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An In-Depth Review of The Contributions of Optical Navigation and Three-Dimensional Imaging Technologies to The Advancement of Minimally Invasive Surgical Practices

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Abstract

Background: Minimally invasive surgery (MIS) has transformed surgical practices in the 21st century, offering significant advantages over traditional open procedures, such as reduced patient discomfort, faster recovery times, and decreased hospital stays. However, the inherent challenges of MIS, including limited visual and tactile feedback, necessitate advanced navigation systems.

Methods: A comprehensive literature search was conducted using databases like PubMed and Springer Link, covering studies from 1990 to 2023 that addressed innovations in endoscopic navigation systems. The review highlights various optical endoscopic modalities, including white-light endoscopy, contrast enhancement techniques, and advanced visualization technologies such as fluorescence imaging and virtual chromoendoscopy. Additionally, it discusses the integration of computer vision (CV) methodologies, such as deep learning algorithms, for real-time instrument tracking and lesion detection.

Results: This review systematically examines the role of optical navigation and three-dimensional (3D) imaging technologies in enhancing MIS, focusing on recent advancements in endoscopic techniques. Results indicate that these technologies significantly improve surgical accuracy, enhance visualization, and facilitate effective navigation during procedures.

Conclusions: The findings underscore the potential of optical navigation systems to revolutionize surgical practices by addressing the limitations of conventional MIS and improving patient outcomes. Future developments in endoscopic navigation systems will enhance the precision and efficacy of minimally invasive procedures.

Keywords: Minimally Invasive Surgery, Optical Navigation, 3D Imaging, Endoscopic Techniques, Computer Vision.

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1. Introduction

Minimally invasive medicine has surpassed conventional surgical procedures, which may seriously injure patients during diagnosis and treatment, as a common medical procedure in the twenty-first century. Minimally invasive medical technology employs less traumatic or non-invasive techniques, offering several benefits, including reduced patient discomfort, expedited recovery post-surgery, greatly abbreviated hospital stays, and less use of medical resources [1]. Due to its rapid advancement, it has emerged as a new medical specialty alongside surgery, internal medicine, pediatrics, and others.

Fuchs [2] noted that most surgeons have a steep learning curve with minimally invasive surgery (MIS), resulting in lengthier operating times compared to open surgery. The constraints of human eyesight and tactile perception may complicate the precise identification of surgical tools and lesions during minimally invasive surgery. This impacts the two essential concerns in surgical navigation systems: "destination" and "route." [3] In recent years, many commercial surgical navigation systems have been used throughout several hospital departments. The predominant surgical navigation systems in orthopaedics and neurosurgery are generally sourced from Medtronic, Stryker, General Electric, and BrainLAB, among others.

The endoscope is a crucial instrument in minimally invasive surgery, functioning as the "eye" of the surgical navigation system. Since 1806, medical endoscopy has been extensively used in many anatomical regions and has seen significant evolution over several generations. The conventional endoscope system typically comprises a light source, a camera, an image controller, a display, and the endoscopic body [4]. Endoscopes are constructed in various configurations for distinct therapeutic purposes. Additionally, they use various data transmission techniques (analog or digital), mechanical configurations for the inserted segment (flexible or stiff), and optical sensors (resolution and spectrum). In recent years, the current generation of endoscopes has been developed using several disciplines, including optics, electronics, mechanics, informatics, and graphics. Advanced endoscopic technology presents novel surgical methodologies to surgeons and underpins less invasive surgical navigation systems [5,6].

Various optical endoscopic methods can now acquire more information than previously possible [7]. The binocular stereoscopic endoscope has two calibrated lenses to acquire stereo data. Subsequently, depth information may be obtained by the stereo-matching technique after epipolar correction. Moreover, multispectral imaging techniques enable physicians to examine tissue shape in non-white-light situations, including narrow-band imaging (NBI, Olympus) and Fujinon intelligent chromoendoscopy (FICE, Fujinon). Surgeons may use magnification technology to observe intricate tissue textures and cellular structures, thereafter relying on their expertise or algorithms for disease identification. Consequently, multimodal optical endoscopes provide a variety of data types for endoscopic navigation systems, which also presents new issues in the domain of computer vision (CV) [8].

