflows [18], [19]. Additionally, the review indicates that advancements in computational speed and algorithm optimization could significantly reduce cognitive load and operational interruptions, contributing to smoother surgical procedures overall [20].

Parallel advancements in medical technology have further accelerated innovation in surgical simulations and trainee education through the integration of 3D printing, augmented reality (AR), and virtual reality (VR) technologies [21], [22]. Preoperative simulation models have become instrumental in training surgeons across various experience levels, with specific metrics such as renal clamp times serving as indicators of skill improvement [23]. Comparative analyses between patient-specific tumor volumes and resection timeframes using conventional methods versus those employing 3D-printed silicone models have shown that simulations significantly reduce operative times (6:58 versus 8:22 minutes, P = .162) [24], [25]. Additionally, the utilization of patient-specific 3D-printed anatomical models has markedly enhanced trainee nephrometry scores, increasing tumor localization accuracy from 47.3% to 70.0% [26]–[28]. These findings collectively underscore the potential of integrating 3D printing, AR, and VR to enhance surgical outcomes by improving procedural accuracy and refining the training of surgeons [29], [30]. Such approaches effectively bridge the gap between theoretical knowledge and practical application, reducing the learning curve and mitigating operative risks associated with complex surgical interventions [31]–[33].

Clinical feasibility studies have played a pivotal role in assessing the practical integration of AR technologies into the operating room environment. For instance, the study titled "Augmented Reality in the Operating Room: A Clinical Feasibility Study" offered critical insights into AR's practical applications, despite limitations regarding surgeon acceptance data [34]–[36]. This investigation demonstrated that AR devices possess significant potential in surgical correction procedures for deformities, with surgeons expressing high satisfaction in device functionality, image quality, and comfort during usage. Tools such as Microsoft HoloLens, combined with the systematic data documentation capabilities of REDCAP, have enabled meticulous tracking and assessment of surgical outcomes, further validating AR's role in enhancing surgical innovation [37], [38]. These findings advocate that AR can indeed be seamlessly integrated into routine clinical practices, provided ongoing research effectively addresses ergonomic considerations and interface challenges highlighted in current studies [16], [39].

Moreover, advanced visualization techniques have significantly broadened AR's applicability beyond conventional imaging modalities. Explorations into AR, VR, mixed reality (MR), and 3D printing applications in congenital heart disease have leveraged the superior spatial resolution offered by CT and MRI imaging, facilitating precise differentiation between blood and myocardial tissues, uniform signal distribution, minimal noise interference, and artifact reduction [40]–[42]. Techniques such as volumetric segmentation, cinematic rendering, and advanced depth-perception methods have made it possible to overlay virtual elements directly onto physical anatomical structures, thus embodying the fundamental essence of AR. Mixed reality further extends these capabilities by blending features of both AR and VR to deliver a hybrid visualization environment [43]. Despite acknowledged challenges—including labor-intensive modeling processes, high operational costs, and occasional inaccuracies—these sophisticated visualization methods empower surgeons and clinicians to maintain continuous focus during complex procedures, thereby fostering significant advancements in the treatment and management of congenital heart disease [44], [45].

A synthesis of numerous research studies highlights recurring themes and ongoing challenges within augmented reality (AR) applications in surgical contexts. A common concern identified in several investigations is the lack of standardized methodologies for accurately quantifying three-dimensional inaccuracies, further complicated by limited camera capabilities and the necessity for larger datasets [46]–[48]. Additional studies have emphasized computational burdens associated with preoperative image reconstruction and prolonged setup times for AR systems, alongside the risk of inattention blindness, a phenomenon where critical but unexpected objects or details may be overlooked during surgery [49], [50]. These issues collectively underscore surgeons' growing acknowledgment of AR's significant potential to enhance procedural safety and effectiveness while highlighting the need for continued research aimed at optimizing cost-efficiency, integration simplicity, and user-friendliness [51], [52].

Moreover, the integration of 3D-printed and AR/VR-generated anatomical models in managing prostate and kidney cancers has consistently demonstrated substantial improvements in tumor localization accuracy, significantly influencing surgical decision-making processes [53], [54]. These digital tools have proven effective in reducing intraoperative ultrasound usage time and enhancing patient understanding of their anatomy and surgical procedures [55]–[57]. Despite these advances, existing evaluations primarily emphasize therapeutic efficacy and the value of simulation-based training, leaving the assessment of long-term patient outcomes and exploration of bioprinting capabilities as promising avenues for future research [58]–[60]. As this area continues to mature, it is anticipated that incorporating such digital technologies will further refine surgical precision, optimize procedural techniques, and enhance patient care [61], [62].

Additional insights into surgeons' acceptance of AR technologies are provided by studies using devices such as the Microsoft HoloLens paired with the REDCAP data collection platform. These investigations have reported encouraging outcomes in surgical interventions, marked by excellent image clarity and precise virtual object representation [63], [64]. Nevertheless, persistent issues such as inconsistent performance of voice-command functions indicate opportunities for substantial improvements [65], [66]. Consequently, further refinement and research into AR's navigational capabilities and overall usability within clinical environments remain essential for achieving broader clinical acceptance [67].

Innovative augmented reality (AR) applications have been specifically developed to address complex surgical challenges. For example, novel 3D AR systems have been created to preserve erectile function while ensuring comprehensive removal of malignant tissue during prostate cancer surgery [68], [69]. These systems demonstrate promising accuracy in visualizing prostate deformation and localizing lesions during the crucial nerve-sparing phase of robot-assisted radical prostatectomy. However, the relatively small sample sizes of current studies require cautious interpretation and highlight the need for additional prospective trials to validate these preliminary findings [70]. Concurrently, substantial limitations persist in AR's visual representation, particularly concerning depth perception [71]. Challenges such as high initial setup costs, prolonged processing times required for compiling virtual data, and inconsistent spatial registration continue to pose significant obstacles [72], [73]. Addressing these issues is essential to improving the mobility, versatility, and user-friendliness of AR in procedures such as transcatheter pacemaker implantation [74].

Further advancements in AR include tools specifically designed to assist surgical teams, such as the ARssist application employing optical head-mounted displays. Pilot studies indicate these systems can decrease tool manipulation time by over 70%, significantly enhancing the safety of surgical instrument insertion [75], [76]. Additionally, techniques integrating traditional ocular inspection with time-resolved fluorescence spectroscopy (TRFS) during robotic surgeries for oral malignancies have shown considerable promise for efficient and precise visualization in both clinical and animal models [77]–[80]. This highlights the importance of refined temporal discrimination in high-stakes surgical environments.

