Research on Optimization Strategy of Surgical Robot CT Navigation System

Chang Zhou*

College of Computer and Control Engineering, Northeast Forestry University, Harbin, 150000, China

*Corresponding author: bubble.zc1028@gmail.com

Abstract. With the development of artificial intelligence, surgical robot technology based on computed tomography (CT) navigation system has been widely used in preoperative diagnosis and intraoperative positioning, improving the success rate of surgery. This paper aims to explore the optimization strategy of surgical robot CT navigation systems. In addition, this paper proposes a new CT navigation system optimization strategy that can be realized in the future to further improve the system's accuracy. The optimization of the CT navigation system mainly includes two aspects: the improvement of CT imaging quality and the improvement of navigation system accuracy. Among them, the key to the optimization of imaging quality lies in the elimination of artifacts, which can be achieved through the metal artifact removal algorithm (MAR) and the adjustment of tube voltage and exposure parameters. Due to the complexity of parameter adjustment operation, the MAR algorithm is better than adjusting scanning parameters. The optimization strategy of navigation accuracy focuses on Three-Dimensional to Two-Dimensional Registration (3D-2D registration) and intraoperative positioning. The current research direction is to integrate a real-time positioning system and CT navigation technology to realize path planning and reduce navigation errors. This article provides ideas for improving CT navigation technology from different aspects in the future, which will help further the development of surgical robot technology.

Keywords: Surgical robot, CT navigation, CT imaging, intraoperative positioning.

1. Introduction

Robot technology has gradually matured and is widely used in various work fields, especially in the medical field. Currently, surgical robots have been adopted in various subspecialties of open and minimally invasive surgery. Compared with doctors, surgical robots can improve surgical accuracy and safety, reduce surgeon fatigue, and solve problems such as insufficient medical personnel [1]. In complex surgical operations, computed tomography (CT) navigation has become an indispensable auxiliary technology due to its high-resolution imaging and accurate positioning performance. Integrated surgical robots have high-precision operation capabilities and real-time imaging of CT navigation, which can achieve more complex and delicate operations and improve surgical results.

However, although CT navigation can provide high-resolution images and accurate real-time positioning, its clinical application still faces challenges such as navigation accuracy, image noise, and intraoperative feedback delay. These problems directly affect the surgical effect [1-3]. Huang and Bingyu proposed that augmented reality and machine learning based on positioning and rendering algorithms improve the accuracy of CT navigation in puncturing non-planar lesions without interference from respiratory motion during prosthetic puncture surgery [2]. Hu W proposed a CT-guided ablation needle path planning method based on a dual deep Q learning network (DDQN), which selects the optimal needle entry point through multi-agent reinforcement learning and optimizes the surgical path on three-dimensional (3-D) reconstructed organ models of different scales. Improve navigation accuracy [3]. Peltonen, J.I. Incorporating O-arm cone beam CT (CBCT) enables imaging protocols that reduce artifacts and improve image clarity by adjusting tube voltage and exposure settings [4]. Bryan S. Benn utilized robot-assisted navigation biopsy (RANB) in conjunction with CBCT, achieving a sensitivity of 84% for malignancy and a diagnostic success rate of 86%.This combined technology significantly improves the malignancy sensitivity and diagnostic accuracy of lung nodule biopsy [5]. Many scholars have proposed various solutions to optimize surgical robot navigation systems, but few articles synthesize these optimization strategies.

Therefore, this paper aims to summarize and evaluate the optimization methods of surgical robot CT navigation system. In Chapter 2, the development status of surgical robots and the principle of CT navigation technology are summarized. In Chapter 3, the optimization strategy of CT navigation technology is explored from different perspectives. In Chapter 4, the advantages and challenges of CT navigation system are analyzed and a possible research strategy for the future is proposed.