Computer Vision (CV) is a scientific discipline that explores methods for enabling computers to comprehend their surroundings via visual data. Initial researchers in computer vision used mathematical methodologies to reconstruct the three-dimensional form and look of objects in photographs, striving to enable computers to comprehend and interpret visuals akin to human perception, a challenging endeavor [9]. Recently, advancements in deep learning have significantly improved certain computer vision challenges, including object identification, motion tracking, and semantic segmentation [10]. At now, deep learning-based computer vision is a prominent study domain, leading to an expanding array of applications in minimally invasive surgery, mostly using endoscopes. Endoscopic vision was created to aid endoscopic surgery. For instance, endoscopic visualization enables the accurate positioning of laparoscopic equipment inside the abdominal cavity via visual feedback [11]. In summary, endoscopic vision is a particular use of computer vision that utilizes endoscopes.

Consequently, endoscopic vision technology has increasingly emerged as the focal point of research initiatives by labs and endoscope manufacturers [12-17]. Extracting critical information from the electronic signals gathered by the many sensors in the endoscope will aid doctors in diagnosis and therapy at different stages. The three-dimensional surface reconstruction technique derives depth information from the organ surface, so enhancing the physician's field of view and supplying data for the accurate placement and navigation of the surgical robot. Device tracking technology can assess the surgeon's procedure, while lesion identification enables physicians to get swifter and more precise detection and diagnosis. These advancements have progressed considerably and are applicable in endoscopic navigation systems.

This review involved a systematic literature search on PubMed and Springer Link for studies published between 1990 and 2023 regarding innovative endoscopic technologies for the implementation of endoscopic navigation systems.

2. Optical Endoscopy Techniques for Endoscopic Visualization

Optical endoscopy technologies have significant potential to use endoscopic vision algorithms for the extraction of multidimensional information across several scales from the area of interest. These modalities may further augment the dependability of the whole navigation system.

2.1. White-Light Endoscopy

A conventional monocular endoscope consists of a tube equipped with a light source and lens that records the scene using charge-coupled device (CCD) or complementary metal-oxide semiconductor (CMOS) sensors. The endoscope may be introduced into the body via a natural opening or a minor surgical incision. A flexible endoscope can navigate effortlessly over anatomical curves. Endoscopes enable typical surgeries that need extensive incisions to be conducted with minimal incisions. Endoscopy is the most effective and least intrusive method for screening precancerous lesions associated with gastric and colorectal cancer.

Binocular endoscopes, or stereo laparoscopes, are essential surgical instruments in contemporary "precision" minimally invasive surgery and surgical robotics, owing to their capacity for clear imaging, extensive field of view with adaptable distal segments, stereoscopic measurements, accurate positioning, and elevated diagnostic efficacy. The real-time 3D field-of-view reconstruction methods used in binocular endoscopy, using stereo imaging techniques and the parallax principle, rebuild spatial depth information from image pixels. Binocular endoscopy enables the reconstruction of a three-dimensional picture, hence augmenting the sense of stereopsis and the field of vision during endoscopic examinations [18]. The real-time reconstruction technique for the three-dimensional field of vision aids the physician in identifying, monitoring, and maneuvering around the lesion. Binocular endoscopy provides an innovative intraoperative navigation tool for endoscopic procedures [19].

2.2. Contrast Augmentation

Endoscopists may identify lesions by evaluating the following attributes: (i) mucosal morphology (ulcer, erosion, protuberance, etc.), (ii) mucosal coloration (suspicious red or white patches), and (iii) vascular features (thickness, distribution, blood concentration, etc.). Furthermore, the pictures of the mucosal capillary microstructures enable endoscopists to distinguish between cancerous and normal tissue owing to the pronounced changes in neoangiogenesis seen in both. Contrast-enhanced endoscopic imaging methods, as seen in Fig. 2, effectively emphasize these objectives. This approach enables endoscopists to decrease lesion detection miss rates and enhance the accuracy of lesion characterization [20].