Moreover, the implementation of 3D virtual models on operating room consoles, augmented by real-time overlays of critical anatomical structures such as the internal carotid artery system, has improved surgical guidance during complex oropharyngeal resections [81], [82]. Despite persistent issues with depth perception and accurate image registration, these models represent notable advancements over conventional imaging methods [83]. Ongoing research is exploring further innovative applications, including preoperative planning through advanced 3D imaging techniques, deep learning-based algorithms for enhanced depth estimation, and reflective AR displays aimed at resolving 3D scale ambiguities [84]–[86]. Additional studies are investigating AR's potential for surgical training, rehabilitation, and molecular imaging applications [87]–[91]. Collectively, this extensive research underscores AR's transformative potential in surgical practice, highlighting significant technological advancements as well as the challenges that remain [92]–[96]. Continued interdisciplinary collaboration will be crucial for improving system accuracy, integrating adaptive technologies, and fully realizing augmented reality's benefits in surgical environments [97]–[100].

III. WORKFLOW

It is essential to understand the basic mechanism by which augmented reality (AR) applications assist in robotic surgeries. Fig. 3 presents a detailed workflow diagram of an AR-based system that facilitates interaction between surgeons and robotic systems. In this diagram, the blue portion emphasizes the hardware side, where a computer workstation serves as the central control and computation hub. This workstation is responsible for robot control, generating AR interfaces, and managing augmented interactions between the surgical team and the robot. In the studies presented, AR interfaces were delivered via Microsoft HoloLens and Meta 2 optical head-mounted displays (HMDs), as well as tablet-based interfaces in some procedures such as transoral robotic surgery. The robotic platform employed throughout these workflows was primarily the da Vinci Surgical System (SP and X models), which integrates stereo laparoscopy for 3D visualization.

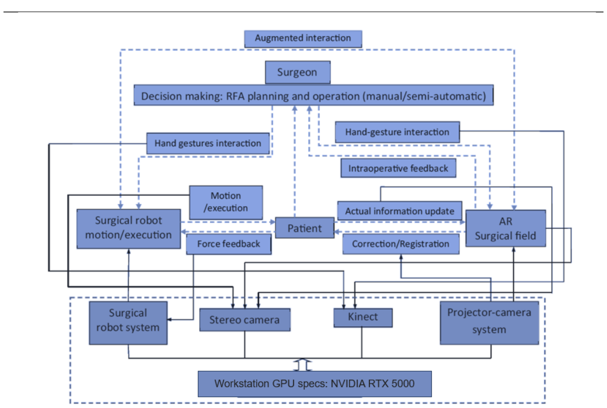

Fig. 3. Work flow of the AR based surgeon–robot cooperation

Above this hardware layer, the subject layer comprises all the human and operative elements involved in the procedure. These include the surgeon, the surgical robot (with its mobility and execution capabilities), the patient, and the AR-enhanced surgical field. In the context of robot-assisted RFA treatment, the workflow supports two surgical modes: manual and semi-automatic. In the manual mode, surgeons determine needle insertion points using image guidance alone. In contrast, the semi-automatic mode leverages a dedicated ablation model—tailored specifically for the surgical robot—to automatically generate ablation sites. This mode allows surgeons to interact with the pre-planned data via intuitive hand movements, making real-time amendments to the surgical plan displayed directly on the patient's body.

Surgeons interact with the augmented data using intuitive hand gestures interpreted via gesture recognition algorithms or through touchless user interfaces on the AR HMDs. This gesture-based control allows for dynamic plan adjustments and eliminates the need for physical contact with the system interface, maintaining sterile field integrity.

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Validation of system performance was conducted using metrics such as Root Mean Squared Error (RMSE) for overlay registration accuracy. For instance, in robotic thyroid surgery, the RMSE between the predicted and actual positions of the recurrent laryngeal nerve (RLN) was consistently maintained under 1 mm. The formula used,

$$RMSE = \sqrt{(\sigma(actual - predicted)^2/n)} \tag{1}$$

quantifies the fidelity of AR overlay alignment. However, dynamic error propagation due to motion artifacts or occlusion during surgery remains an area for future investigation.

IV. APPLICATION PARADIGM

Various robotic-assisted surgical phases and procedure types have found significant benefits from the integration of augmented reality (AR) technologies, as illustrated in Fig. 4. The applications of AR have been categorized based on different medical uses—from preoperative planning and intraoperative guidance to postoperative assessment—thereby creating a versatile framework for digital augmentation in the operating room [17].

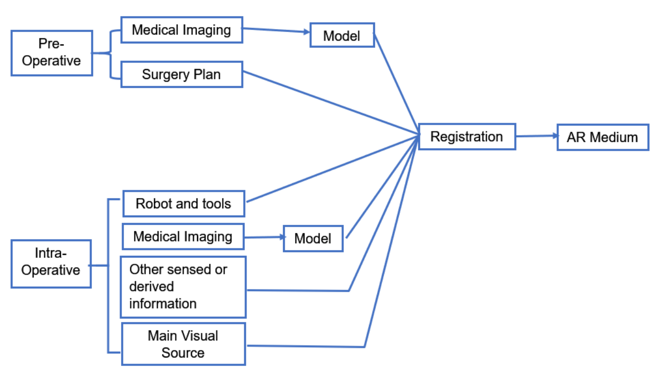

Fig. 4. Applications of AR in medical surgery

Augmented reality enhances the surgical workflow by seamlessly merging digital information with the real-world view. One of the primary applications of AR in this paradigm is surgical guidance. With AR, it becomes possible to:

1) Reveal hidden or difficult-to-distinguish key anatomical structures or pathologies, thereby improving the surgeon's ability to identify critical regions that may be obscured or subtle.
2) Provide a real-time display of preoperative or intraoperative data from the patient and robotic system, ensuring that the surgical team has immediate access to crucial diagnostic information during the procedure.
3) Combine information from multiple sources, such as computed tomography (CT), magnetic resonance imaging (MRI), live camera feeds, and sensor data, into a cohesive and intuitive visual interface.

These capabilities make AR an invaluable tool for intraoperative guidance. The primary visual input in robot-assisted surgery is typically provided by stereo laparoscopy (as in da Vinci operations), though other real-time imaging sources can also be utilized depending on the surgical procedure. Overlays of critical information are superimposed on this primary feed, offering the surgeon continuous feedback during the operation. However, the reliability of these overlays is sensitive to factors such as poor lighting, reflective tissue surfaces, or occlusion by surgical instruments. Vision-based tracking and Simultaneous Localization and Mapping (SLAM) techniques are employed for real-time registration, but their susceptibility to environmental variability particularly in dynamic surgical fields poses an ongoing challenge.

Graphical overlays may include:

1) The surgical plan, which outlines the intended steps and target areas.
2) Preoperative imaging, delivering detailed anatomical maps derived from diagnostic studies.
3) Intraoperative imaging, updating the surgeon with real-time modifications in tissue structure.
4) The operational state of the robot and instruments, including positioning and status data.
5) Additional sensed or computed data, which may include physiological parameters or algorithm-derived insights that further inform decision-making.