2. Overview of CT navigation system

2.1. Development status of surgical robots

Robotic surgery (RS) is an advanced minimally invasive surgical method that integrates medicine, robotics, and engineering. It aims to improve the operating accuracy of surgeons in complex and narrow anatomical spaces through a specialized robotic platform. RS technology can effectively filter hand tremors, enhance flexibility, and reduce involuntary errors, thereby reducing the risk of surgical complications [6]. With the rapid development of imaging technology, computer vision, and other fields, robotic technology has gradually been combined with these technologies and expanded to a variety of surgical applications. In these applications, CT navigation technology is widely used in preoperative planning and intraoperative navigation due to its advantages such as providing high-resolution 3-D images. However, the real-time performance of CT navigation technology is limited by static imaging. In addition, when facing complex surgeries, the resolution of CT imaging still needs to be further improved to ensure the success rate of the operation.

2.2. CT navigation technology principle and process

CT navigation technology is widely used in neurosurgery, orthopedics, tumor resection and other surgeries due to its high resolution, high contrast and fast imaging speed. This technology is based on preoperative or intraoperative computed tomography images and enables surgical guidance through a real-time positioning system. First, CT scanning equipment uses X-ray beams to generate high-resolution two-dimensional images and generates three-dimensional anatomical models through reconstruction algorithms to plan surgical navigation paths. Then, the optical or electromagnetic positioning system monitors the position of the surgical instrument in real time and accurately registers it with the pre-acquired CT images, allowing doctors to achieve precise positioning and operation in complex anatomical environments. This feedback mechanism effectively reduces damage to healthy tissue and significantly improves the safety and success rate of surgery. The CT navigation system consists of five main components: CT scanning equipment, an image reconstruction and registration system, a positioning system, a navigation workstation, and a display feedback system. CT scanning and intraoperative positioning are the decisive factors for the success of the operation. Optical positioning methods are not subject to electromagnetic interference during surgery, but they need to ensure that the light is not blocked, while electromagnetic positioning methods are easily affected by magnetic fields and have relatively low positioning accuracy.

3. Overview of Optimization Methods

The main function of the CT navigation system is to accurately identify the surgical site using high-quality three-dimensional images, and to effectively guide the flexible movement of instruments during surgery. Therefore, the optimization of the CT navigation system can be divided into two main parts: imaging quality optimization strategy and intraoperative navigation optimization strategy.

3.1. Imaging quality optimization strategy

Traditional CT navigation systems rely on static imaging technology, which is mainly used for preoperative planning and reference but is not updated in real-time during surgery. Traditional CT systems are easily disturbed by artifacts caused by metal implants in patients during orthopedic and spinal surgery, affecting doctors' accurate judgment of anatomical structures and surgical planning.

In response to the above problems, Bryan S. Benn proposed integrating RANB and CBCT technology to solve the problem of low sensitivity of traditional technology in biopsy of suspicious pulmonary nodules [5]. The innovation is that CBCT provides real-time imaging guidance, which helps doctors accurately locate lung nodules and improves the success rate of biopsy and the accuracy of diagnosis. According to clinical studies, the diagnostic success rate of RANB combined with CBCT reached 83%, of which the sensitivity for malignant lesions was 84%, and the overall diagnostic success rate was 86%. Compared with traditional percutaneous lung needle biopsy (TTNA), this technology effectively reduces the risk of complications such as pneumothorax and bleeding. CBCT technology provides support for surgical navigation with real-time imaging, significantly improves the success rate of biopsy, and reduces the risk of complications such as pneumothorax and bleeding. However, due to the limitation of detector size, CBCT cannot obtain enough information about adjacent tissues. In addition, ray dispersion can lead to increased noise, which can lead to truncation artifacts, which are distortions caused by reduced image edge sharpness [7]. Truncation artifacts can cause a loss of clarity at the edge of the image, especially in large or irregularly shaped anatomical areas such as the chest or lung edges, thereby affecting the precise localization and identification of pulmonary nodules. In addition, truncation artifacts may obscure the actual morphology of nodules or other diseased tissue, thereby increasing the risk of misdiagnosis.