Fluorescence enables thorough and precise identification of the structure and dynamics of the targeted tissue. Diverse fluorophores exhibit distinct fluorescent characteristics, and their fluorescence spectra are often used in diagnostics [21] since they provide comprehensive information about fluorescent molecules, including conformation, binding locations, and interactions inside cells and tissues [22]. Fluorophores are categorized into endogenous and exogenous types [23]. Customized optical filters effectively attenuate spurious excitation light, allowing sensors in fluorescence imaging optical platforms to capture a portion of the emitted fluorescence from the tissue. This component of the fluorescence will aid in the creation of the final pictures [24]. Currently, current fluorescent endoscopic systems include autofluorescence imaging (AFI) [25-27] and near-infrared imaging using indocyanine green (NIR/ICG) [28-30]. AFI uses violet light to activate endogenous fluorophores, while NIR/ICG utilizes a modified light spectrum to stimulate exogenous fluorochromes applied to the area of interest.

Virtual chromoendoscopy (VCE) enhances the detection of spatial variations in light absorption and scattering characteristics of tissues and organs, hence strengthening the contrast between pathological and healthy tissues in diagnosis and treatment. VCE can be classified into three categories based on the illumination light and image processing techniques employed: pre-processing VCE (e.g., NBI and blue-light imaging), which utilizes a modified light spectrum that aligns with the peak absorption characteristics of hemoglobin in blood vessels, thereby enhancing the contrast between capillaries and surrounding mucosal and submucosal tissue; post-processing VCE (e.g., FICE, i-scan, and the Storz professional image enhancement system), which processes digital images to replicate the effects of pre-processing VCE through spectral reconstruction algorithms; and linked colour imaging and i-scan optical enhancement, which integrate both pre- and post-processing techniques [31-36].

2.3. Enhanced Examination

Images with a superior objective resolution beyond human visual capability may provide more efficacious diagnostic information for endoscopists. Close focus (CF) and optical and electronic magnification enhance the physician's visual clarity while minimizing the miss rate for tiny lesions. Furthermore, surface characteristics, such as pit patterns and vascular systems, may be augmented by zoom lenses that magnify pictures by as much as 150 times [37,38]. Furthermore, endocytoscopy (EC) [39] and confocal laser endomicroscopy (CLE) [40], which facilitate real-time micron-level imaging, allow endoscopists to delineate suspicious lesions by observing multicellular structures such as capillaries and villiform formations; cellular morphologies (e.g., crypt, goblet, or epithelial cells); and subcellular organelles (nuclei and cytoplasm). Consequently, EC and CLE may enable in vivo "optical biopsy" and provide intriguing alternatives to ex vivo histology, the current gold standard for endoscopic diagnosis. Additionally, these approaches may be incorporated into the distal end of standard white-light endoscopy, enabling endoscopists to see the mucosa at both macro and microscopic levels [20].

3. Advanced Endoscopic Visual Technology

The field of endoscopic vision encompasses several objectives and viewpoints. This review aims to provide a comprehensive summary of pertinent research in endoscopic navigation and to integrate findings from several disciplines to address practical challenges. In our comprehensive literature review, papers that satisfied the inclusion criteria were categorized into three groups: instrument tracking, endoscopic view enhancement, and suspicious lesion monitoring.

3.1. Tracking of Instruments

Minimally invasive surgical instruments include endoscopic cameras and surgical implements, including endoscopic ultrasonography sensors, biopsy forceps, and minimally invasive surgical robots. The surgeons may find it challenging to visually monitor this equipment because of the restricted field of vision. Consequently, instrument tracking technology is a crucial element of endoscopic navigation. This technology may be categorized into endoscopic camera tracking and surgical instrument tracking based on the used tracking methodologies.

I. Tracking of Endoscopic Cameras

Video-based tracking uses video and images only to identify the position of the endoscopic camera. This tracking technique, referred to as visual odometry (VO), primarily relies on simultaneous localization and mapping (SLAM) algorithms, which are prevalent in robotics and autonomous driving sectors [41]. The camera's movement may be anticipated by identifying key components in the film and analyzing the variations in their positions over successive frames.