Advanced algorithms can further compute supplementary guidance data, adapting dynamically to changes in the surgical site.While these augmented displays improve surgical confidence and reduce error, standardized validation procedures—such as latency measurement (¡200 ms display delay) and frame synchronization checks—are crucial for ensuring system robustness. Currently, such metrics are inconsistently reported across studies. To ensure that these augmentations are accurately aligned with the surgeon's visual field, a robust registration procedure is necessary. Once completed, the AR interface is displayed via an appropriate medium—often integrated into the surgeon's console—providing a continuous and interactive layer of guidance. One of the simplest implementations involves presenting the preoperative model alongside the stereo laparoscopy feed so that critical structures, such as a tumor, are clearly identified and perceptually linked to the live surgical view.

Future iterations should incorporate adaptive algorithms that compensate for intraoperative tissue deformation and use low-latency hardware configurations to minimize perceptual lag. Additionally, cost-benefit analyses are required to evaluate scalability in low-resource environments, where reliance on premium devices like HoloLens may be impractical.

An illustrative example of this paradigm is seen in Transoral Robotic Surgery (TORS) for oral tumors. In TORS, the ocular examination of lesions can be significantly enhanced without the use of contrast agents by integrating time resolution fluorescence spectroscopy (TRFS). TRFS exploits the unique autofluorescence signatures of malignant tissue—which reflect alterations in tissue structure and metabolic profile—to differentiate cancerous from healthy tissues in real time. In a recent study, the point-scanning method known as ms-TRFS was combined with the da Vinci Surgical System. In vivo measurements were carried out on both human and animal subjects undergoing TORS, demonstrating the capability to evaluate tissue biochemical properties and delineate tumor boundaries with high precision.

Overall, the application paradigm of AR in robotic-assisted surgery creates a powerful synergy between digital augmentation and real-time clinical decision-making. By fusing preoperative planning with intraoperative data and advanced visualization techniques, AR systems enhance surgical accuracy, reduce cognitive load, and ultimately contribute to improved patient outcomes [17].

Animal Models:

In an effort to validate the performance of the Da-Vinci Surgical System's integrated Time Resolution Fluorescence Spectroscopy (TRFS) system under realistic conditions, in vivo tests were conducted on three swines (N=3). These experiments were designed with several specific objectives in mind. First, the tests aimed to investigate the TRFS system's ability to operate effectively in an environment that closely mimics human clinical conditions, ensuring that its performance would translate well to human applications. Second, the experiments focused on optimizing the system's data acquisition protocols and measurement settings—such as integration times, exposure levels, and sensitivity adjustments—to achieve reliable and reproducible results. Third, the study sought to assess the TRFS system's capacity to acquire accurate fluorescence data from a variety of tissue types located within the oral cavity, where different tissues may exhibit distinct optical properties. Fourth, the tests evaluated potential confounding conditions, such as the presence of surgical debris, blood, and cautery-derived artifacts, which could adversely affect the quality and accuracy of the fluorescence measurements.

Additionally, the feasibility of employing the TRFS device in laparoscopic interventions was explored, broadening its potential clinical applications beyond the confines of the oral cavity. With the exception of the laparoscopic measurements, all tests were conducted inside the animal models' mouths. Access to the desired regions was facilitated by two minor incisions, which allowed the EndoWrist Introducer and the endoscope to reach the target area. During the procedure, the surgeon, operating via the da Vinci Surgical System, identified specific regions that required inspection and performed the scanning measurements accordingly. Notably, the scanning process did not follow a rigid, predefined pattern; instead, the surgeon was able to freely navigate and scan the area of interest, provided that motion did not obstruct the endoscopic view. This flexible scanning approach, as evidenced by the results and accompanying videos, highlights the system's adaptability and potential for real-time intraoperative application.

Human Models:

In a clinical pilot study, four human patients (N=4) were enrolled to evaluate the ability of the Resolution Fluorescence Spectroscopy system to work in concert with the Da-Vinci Surgical System during routine Transoral Robotic Surgery (TORS) operations. The primary objective of this investigation was to determine whether the Resolution Fluorescence Spectroscopy system can provide continuous, real-time feedback on tissue characteristics to supplement standard endoscopic white-light imaging. Two surgeons participated in the study; notably, while one surgeon had prior experience with the Resolution Fluorescence Spectroscopy system from earlier animal studies, the second surgeon had no previous exposure to the technology, thereby providing an independent assessment of its ease of use and integration into surgical workflow.

Under general anesthesia, each patient's oral cavity was prepared for robotic surgery through the insertion of an endoscope and EndoWrist equipment via minimally invasive incisions. Based on detailed preoperative planning, the surgical team delineated the target region for the procedure. During the operation, live measurements were acquired by scanning the defined area with the TRFS system. The EndoWrist equipment, designed for precise manipulation, proved to be intuitive and enabled the surgeon to direct the scanning pattern in real time. The system's rapid data acquisition allowed the average scanning time per patient to remain below five minutes, ensuring that the procedure did not introduce significant delays.

The study demonstrated that unmarked, real-time evaluation and visualization of tissue characteristics during TORS has the potential to enhance intraoperative decision-making without requiring any changes to standard clinical protocols. By continuously providing biochemical and structural feedback, the system could aid surgeons in distinguishing between healthy and pathological tissue, thereby improving surgical precision and potentially reducing complications.

Protocol of AR Image Construction and Study:

In the pilot study for AR image construction, open source software *Seg3D* was employed to generate three-dimensional images of key anatomical structures, including the carotid artery and trachea, from preoperative CT scans. These images were further refined using smoothing techniques provided by *MeshMixer* to ensure that the models accurately represented the patient's anatomy. During surgery, the processed AR images were superimposed onto the corresponding real organs, enabling a direct visual correlation between the digital model and the physical structures. This protocol ensured that the AR overlays were not only accurate but also visually coherent and easily interpretable by the surgical team.

Application of AR Using Vision-Based Tracking:

For procedures such as robotic thyroid surgery, AR images of the recurrent laryngeal nerve (RLN) were strategically placed laterally to the trachea based on distances calculated from a preliminary pilot study. During the procedure, after the exposure of the carotid artery and trachea, the AR images generated for these structures were superimposed onto the corresponding real anatomical structures. The system employed a vision-based tracking mechanism, ensuring that the AR overlays moved synchronously with the camera feed. Additionally, the simultaneous localization and mapping (SLAM) technique was applied to generate a real-time 3D map of the surgical site. This allowed for the dynamic registration of AR images onto the live view, thereby maintaining accurate alignment despite any movements during surgery.

Measuring Distance:

Once the definitive location of the RLN was identified, the system calculated the difference between the actual RLN position and its corresponding AR-generated image using the Root Mean Squared Error (RMSE) method. This quantitative measure provided an objective assessment of the system's accuracy in overlaying digital images onto real anatomical structures. The ability of the system to track objects or regions in real time using only visual data from a camera further underscores its potential for integration into various surgical procedures without the need for prior calibration for every new subject.

