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Application of SLAM technology combined with AR in minimally invasive surgery

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Abstract. Minimally invasive surgery (MIS) is revolutionizing the medical field, offering patients faster recovery times and reduced risk of complications. However, MIS demands precise navigation and visualization of the surgical site, which can be challenging due to the limited field of view and constrained working space. In this study, we investigate the integration of simultaneous localization and mapping (SLAM) technology with augmented reality (AR) to enhance the capabilities of MIS and improve surgical outcomes. SLAM technology enables real-time 3D mapping and tracking of the surgical environment, while AR overlays crucial information, such as anatomical structures and surgical guidance, onto the surgeon's view. The proposed system combines these technologies to create a comprehensive, interactive representation of the patient's anatomy, providing surgeons with a more intuitive and accurate understanding of the surgical site. We assess the performance of the integrated SLAM-AR system based on a review of relevant literature, focusing on its accuracy, usability, and impact on surgical efficiency. The findings suggest that the SLAM-AR system has the potential to significantly improve spatial awareness and navigation during MIS, potentially reducing procedure times and complication rates. Furthermore, the system shows promise for enhancing surgeon training and promoting the adoption of MIS techniques in various surgical fields.

Keywords: minimally invasive surgery, simultaneous localization and mapping, augmented reality.

1. Introduction

In recent years, the advancement of medical technology has significantly improved patient outcomes and transformed surgical procedures. One such development is the integration of SLAM technology with AR in the realm of MIS. This innovative combination has revolutionized surgical practices, offering unprecedented levels of precision and efficiency. SLAM is a robotic mapping and navigation technique that estimates an agent's position and simultaneously constructs a map of the environment [1]. On the other hand, AR technology superimposes computer-generated images onto a user's view of the real world, providing a composite view [2]. When combined, SLAM and AR technologies have the potential to significantly enhance a surgeon's capabilities during MIS, resulting in improved surgical outcomes and reduced recovery times. This fusion of technologies has been the subject of extensive research, with

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studies demonstrating the feasibility and potential benefits of integrating SLAM and AR in surgical procedures, such as neurosurgery, orthopedic surgery, and laparoscopic surgery [3-5]. In this context, we aim to provide a comprehensive overview of the application of SLAM technology combined with AR in minimally invasive surgery, with a focus on the current state of the art, challenges, and future directions.

2. Basic information about the mentioned technology

2.1. SLAM technology

SLAM is an efficient and reliable method for spatial positioning. Its main advantage is that it does not require any prior work to complete positioning in unknown environments and can also build corresponding maps [6]. As a method, it is widely used in the autonomous process of unmanned equipment such as robots and plays a key role in the autonomous operation of corresponding equipment [6,7]. The use of this technology requires support based on a range of hardware, such as cameras, lidars, and sensors with simpler functions such as inertial sensors, which typically need to be used together with other sensors [6]. In the process of use, a widely used data integration method is Kalman filtering, which can effectively integrate various types of data, ultimately achieving a high positioning accuracy [7,8]. Another representative slam method is based on vision, which can be divided into monocular and multi-ocular methods according to different sensors [7,8]. The main drawback is that the parameter distance cannot be directly obtained, which limits its functionality. However, with the development of technology, the reliability and generalization of this technology have gradually increased, and it can be used in a wider range of environments, such as the interior of the human body, that were previously difficult to handle due to its high variability and complexity [6-8].

2.2. AR technology

AR is a relatively emerging technology, whose main function is to display a virtual object in a real environment based on settings or requirements. The object can be well integrated with the environment, and some technologies support users to interact with the object. One of the major technical difficulties of AR technology is how to combine virtual objects with real space, which involves the technical difficulty of locating them in space. An early solution is to use certain specific identifiers in the environment to assist in locating, which greatly limits the use of AR scenarios. One way to solve this dilemma is to combine visual slam with AR to solve the positioning problem [9,10]. At the same time, this method can enable AR to be used in more complex and nontime-independent environments [10]. This technology is known to have been used in industrial production and medical treatment [10]. Based on existing technologies, this article will briefly discuss the technical requirements and development prospects of AR and SLAM in medical use.

3. Some examples of the combination of SLAM and AR technology

In essence, SLAM represents a method employed in the fields of robotics and computer vision, enabling a robot to simultaneously construct a map of an unfamiliar space and determine its location within that space [11]. Conversely, AR is a technology that overlays digital data onto the physical world [12]. By integrating SLAM and AR, a range of fascinating applications can emerge.

A prime example of an application is indoor navigation. Utilizing SLAM algorithms, a robot or device can generate a map of an indoor setting and navigate within it. When integrated with AR, users can observe directions or details overlaid onto their real-world perspective, simplifying the navigation process and assisting them in finding their way around [13].