Grasa et al. [12] used a visual SLAM module in endoscopic tracking to generate a scaled 3D model of the observed cavity and endoscope trajectory, verified using synthetic data and in vivo picture sequences from 15 laparoscopic hernioplasties. Lin et al. [42] concentrated on preoperative and intraoperative data, developed a parallel tracking and mapping framework, and adapted it for stereoscopic applications [42]. Mahmoud et al. [43] used ORB-SLAM to ascertain the position of the endoscope and the three-dimensional configuration of the surgical environment. Subsequently, he introduced a monocular, quasi-dense reconstruction methodology using a depth propagation method based on keyframe pictures [44,45]. This approach is resilient to significant variations in light, suboptimal texturing, and minor deformations in endoscopic surgery. Prendergast et al. [46] used the ORB-SLAM2 technique in capsule endoscopy for the diagnosis of gastrointestinal (GI) disorders. Their technique was shown using a robotic endoscope and an intestinal model. Turan et al. [47] used convolutional neural network (CNN)-based visual odometry and depth learning techniques in capsule endoscopy, yielding favorable outcomes. The efficacy of the approach was shown via the use of ex vivo porcine gastric models. Wang et al. [48] introduced a visual SLAM technique for bronchoscope tracking that significantly outperformed ORB-SLAM.

Video-based tracking solutions do not need supplementary sensors. Consequently, the endoscope's diameter may be engineered to be reduced. Nevertheless, because to the suboptimal imaging conditions inside the human body, purely video-based tracking methodologies still possess significant potential for improvement in precision and applicability.

II. Tracking of Surgical Instruments

Surgical instrument tracking is a critical issue in endoscopic navigation and is often a precondition for computer- and robot-assisted procedures [49]. Surgical instrument recognition and tracking data are now obtained by image-based (or vision-based) and sensor-based methods [50]. Sensor-based methodologies are now prevalent in clinical practice. Following calibration and coordinate system transformation, the location of the surgical tool's tip may be reliably obtained in real-time. In bronchoscopic navigation surgery, biopsy forceps equipped with electromagnetic sensors may be seen in the virtual endoscope in real time after initial calibration [51]. Optical sensor-equipped puncture needles may assist surgeons in attaining accurate ablation inside hepatic navigation systems [49].

Initial research introduced several image-processing techniques for the segmentation of color markers on surgical instruments for tracking purposes [52-54]. While the aforementioned approaches could be executed effectively on a computer, they also exhibited clear limits. The chosen materials must exhibit excellent biocompatibility; however, most current endoscopic impact data fail to satisfy these criteria and are susceptible to variations in light and shadow. [55]. Subsequently, other research has introduced various feature extraction techniques to improve the robustness of surgical tool tracking. Color is the most prevalent natural characteristic, and almost all current surgical tracking techniques use color data as input. Lee et al. [56] first suggested the use of RGB color space within the framework of minimally invasive surgery. Despite the convenience of color features, their performance was subpar in areas with shadows and highlights. Gradients are a highly favored attribute. The Hough transform and histogram of oriented gradients (HOG) descriptors are often used to extract the edges of surgical instruments. The gradient characteristics effectively delineate the edges and corners of surgical instruments, yet they are susceptible to interference from noise. Additionally, texture feature extraction techniques, such as scale-invariant feature transformation (SIFT) [57] and Colour-SIFT [58], have been suggested to enhance the robustness of the tracking system.

In recent years, the ongoing advancement of CNNs has led to a growing number of researchers using them for surgical tool tracking. Convolutional Neural Networks (CNNs) have superior skills in feature extraction and representation. Initially, CNN techniques were used to substitute certain phases in surgical instrument tracking. Zhang et al. [59] introduced a methodology using a line segment detector to ascertain the locations of designated lines and a CNN to identify the tip of the surgical instrument. Wang et al. [60] integrated VGGNet [61] and GoogleNet [62] for the detection of surgical instruments and then used an average ensemble learning technique to mitigate overfitting in the two deep neural networks. Recently, end-to-end convolutional neural network methodologies have emerged as a prominent research focus in the domain of surgical instrument tracking. Redmon et al. [63] introduced a real-time detection technique using the 'You Only Look Once' (YOLO) algorithm [64]. U-Net-based methodologies have been extensively used in the monitoring of surgical instruments. Colleoni et al. [13] suggested a U-Net architecture integrated with 3D fully convolutional neural networks (3D FCNNs) for the detection of surgical instrument positions. In the 2019 Robust Medical Instrument Segmentation (ROBUST-MIS) Challenge [62], the Haoyun team employed the DeepLabV3+ [65] architecture to emphasize high-level information; a pre-trained ResNet101 [66] served as the encoder, and the focal loss was integrated with the Dice similarity coefficient to train the network [67], resulting in the team achieving the highest success in the challenge.