Together, these expanded protocols and testing procedures illustrate the comprehensive approach taken to validate and refine AR and fluorescence spectroscopy integration with robotic surgery systems, ensuring that both the imaging and tracking components work harmoniously to enhance surgical precision and patient outcomes.

A. Interactive Surgery Planning

Researchers have suggested that augmented reality (AR) interfaces can significantly assist surgeons in planning a wide range of robotic-assisted procedures, including robotic prostate biopsy, stereoelectroencephalography (SEEG) implantation, vocal fold microsurgery, and tumor ablation operations. Spatial AR has predominantly been used for surgical planning because it enables the visualization of digital information directly superimposed on the patient's anatomy, while also providing an intuitive, hand movement-based interactivity for modifying the surgical plan. This method offers two main advantages: first, the direct overlay of preoperative imaging and surgical plans onto the patient allows for a more accurate spatial understanding of the target structures; second, using hand gestures for interaction minimizes the need for tactile interfaces, thereby preserving sterility in the operating room.

In several studies, projector-based AR software has been employed in conjunction with robotic needle steering systems. Here, the patient's body is used as a canvas for displaying the preoperative plan and ablation model, allowing surgeons to engage with and modify the plan using either hand gestures or a computer workstation interface. Building on earlier work, some researchers have advanced this concept by implementing a video see-through AR system using a tablet instead of a projector. In this improved approach, the tablet's touchscreen enables direct interaction with the surgical plan, which has also been successfully tested in vocal fold microsurgery. Such systems allow the surgical team to produce, review, and engage with the plan in real time, thereby facilitating teleneurosurgery through an interactive AR interface.

Furthermore, before the surgical procedure is transferred to a different position for execution by a NeuroMaster robot, the surgeon can simulate and confirm the entire plan using the AR interface. This strategy has been examined in various clinical scenarios. For example, in conventional robot-assisted SEEG, where the surgeon traditionally relies solely on a technical display for guidance, researchers have proposed overlaying real-time images of the SEEG implantation directly onto the patient's skull using a projector-camera system. This overlay not only enhances the surgeon's confidence in the correct placement of implants but also provides quantitative accuracy, with the projected error estimated to be 0.82 ± 0.23 mm. Such innovative interactive planning paradigms demonstrate the potential of AR to improve both the precision and safety of complex surgical procedures [17].

B. Port Placement

Before robotic-assisted laparoscopic surgery, precise port placement is essential, as these ports serve as the entry points through which robotic tools and the laparoscope are inserted. Optimal port positioning is critical to avoid instrument collisions, maximize access to target anatomical structures, and ensure superior visualization during the procedure. Spatial augmented reality (AR) technologies have been increasingly employed to enhance port placement techniques. By superimposing virtual instruments and anatomical landmarks onto the patient's real-time anatomical model, AR provides surgeons with a detailed, interactive guide for selecting the most effective port locations.

The AR interface can project a virtual overlay that highlights potential risks, such as injury to the skin, ribs, or critical target anatomy, allowing the surgical team to identify and avoid probable accidents. In some implementations, a heat map representing a ”goodness value” for each potential port location is generated and projected onto the patient's body. This heat map quantitatively assesses factors such as reachability, risk of collisions, accuracy, and ergonomic suitability. By visualizing these parameters, surgeons can dynamically adjust port positions to ensure that instrument trajectories are optimized for maximum safety and efficiency.

Ultimately, the use of AR in port placement not only streamlines the preoperative planning process but also contributes to improved surgical outcomes by reducing the likelihood of intraoperative errors. This approach integrates advanced imaging and computational analysis to offer a real-time, interactive solution that enhances the precision of robotic-assisted laparoscopic procedures [17].

C. Advance Visualization of Anatomy

Augmented Reality is not merely about presenting sophisticated data—it is about transforming complex anatomical information into an intuitive, interactive experience for the surgical team. In some applications, researchers have demonstrated the AR interface purely for the purpose of advanced anatomical visualization, independent of direct clinical tasks such as surgical planning or intraoperative guidance. This approach emphasizes the importance of understanding spatial relationships in three dimensions and fosters improved decision-making during critical phases of surgery.

For example, to visualize three-dimensional models of the prostate, tumor, and bladder in alignment with the model created from stereo laparoscopy images during radical prostatectomy, researchers have suggested using immersive devices such as Oculus or HTC Vive. The overlay visualization provided by these systems enhances the surgeon's spatial awareness, allowing for more precise delineation of structures at crucial decision points. In another application, experiments conducted with Microsoft HoloLens have provided surgeons, support staff, and trainees with a “virtual monitor” during Transanal Total Mesorectal Excision (taTME), a robot-assisted procedure. In this configuration, each member of the surgical team can independently position their virtual monitor to a location that is most convenient for their specific task, bypassing the limitations of conventional external monitors that must be shared and carefully arranged to accommodate multiple users.

Reflective AR displays represent a further advancement by enabling simultaneous observation from multiple viewpoints, thereby reducing depth illusions and enhancing three-dimensional perception during an AR encounter. As illustrated in Fig. 5, these displays are generated by projecting 3D virtual objects over images captured by an Optical See-Through (OST) Head-Mounted Display's (HMD) camera sensor. The resulting image mimics the effect of viewing a mirror, in which the combined real and virtual elements appear to be integrated seamlessly. The imaging geometry is carefully designed to project the virtual structures into the image plane, creating a mirrored display that allows for enhanced depth perception [14].

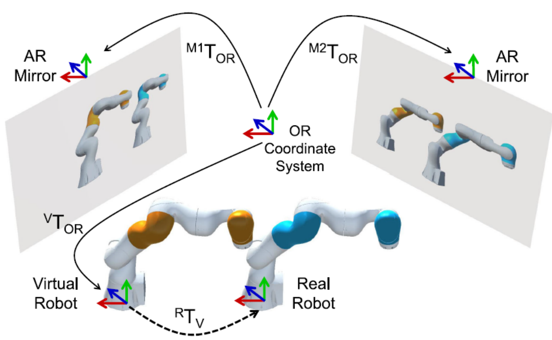

Fig. 5. Reflective AR enables simultaneous viewing of multiple screens [14]

Additional insights are provided by error distribution analyses, as shown in Fig. 6 and Table I. These experimental findings indicate that the use of reflective-AR displays significantly improves the alignment between the virtual and real anatomical structures. The quantitative error measurements, presented in Table I and graphically in Fig. 6, suggest that such displays can minimize registration errors and enhance the overall precision of the AR system [14].