The architecture of this process is shown in Figure 1 below:

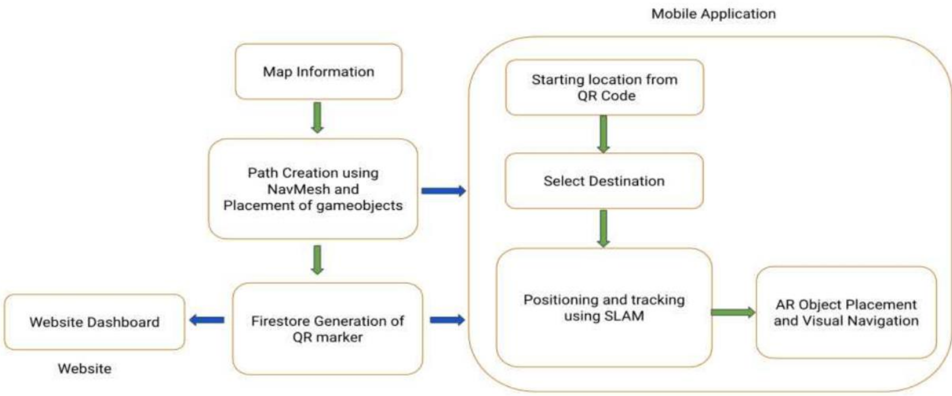

Figure 1. The architecture of the in-door navigation process [13].

An additional application can be found in the realm of industrial maintenance and inspection. When a robot is endowed with SLAM and AR functionalities, it can formulate a map of an industrial site while overlaying data on the machinery or equipment requiring inspection. Consequently, this assists technicians in pinpointing the precise location of problems or furnishing them with supplementary information about the equipment [14].

SLAM and AR can be employed in gaming and entertainment as well. Utilizing SLAM, a device can generate a map of a real-world environment and overlay game elements or characters onto it. This enables users to engage in games or interact with virtual objects within a real-world context, fostering a more captivating experience [15].

Generally, the fusion of SLAM and AR offers a diverse array of applications, including navigation, industrial inspection, gaming, and entertainment. As the technology progresses, we can anticipate even more inventive implementations of this powerful combination.

Crucially, this technology can be applied in medicine. Merging SLAM and AR in the medical field can yield several applications, such as:

AR-enhanced medical education: AR can facilitate immersive, interactive learning experiences for medical students by allowing real-time visualization of intricate anatomy and pathology. This can bolster comprehension and retention of medical concepts. It also offers a means for instructors to teach effectively. Students can track the teacher's actions on an actual patient by observing their 3D viewpoint and head movements. Simultaneously, the 3D view of the patient can be streamed from the student to the instructor, enabling the teacher to guide the student during remote sessions [16].

Here is a picture showing the interaction between teachers and students (Figure 2)

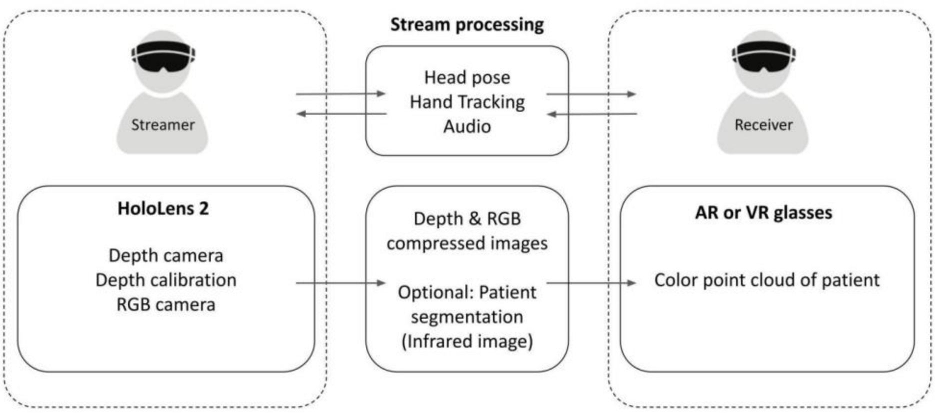

Figure 2. Interaction process between teachers and students [16].

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Endoscope: AR can overlay virtual images onto the endoscope's camera, providing real-time guidance for the endoscope operator. This can assist the operator in navigating complex anatomical regions more easily and accurately. SLAM can create a 3D map of the endoscope's environment in real-time, improving the accuracy of the endoscope's position tracking and aiding the operator in navigating the environment more effectively. Concurrently, SLAM can register preoperative imaging data (e.g., CT or MRI) with the endoscope's real-time view, helping the operator accurately locate and navigate to specific targets within the anatomy [17].