Maxim Privalov evaluated the metal artifact removal (MAR) algorithmto determine whether software-based artifact reduction can improve the image quality of spinal surgery using intraoperative 3D imaging [8]. The MAR algorithm aims to improve the visualization of tissue near metal screws in 3D datasets by reducing metal artifacts. The algorithm reconstructs volume data containing voxels, detects metal objects through 3D segmentation, identifies metal shadows, and uses a "painting" technique to interpolate and replace artifact areas to generate images without metal artifacts. A dataset of intraoperative 3D images of 49 patients undergoing pedicle screw implantation was collected and processed using the MAR algorithm to examine the visibility of anatomical structures and the diameter of pedicle screws. The effects before and after the application of the artifact removal software were compared. The study found that the MAR algorithm improved the quality from 1.7 to 2.0 and significantly improved the visibility of anatomical structures ($P < 0.01$). In addition, MAR significantly reduced halo artifacts ($P < 0.01$). However, the disadvantage of this strategy is that the image needs to be distorted during image patching and new artifacts may be introduced during the patching process. Juha I. Peltonen proposed a strategy for optimizing metal artifacts in O-arm CBCT imaging [4]. By adjusting imaging parameters such as tube voltage (kVp) and exposure time (mAs), the study aims to enhance the penetration ability and image contrast of X-rays. This process helps to reduce the high reflection and scattering caused by metal objects, as well as the intensity of artifacts from metal implants, ultimately improving overall image quality. The authors simulated orthopedic patients by using a humanoid prosthesis of the pelvis, which contained a metal implant (a 3.2 mm diameter steel rod). The O-arm CBCT device was used for imaging. Different tube voltages and exposure settings were used during the scanning process, and comparative experiments were conducted with and without metal implants. The size and intensity of the artifacts were recorded and analyzed, and the corresponding effective dose was calculated using a Monte Carlo dose simulation program. The experimental data showed that the size and severity of metal artifacts increased significantly with the increase in tube voltage and exposure. Therefore, by optimizing the scanning parameters, the size of metal artifacts can be effectively controlled and image quality can be improved. However, this strategy is limited by the size of the metal implant. When the implant is too large or the position is complex, adjusting the parameters may not completely eliminate the artifacts, which stillaffect the image quality.

3.2. Intraoperative Navigation Optimization Strategy

The intraoperative positioning of traditional CT navigation systems mainly relies on optical positioning and electromagnetic positioning technology. Optical positioning captures the position of surgical instruments in real time through the collaboration of cameras and reflective markers; electromagnetic positioning tracks the spatial position information of instruments based on changes in electromagnetic fields. However, optical positioning is easily affected by line of sight obstructions, while electromagnetic positioning is susceptible to electromagnetic interference in surgeries involving metal instruments or implants, affecting positioning accuracy. Touchette and Michèle proposed an artificial X-ray imaging system (AXIS), which includes an optical tracking system and a digitally reconstructed radiographic image (DRR) algorithm to detect C-arm motion and generate simulated perspective X-ray images in real time to improve the positioning accuracy of the lateral C-arm axis [9].

Fig.1 shows the main reference coordinate systems used in the system and the key methods used to accurately position the C-arm and beam. Touchette, Michèle selected 30 participants who had little experience in using C-arms to perform pelvic imaging tasks that replicated a set of target X-ray images with and without AXIS guidance and recorded the number of X-rays required for each imaging task, the task time, and the positioning accuracy of the C-arm. Paired t-tests were used to evaluate the statistical differences between AXIS-assisted and non-AXIS-assisted. The study used Holm-Bonferroni follow-up corrections, with a significance level set at $\alpha = 0.05$. The results showed that when using AXIS guidance, the number of X-rays used by participants was reduced by an average of 53%, especially when achieving the best distance and best angle accuracy, which were reduced by 68% and 69%, respectively. In addition, the lateral C-arm axis positioning accuracy was improved by 10-26%. However, the limitation of this system is that the DRR generation frequency is only 2Hz, which is too low. The speed will cause a significant delay between the C-arm movement and the AXIS update, and the DRR images are slightly lower in contrast and spatial resolution than real X-rays. Therefore, future research can optimize the DRR algorithm to speed up the calculation and render more pixels per unit time to reduce latency and improve image resolution.