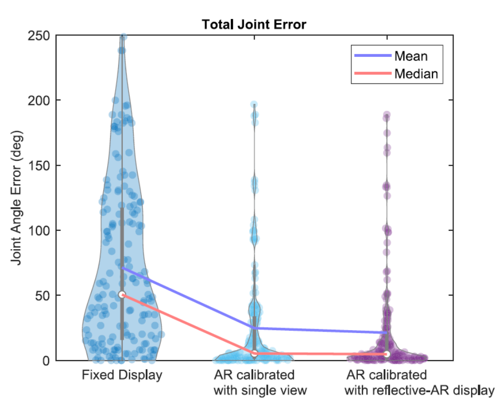

Fig. 6. Error distribution for all joint AR-display [14]

Another critical component of advanced anatomical visualization is the integration of real-time tracking and transformation mapping within systems such as ARssist. The system must track both robotic and handheld instruments with high fidelity to ensure that the AR overlays are displayed at the viewer's optimal position and orientation [15]. Once docked during robotic surgery, the robot remains stationary, and its precise control over the surgical equipment is maintained throughout the procedure. To facilitate optical tracking on the HMD, fiducial markers are attached to specific robot components and handheld devices. Because the HMD may not always have a direct view of these markers during surgery, they are integrated into the robot's kinematics chain. Modern HMDs, such as the Meta 2 and Microsoft HoloLens, further improve this process by providing inside-out localization, thereby enhancing overall tracking accuracy. The ARssist system employs a two-phase approach to ensure that transformations are accurate and dependable. During an offline phase, the system assesses the priority of each transformation using historical data, and then composes modifications with varying priorities to establish a robust tracking hierarchy. In the online phase, the system continuously employs the highest-priority tracking method available and seamlessly shifts to lower-priority techniques if a loss of line-of-sight occurs. This dynamic approach ensures that the AR overlays remain stable and accurately registered to the patient's anatomy even when tracking conditions fluctuate.

TABLE I. READINGS OF ERROR DISTRIBUTION FOR ALL JOINT AR-DISPLAY [14]

Joint Error	Mean	Median	Min	Max	Max
Reflective AR Display	23.7	4.93	0.02	188	41.1
AR	26.8	5.88	0.00	197	42.2
Fixed Display	71.4	50.6	0.64	249	61.8

Moreover, the endoscopic view can be rendered via ARssist on a "virtual stereo monitor" that offers greater adaptability than conventional monitors; its scale and position can be adjusted dynamically according to the surgeon's preference. The endoscope's pose is determined in real time using the mechanics of the endoscopic arm, and the complete data flow—depicting the interactions among various system components—is illustrated in the data flow diagram in Fig. 7.

The practical implications of these advanced visualization techniques are significant. The use of ARssist has the potential to enable first assistants to complete their tasks more quickly, thereby enhancing the overall success of robotically assisted laparoscopic procedures. By integrating sophisticated tracking, real-time feedback, and intuitive visualization platforms, these systems promise to improve surgical precision, reduce cognitive load, and ultimately contribute to better patient outcomes [15].

D. Supervised Robot Motion

In autonomous surgical procedures, particularly when using patient-side manipulator robots, it is critical for the surgeon to closely monitor the robot's motion and "intention" (i.e., its predicted action). Augmented reality provides a real-time display of the robot's trajectory, enabling the surgeon to verify that the motion aligns with the preoperative plan and to intervene promptly in the event of any deviation.

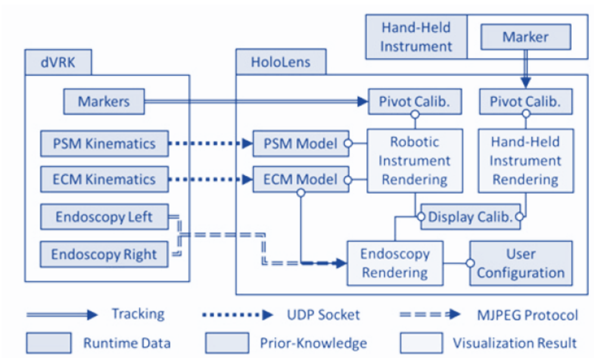

Fig. 7. Data Flow Diagram of ARssist

The AR interface—implemented via projector-based or tablet-based systems—superimposes the intraoperative vision of the needle's path, the preoperative model, and the ablation plan directly onto the live surgical field. In phantom testing, the system demonstrated an accuracy ranging between 1.74 mm and 2.96 mm, ensuring that even small deviations are detected. Additionally, the interface allows the surgeon to directly influence the robot's motion through intuitive hand gestures, thereby merging autonomous robotic function with active human oversight to enhance safety and precision.

E. Sensory Substitution

Direct haptic feedback during robotic manipulation remains technically challenging; therefore, an alternative approach involves replacing tactile feedback with visual cues derived from force measurements. In this method, sensors detect the force applied by the surgical instruments, and the data is translated into a visual signal integrated within the AR interface. The force is categorized into three distinct zones—low, ideal, and excessive—and each category is represented by a colored sphere. This sphere is displayed in proximity to the tool tip, so that the surgeon receives immediate visual feedback on the pressure being applied. In a multi-user study involving one surgeon and eight non-surgeons, this AR-based sensory substitution approach resulted in a significant decrease in the number of loose knots and damaged sutures. For robotically assisted surgery, an autonomous system for estimating tissue stiffness was also developed. The predicted stiffness value is conveyed using an RGB color channel overlay, and subsequent iterations of this technology produced a three-dimensional stiffness map that is superimposed directly onto the reconstructed anatomical mesh. This enhancement not only offers a more precise assessment of tissue consistency but also provides the surgeon with a richer, real-time understanding of force interactions during surgery.

F. Bedside Assistance

In robotic-assisted surgery, effective bedside assistance is essential to support the overall procedure. Augmented reality can significantly enhance the performance of the bedside assistant by providing a comprehensive view of the surgical environment. Using optical see-through head-mounted displays, systems like ARssist allow the assistant to virtually observe both robotic and handheld instruments, as well as the laparoscopic field of view and video feeds from inside the patient's body. This integrated perspective helps the assistant quickly comprehend the spatial arrangement of tools, even when certain instruments are not clearly visible on conventional monitors. By facilitating tasks such as instrument exchange and setup through a more intuitive, hands-free interface, AR-based bedside assistance has been shown to improve hand-eye coordination and spatial awareness. Inexperienced users, in particular, have reported a marked improvement in task performance when using ARssist, indicating that such systems can make the overall process more efficient and reduce errors in instrument handling.

G. Skill Training

Augmented reality methodologies have been widely adopted in proctor-trainee training scenarios for robot-assisted surgery, providing a dynamic and immersive mentoring environment. In these setups, both the proctor and the trainee view virtual tools and annotations overlaid onto a live surgical feed, which allows the examiner to control and manipulate the displayed augmentations in real time. This interactivity enables the proctor to demonstrate complex surgical maneuvers, guide the trainee through critical steps, and provide immediate corrective feedback. Early evaluations involving a small group of participants have shown that both proctors and learners prefer AR-based mentoring techniques over traditional training methods. Furthermore, the use of head-mounted displays for augmented vision—rather than relying on conventional 3D monitors—offers a more immersive and natural experience that enhances the transfer of surgical skills. This approach not only accelerates the learning curve but also ensures that trainees develop a more comprehensive understanding of spatial relationships and robotic instrument handling in a controlled, risk-free environment.