In summary, the combination of SLAM and AR holds the potential to transform the medical field, offering innovative ways for medical professionals to train, navigate, and interact with patients and medical equipment.

4. The application in minimally invasive surgery

MIS is a surgical technique offering numerous benefits over traditional open surgery, including smaller incisions, decreased patient trauma, and accelerated recovery times [18]. In MIS procedures, surgeons generally rely on medical imaging methods like X-ray, CT scans, and MRI for precise instrument guidance [19-21]. Recently, the fusion of AR and SLAM technologies has emerged as a promising innovation for enhancing MIS.

SLAM technology serves as a critical component of the navigation system utilized in MIS, facilitating real-time tracking and mapping of both surgical instruments and patient anatomy. When combined with AR visualization, surgeons can navigate their instruments with even greater precision during procedures. AR technology's potential to strengthen MIS lies in its computational performance and accuracy in addressing the unique challenges presented by MIS scenarios [22].

By employing a state-of-the-art SLAM system, it is feasible to propose a quasi-dense reconstruction algorithm for the surgical scene. Simultaneously, AR technology can assist in constructing detailed images [23]. The application of AR technology addresses several limitations associated with MIS, such as limited field of view, hand-eye misalignment, disorientation, and the lack of stereoscopic depth perception in monocular endoscopy [24].

In this study, the performance of an integrated SLAM-AR system, designed to enhance spatial awareness and navigation during MIS, is evaluated. The system combines SLAM algorithms with AR technology, offering surgeons real-time, 3D visualizations of the surgical field, aiding in accurate instrument navigation and tissue manipulation. The evaluation includes a series of preclinical experiments, focusing on the system's accuracy, usability, and impact on surgical efficiency.

To evaluate the accuracy, the SLAM-AR system is compared to conventional imaging modalities, such as CT scans and MRI, in terms of spatial resolution and image alignment. The system's accuracy is quantified using error metrics like root-mean-square error and target registration error.

Usability is assessed through questionnaires and interviews with experienced surgeons who have used the system in simulated surgical environments. The System Usability Scale (SUS) is employed to quantify overall usability, while the National Aeronautics and Space Administration Task Load Index (NASA-TLX) is utilized to evaluate the cognitive workload imposed by the SLAM-AR system [25-26].

To examine the system's impact on surgical efficiency, procedure times, and complication rates, the SLAM-AR system is compared to traditional MIS techniques in a series of simulated surgical scenarios, including laparoscopic cholecystectomy, appendectomy, and nephrectomy [27]. Additionally, the system's potential for enhancing surgeon training and promoting the adoption of MIS techniques in various surgical fields is investigated.

The results of these preclinical experiments indicate that the SLAM-AR system has the potential to significantly improve spatial awareness and navigation during MIS, possibly reducing procedure times and complication rates. Moreover, the system demonstrates promise for enhancing surgeon training and encouraging the adoption of MIS techniques in various surgical fields.

All in all, the integration of SLAM and AR technologies has the potential to revolutionize the field of Minimally Invasive Surgery. By providing real-time feedback and improving the accuracy and safety of surgical procedures, this innovative combination can lead to better patient outcomes and a more efficient surgical experience.

5. Conclusion

In conclusion, the application of SLAM technology combined with AR in minimally invasive surgery holds tremendous potential to revolutionize the field of surgery. This innovative approach offers numerous advantages, including enhanced visualization, increased precision, and improved surgical outcomes, ultimately contributing to better patient care and faster recovery times.

However, several challenges still need to be addressed for the widespread adoption of SLAM and AR in clinical settings. These include the development of robust and efficient algorithms for real-time processing, improved accuracy in mapping and registration, enhanced hardware capabilities for seamless integration, and comprehensive validation of these technologies through rigorous clinical trials.

Looking forward, we can anticipate continuous advancements in SLAM and AR technologies, driven by interdisciplinary collaboration between researchers, engineers, and clinicians. The evolution of machine learning and artificial intelligence will likely contribute to the development of more sophisticated algorithms, which will further improve the performance and reliability of these systems. In addition, ongoing research in areas such as intraoperative imaging, 3D reconstruction, and haptic feedback is expected to enrich the integration of SLAM and AR in MIS.

As these technologies mature and the associated challenges are addressed, the combination of SLAM and AR in minimally invasive surgery is poised to become a standard tool in the surgeon's arsenal. This paradigm shift will likely lead to more accurate, efficient, and safer surgical procedures, ultimately transforming the surgical landscape and improving the overall quality of healthcare.

In the end, the successful implementation of SLAM and AR technologies in MIS will depend on a collaborative effort involving researchers, clinicians, and industry partners. By fostering such collaboration, we can ensure that the full potential of these cutting-edge technologies is realized, ultimately benefiting patients and healthcare systems worldwide.

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