Sensor-based techniques for monitoring surgical tools need costly equipment and hardware. Endoscopic vision methods may immediately ascertain the tool's location inside the video frame using endoscopic imagery, without altering the instrument or the surgical technique [68], establishing them as state-of-the-art in surgical tool tracking for endoscopic navigation.

4. Conclusions

Endoscopic navigation offers surgeons enhanced accuracy, efficacy, and reliability in diagnosis and treatments during minimally invasive surgery (MIS). The next generation of endoscopic navigation systems, integrated with improved endoscopic vision technology, is now in development. This study summarizes several optical endoscopy modalities, including white-light imaging, contrast enhancement, and advanced endoscopic visualization technologies that are being used or may be utilized in endoscopic navigation systems. Endoscopic optical imaging methods include white-light imaging, contrast-enhancement techniques, and magnification observation technologies. Endoscopic vision technologies include instrument tracking, enlargement of the endoscopic view, and monitoring of worrisome lesions. All these technologies will transform future surgical navigation systems. To address various and complicated clinical demands, it is essential to incorporate sophisticated endoscopic technologies for enhanced navigation precision.

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مراجعة معمقة لمساهمات التنقل البصري وتقنيات التصوير ثلاثي الأبعاد في تقدم ممارسات الجراحة طفيفة التوغل

الملخص

الخلفية :أحدثت الجراحة طفيفة التوغل (MIS) تحولًا جذريًا في الممارسات الجراحية في القرن الحادي والعشرين، حيث تقدم مزايا كبيرة مقارنة بالإجراءات التقليدية المفتوحة، مثل تقليل انزعاج المرضى، وتسريع فترات التعافي، وخفض مدة الإقامة في المستشفى. ومع ذلك، فإن التحديات الملازمة لـMIS ، مثل محدودية الرؤية والقدرة على اللمس، تستلزم أنظمة ملاحة متقدمة.

الطرق :تم إجراء بحث شامل في الأدبيات باستخدام قواعد بيانات مثل PubMed وSpringer Link، مع تغطية الدراسات من عام 1990 إلى 2023 التي تناولت الابتكارات في أنظمة التنقل بالمناظير. تسلط المراجعة الضوء على أساليب التنظير الداخلي البصري المختلفة، بما في ذلك التنظير بالضوء الأبيض، وتقنيات تعزيز التباين، وتقنيات التصوير المتقدمة مثل التصوير التألقي والتنظير الافتراضي بالكرومو. كما تناقش تكامل منهجيات الرؤية الحاسوبية(CV) ، مثل خوارزميات التعلم العميق، لتتبع الأدوات واكتشاف الآفات في الوقت الفعلي.

النتائج :تفحص هذه المراجعة بشكل منهجي دور تقنيات التنقل البصري والتصوير ثلاثي الأبعاد (3D) في تعزيز الجراحة طفيفة التوغل، مع التركيز على التطورات الحديثة في تقنيات التنظير الداخلي. تشير النتائج إلى أن هذه التقنيات تحسن بشكل كبير من دقة الجراحة، وتعزز الرؤية، وتسهّل التنقل الفعال أثناء الإجراءات.

الاستنتاجات :تؤكد النتائج على الإمكانات الكبيرة لأنظمة التنقل البصري في إحداث ثورة في الممارسات الجراحية من خلال معالجة قيود الجراحة التقليدية طفيفة التوغل وتحسين نتائج المرضى. ستساهم التطورات المستقبلية في أنظمة التنقل بالمناظير في تعزيز الدقة والفعالية لهذه الإجراءات.

الكلمات المفتاحية :الجراحة طفيفة التوغل، التنقل البصري، التصوير ثلاثي الأبعاد، تقنيات التنظير الداخلي، الرؤية الحاسوبية.