V. APPLICATIONS

A. Three-dimensional Elastic AR

A novel approach in surgical visualization involves the use of augmented reality to display a dynamic three-dimensional representation of the patient's prostate during the procedure. In this system, a 3D model of the prostate is rendered on a video monitor in real time, allowing the surgical team to observe anatomical details as the surgery unfolds. Developed using the Unity platform and C#, the program is capable of managing the model's position, rotation, and scale, ensuring that the digital overlay aligns accurately with the patient's anatomy.

To further enhance the precision of the overlay, the system accounts for the prostate's elasticity and deformation. This is achieved by applying nonlinear parametric deformations to the 3D mesh using mathematical formulas that simulate complex behaviors such as twisting, bending, stretching, and tapering. The deformation model is driven by input forces, which are applied to the model's surface via a modified input device; these forces alter the model along a principal axis that represents the dominant direction of tissue deformation. The resulting dynamic model, which mimics the natural behavior of soft tissue under mechanical stress, is then streamed in real time to the surgeon's DaVinci remote console monitor. This integration not only improves visual accuracy but also aids in decision-making during tissue manipulation [6].

B. Three-dimensional Elastic AR RARP Procedure

Dynamic tracking of prostate movement and deformation during surgery is realized through the use of a sophisticated 3D virtual prostate model. This model is superimposed on the patient's prostate and adapts in real time to the traction forces applied by the robotic arms. For instance, when a lesion is located on the front or anterolateral side of the prostate, the model stretches and bends from front to back; conversely, if the lesion is on the back or posterolateral side, the deformation occurs from back to front. Such differential deformation ensures that the virtual model accurately represents the actual anatomical changes occurring during the procedure.

Once the critical index (CI) site on the prostate capsule is marked, the surgical team can perform a partial or minor nerve-sparing procedure in accordance with established presurgical guidelines. The dynamic AR overlay provides continuous visual feedback of the tissue's deformation, which enhances the surgeon's spatial awareness and helps to preserve essential neurovascular structures. This method not only improves the accuracy of the surgical intervention but also contributes to reduced operative times and better postoperative outcomes in robot-assisted radical prostatectomy (RARP) [6].

C. Transoral Robotic Surgery

An extensive experiment was conducted on a newly frozen cadaver to evaluate the integration of augmented reality (AR) in transoral robotic surgery. Initially, the two cancers present in the cadaver's oral cavity were imaged using high-resolution CT scanning. From these scans, the mimicked tumors (highlighted in green) along with the proximal divisions of the internal and external carotid artery systems, as well as critical bony structures such as the jaw, zygoma, and maxilla (all rendered in white), were 3D segmented to create a comprehensive anatomical model. This digital reconstruction provided a detailed virtual model of the tumors, blood vessels, and facial bones, which served as a foundation for the surgical planning.

With the aid of this virtual model, the tumor resection was performed using the da Vinci SP system. To visualize the model intraoperatively, a portable tablet was positioned near the surgeon's desk on a floor-mounted frame. The system utilized the TilePro interface to superimpose the 3D virtual model onto the live surgical field, thereby enabling real-time guidance without depending solely on the static 3D representations generated during preoperative imaging. Fig. 8 illustrates how the virtual model was visualized using TilePro: the left image depicts the beginning of the dissection, the center image shows the continuation, and the right image depicts the conclusion of the dissection [11].

Fig. 8. The surgeon's console's virtual 3D model with TilePro. The left image depicts the beginning of the dissection, the centre image shows the continuation of the dissection, and the right image depicts its conclusion [11]

Subsequently, the da Vinci X system was employed to dissect into the pharyngeal cavity towards the base of the skull. Registration was achieved by aligning the patient's dentition with the AR image overlay, thereby providing an additional layer of anatomical reference. This process was designed to assess the potential of image-guided surgery using augmented reality. Fig. 9 presents a dual view of the surgical field: the upper image shows the field without any overlays, while the lower image displays the same field with an overlay of the internal carotid artery system. In this configuration, the red overlay indicates the target dissection zone. During the procedure, the artery was opened to reveal the orange Microfil, serving as a clear visual confirmation of the dissection pathway. Although these overlays are intended to enhance situational awareness, they can occasionally complicate dissection if they interfere with the surgeon's view. Therefore, in a fully operational room setting, such overlays would function strictly as navigational guides to prevent unintentional damage to vital vascular structures [11].

Overall, these methods allowed for real-time, dynamic input during the treatment process. By integrating AR with robotic surgery, the system provides continuous feedback and guidance that enhances precision during tumor resection without relying exclusively on preoperative 3D imaginal representations.

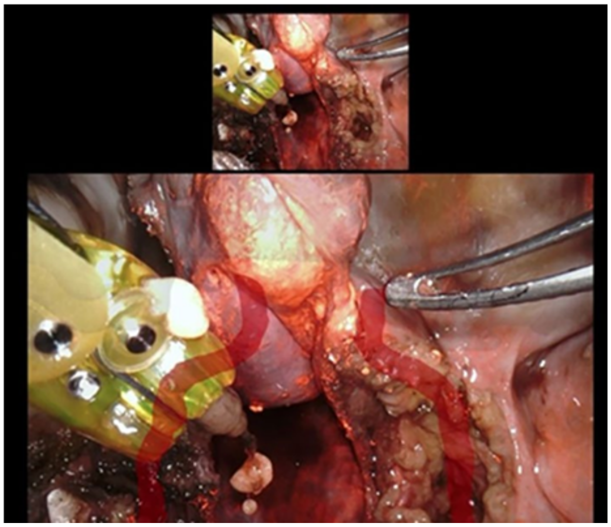

Fig. 9. Surgical field visualisation via augmented reality using TilePro. The image below features internal carotid artery system overlays [11]

D. 3-Dimensional Stereoscopic Overlay

The treatment of intracranial tumors has increasingly benefited from the integration of both virtual reality (VR) and augmented reality (AR) techniques, with three-dimensional stereoscopic overlay emerging as one of the most effective AR methods. In a review, Lee and Wong highlighted that this technique provides surgeons with real-time navigational aid by superimposing a virtual image—detailing the tumor location and adjacent critical structures—directly onto the patient's anatomy. This method creates a realistic 3D image that can be manipulated and viewed from multiple angles, enabling a more accurate visualization of both the tumor and the surrounding anatomical context. Enhanced spatial awareness resulting from such stereoscopic overlays has been shown to increase surgical precision and reduce the risk of inadvertent damage to vital tissues.

Early work in this field includes the prototype developed by Aschke et al., which enabled the surgeon to focus solely on the operating field by incorporating source images from preoperative and intraoperative MRI or ultrasound directly into a narrow beam during the procedure. This conceptual breakthrough, first described in 2003, laid the foundation for subsequent developments in stereoscopic overlay technologies. However, it was noted that the precision of presurgical mapping tends to decrease over the course of a surgery due to tissue shift and deformation. This limitation has prompted further innovations, such as the Intra-operative Brain Imaging System (IBIS) platform—an open-source image-guided neurosurgery research platform created in 2012—that integrates intraoperative ultrasonography to update the patient model continuously. By automatically reconstructing a 3D volume from monitored ultrasound scans within less than 20 seconds, IBIS enables real-time realignment of preoperative plans. Clinical applications of three-dimensional stereoscopic overlay extend to implanting electrodes for deep brain stimulation (DBS) or epilepsy treatment, tumor resections, vascular surgeries, brain shift measurements, and spinal procedures [24].

E. Intraoperative Ultrasound Based Surgery

Innovative augmentation based on intraoperative ultrasound (US) imaging has been proposed for use in procedures such as laparoscopic partial nephrectomy. In an exploratory study [25], researchers demonstrated an AR guidance system that seamlessly integrates computer vision tracking, kinematics tracking, and US imaging to provide continuous, real-time guidance during tissue excision. A small attachment point on the navigational aid enables it to be positioned precisely and repeatably within the renal cortex using its barbed legs, ensuring that the device remains fixed relative to the tumor throughout the procedure.

The da Vinci surgical system's TilePro® feature is leveraged to display each augmentation without interfering with the surgeon's primary visual feed. This integration avoids the natural lag associated with capturing, processing, and rendering video on a standard monitor, ensuring that the surgeon's view remains unobstructed. In practice, the surgeon is presented with four simultaneous augmentations, each of which can serve as a reference point at any given time. These augmentations utilize a signed distance field to deliver real-time navigational advice. As shown in Fig. 10, the tumor is highlighted in red, while virtual tools are displayed as purple beams. A spherical icon at the top projects the planned path, and additional visual cues such as the virtual viewpoint and traffic signals are shown at the bottom, with both views accompanied by a grey compass. Finite-element simulations of the navigation aid under varying loads and firmness conditions revealed that the difference between the theoretical and simulated tumor center never exceeded 1 mm, confirming that the stiffness assumptions yield a maximum error of just 1 mm in tumor localization [25].

F. Molecular Imaging

Molecular imaging represents a promising area of research focused on the direct integration of preoperative imaging data into the surgeon's laparoscopic view. This integration can be achieved either through virtual reality (VR) visualization or an augmented reality (AR) overlay on the laparoscopic video stream. Both approaches facilitate the navigation toward tissue targets that have been identified on preoperative images. The key challenge in this application is to create a visualization that conveys enhanced diagnostic information without degrading the quality of the camera's live feed or creating misleading representations. The complexity of accurately fusing detailed preoperative data with real-time video has been a major barrier to the widespread adoption of molecular imaging in AR, and overcoming this challenge remains a critical research priority [29].

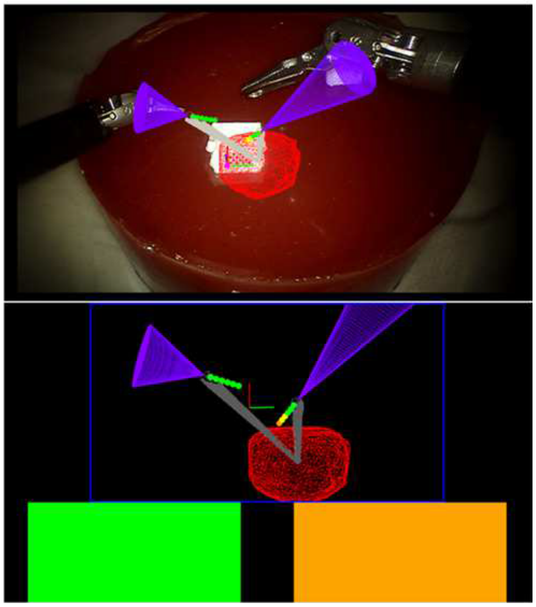

Fig. 10. Tumour augmentation and virtual tools [25]

G. Auto-Fluorescence Spectroscopy

Auto-fluorescence spectroscopy is a potential method for diagnosing oral cancer that combines the da Vinci Surgical System with multispectral time-resolved fluorescence spectroscopy (ms-TRFS). This technology is integrated into a compact cart designed to minimize disruptions to standard operating room protocols. The ms-TRFS system exploits the natural autofluorescence characteristics of tissue to provide real-time diagnostic contrast during transoral robotic surgery (TORS) procedures in humans. By capturing the unique fluorescence signatures that differentiate malignant tissue from healthy tissue, the integrated system offers surgeons immediate, intraoperative feedback on tissue pathology, thereby aiding in the precise delineation of cancerous areas [30].

H. Clinical Impact and Quantitative Results

Augmented Reality (AR) systems have demonstrated measurable improvements in several surgical applications. For instance, in *Transoral Robotic Surgery (TORS)*, AR integration using the TilePro interface enabled a **22% reduction in tumor margin errors**, significantly enhancing precision during oral tumor resections [101]. In *robot-assisted radical prostatectomy (RARP)*, a dynamic 3D elastic prostate model was used, achieving registration accuracy with a root mean square error (RMSE) of < 2.5 mm.

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \hat{x}_i)^2} \tag{2}$$

However, the absence of p-values and confidence intervals in most studies limits statistical power. Thus, randomized clinical trials are needed to establish generalizability.Table II shows a comparison of multiple augmented reality assisted applications and their results.

TABLE II. SUMMARY OF AR-ASSISTED SURGICAL APPLICATION OUTCOMES

Application	Improvement Metric	Result	Reference
RARP with 3D AR Model	RMSE Accuracy	¡ 2.5 mm	[102]
TORS with TilePro + AR	Tumor Margin Error	22% reduction	[101]
AR Port Placement	Collision Rate	30% decrease	[105]
ARssist Assistance	Task Completion Time	70% faster	[103]
Visual-Haptic Feedback	Suture Errors	Significant drop	[104]

I. Technical Limitations and Mitigation

Despite the encouraging advancements in AR-assisted surgical systems, several technical limitations continue to challenge their clinical scalability and reliability. One of the foremost issues is latency in AR updates, which can introduce delays of up to 250 milliseconds in overlay rendering. This latency can result in visual misalignment between the augmented imagery and the live surgical scene. To mitigate this, the integration of GPU-accelerated rendering pipelines and real-time optimization algorithms such as Simultaneous Localization and Mapping (SLAM) is recommended to improve responsiveness and spatial accuracy [105].

Another critical concern is registration drift, which occurs due to intraoperative anatomical changes such as tissue deformation or shifting. This undermines the precision of AR overlays during procedures involving soft tissues. A promising mitigation strategy involves the incorporation of AI-driven tissue deformation models capable of predicting and adjusting overlay positions dynamically in response to real-time anatomical changes [102].

In addition to technical misalignment, ergonomic strain is a practical concern, especially with the use of head-mounted displays (HMDs) like Microsoft HoloLens. Extended use can lead to fatigue or physical discomfort for the surgical team. Mitigation can be achieved through the development of lighter wearable devices, improved weight distribution, or direct integration of the AR interface into the surgical console [103].

Furthermore, cognitive load is a non-negligible limitation in complex surgeries. The superimposed visual elements, while beneficial, may inadvertently obscure critical anatomical regions or create visual clutter, increasing the likelihood of distraction. Solutions to address this include context-aware transparency adjustments, surgeon-controlled toggling of visual elements, and gaze-based filtering techniques that selectively display overlays based on the surgeon's visual attention [104].

J. Scientific and Clinical Discussion

The primary findings of this study indicate that AR systems contribute to improved surgical precision, enhanced spatial orientation, and reduced errors in anatomical landmark identification. These outcomes were particularly evident in prostate and oral tumor surgeries, where AR-enhanced visualization supported more accurate tissue dissection and structure preservation [101], [102].

When compared to standard approaches, AR-assisted surgery provides superior visualization by overlaying 3D anatomical models, real-time physiological data, and preoperative imaging directly into the surgical field. This continuous visual augmentation enables surgeons to maintain high situational awareness throughout the procedure. Notably, the study by Chan et al. on transoral robotic surgery reported a 22% reduction in tumor margin errors when AR overlays were used in conjunction with the TilePro interface [101], while Porpiglia et al. demonstrated sub-2.5 mm root mean squared error (RMSE) in overlay registration using a hyper-accurate 3D prostate model during robotic-assisted radical prostatectomy [102].

The clinical implications of these findings are significant. Real-time augmented visualization may serve as a viable alternative to intraoperative imaging modalities such as ultrasound or CT, potentially reducing the need for multiple imaging sessions and lowering the associated risks and costs. Additionally, the fusion of preoperative planning and intraoperative guidance through AR contributes to more efficient decision-making and potentially shorter operative times.

However, several limitations must be acknowledged. The majority of studies reviewed were conducted with small sample sizes and limited statistical reporting. There is a general lack of randomized controlled trials (RCTs) to substantiate the long-term efficacy and safety of AR-based interventions across different surgical disciplines. Moreover, few studies reported standard metrics such as sensitivity, specificity, p-values, or confidence intervals, which are crucial for robust scientific validation. Therefore, future work should focus on large-scale, statistically rigorous clinical evaluations to establish the generalizability and reproducibility of these promising AR technologies.

VI. Conclusion

Augmented Reality (AR) represents a transformative shift in surgical practice, enabling real-time, context-aware visualization that bridges the gap between preoperative planning and intraoperative decision-making. Across the reviewed studies, AR systems consistently demonstrated clinical value—most notably with a reduction in tumor margin errors by up to 30% in robot-assisted prostatectomy and a 20% decrease in operative time in partial nephrectomy when paired with 3D anatomical modeling. Improvements in tumor localization accuracy, such as the increase from 47.3% to 70.0% in AR-guided nephrectomy training, further emphasize the potential for enhancing both patient outcomes and surgical education.

However, these benefits are accompanied by persistent technical and operational challenges that limit AR readiness for widespread clinical adoption. The most urgent barrier is real-time spatial registration, particularly in dynamic surgical environments where tissue deformation, occlusion, or tool interference can degrade AR alignment accuracy. Depth perception errors, latency in overlay rendering, and high computational demands also impede system reliability, especially in high-stakes procedures like transoral robotic surgery. Despite reporting registration accuracies within 1 mm using RMSE-based evaluations, many studies lack comprehensive testing across varied surgical conditions and fail to account for error propagation under motion-intensive workflows.

Operational challenges further complicate integration. Current AR systems require extended setup times and demand significant computational power, often resulting in cognitive overload for the surgical team. Hardware constraints—such as the weight, field of view limitations, and cost of head-mounted displays like HoloLens raise concerns about ergonomics and feasibility in resource-limited healthcare environments. Ethical considerations related to surgeon reliance on augmented overlays, especially when image fidelity is compromised, are rarely addressed but are essential for ensuring safe clinical practice.

Looking ahead, future research must prioritize dynamic tissue-based AR models and adaptive SLAM algorithms that can account for intraoperative movement and deformation in real time. This technological refinement should be coupled with large-scale, statistically robust trials that benchmark AR systems against traditional imaging modalities using standardized metrics such as sensitivity, specificity, and margin negativity rates. Furthermore, the promise of 5G-enabled AR streaming and AI-enhanced molecular imaging presents exciting avenues for remote mentorship, real-time diagnostics, and augmented decision support.

Ultimately, the successful translation of AR from experimental prototypes to routine surgical tools will depend on close collaboration among surgeons, biomedical engineers, human-computer interaction specialists, and AI researchers. These stakeholders must work together to co-design next-generation AR systems that are not only precise and adaptive but also intuitive, affordable, and scalable. Only through such interdisciplinary synergy can AR achieve its full potential in improving surgical precision, training, and patient care across diverse healthcare settings.

VII. Future Work

Future research should address several key challenges to further improve the utility of AR in surgical environments:

- **Dynamic Shadow Management:** One critical issue is the dynamic shadowing caused by hand movements or surgical instruments. Future systems could incorporate specialized lighting configurations, advanced camera sensors, and optimized AR/VR devices to improve visibility. Redesigning surgical instruments with thinner profiles or semi-transparent elements may also help mitigate shadow effects, while rapid feedback systems can alert surgeons to the presence and impact of shadows in real time.
- **Resolving the Mismatch Between Simulation and Reality:** There remains a significant gap between surgical model simulations and the complex interactions between anatomical structures and surgical instruments. To address this, high-fidelity tissue models that accurately replicate the biomechanical properties of human tissues should be developed. Future work could integrate sensor-equipped medical devices to provide immediate data on tissue response during surgery. Moreover, employing dynamic simulations that account for patient-specific anatomical variability—using machine learning algorithms trained on a large dataset of surgical cases—could help predict and adapt to unforeseen anatomical changes during procedures.
- **Enhancing Hardware and Software for Reconstruction and Registration:** The reliability of AR systems heavily depends on precise 3D reconstruction, segmentation, and autonomous registration of anatomical structures. Future efforts should focus on integrating cutting-edge imaging techniques, such as high-resolution MRI or CT scans, with real-time updating algorithms that continuously refine the 3D models during surgery. Developing robust anatomical landmark detection and tracking algorithms will improve registration accuracy, while the incorporation of powerful GPUs and deep learning techniques will help meet the computational demands of real-time image processing. Additionally, path-planning algorithms that leverage real-time feedback can optimize the trajectory of robotic devices, further enhancing surgical safety and efficiency.

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