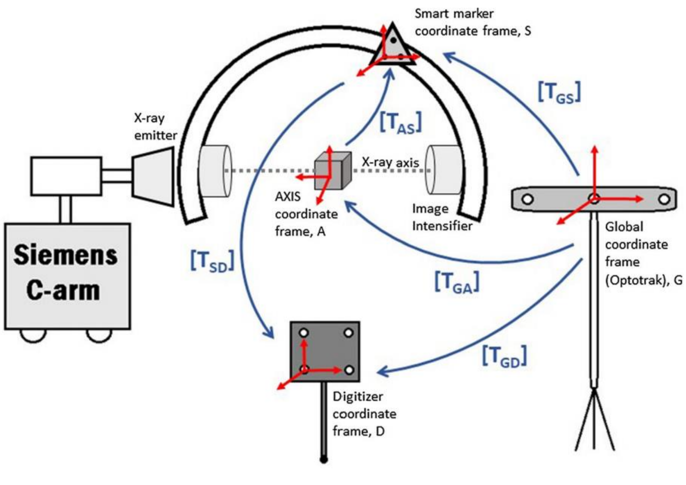

Fig.1 System digitizing probe tool and its local coordinate frame description [10]

Chao and Yin-Kai proposed a strategy of using cone beam CT and laser navigation system for intraoperative positioning to reduce radiation exposure [10]. Chao et al. conducted a controlled experiment and divided patients into two groups: preoperative CT guidance (POCT) and intraoperative CT guidance (IOCT). The continuous variables were compared using a two-sample t-test, and the categorical data were analyzed using a chi-square test or Fisher's exact test. The results showed that the IOCT group was significantly superior to the POCT group in terms of operation time and radiation exposure, with an average operation time reduction of 15.83 minutes and a radiation exposure reduction of 15.59 mSv. Although the two groups were similar in operation time, the total time of general anesthesia in the IOCT group was significantly prolonged, increasing by 34.96

minutes. These data show that compared with the traditional POCT method, IOCT can effectively improve operation efficiency while reducing radiation risk.

Han, R. To solve the problem of low surgical accuracy caused by long fluorescence exposure and trial and error in pelvic reduction surgery, a 3D-2D registration method combining preoperative CT and intraoperative 2D fluorescence fluoroscopy images was proposed [11]. This method uses statistical shape model (SSM) and statistical posture model (SPM) to automatically estimate the reduction posture of the dislocated bone and achieves high-precision posture estimation through multi-body bone segmentation and 3D-2D registration technology. To verify the applicability of this method in different scenarios, Han designed a series of simulation experiments to evaluate the translation and rotation errors of the reduction posture estimation and test its robustness under low radiation dose conditions. The experimental results show that this method shows high accuracy in various dislocation modes and dose sensitivity tests. This strategy achieves millimeter-level posture estimation accuracy in multiple experimental scenarios, reducing the trial and error process and radiation exposure during surgery. However, the main defect is the use of a simplified SawBones phantom model, which lacks soft tissue structure and real bone characteristics, resulting in limited accuracy and representativeness of the results.

Huang and Bingyu proposed a CT-guided puncture navigation system based on augmented reality and machine vision. Augmented reality technology ensures accurate registration of the surgical space and the image space by establishing a surgical space coordinate system and adopting a hierarchical optimization framework [2]. Machine vision tracking technology integrates AR display technology to track the position of surgical instruments in real-time and provide visual support for puncture navigation to improve navigation accuracy and puncture precision. Experimental data show that the navigation system works best in short-distance puncture. The error increases slightly with increasing distance, but the overall accuracy still meets clinical requirements. In the short-distance experiment, the average target positioning error is 1.90 mm and the angle error is 1.39°. However, the study used a static model and failed to simulate the patient's breathing and movement that may exist in real clinical practice. In addition, the needle may cause the sticker to deform during puncture, affecting machine vision recognition. Therefore, future research can further evaluate the model in a dynamic model or clinical scenario. In addition, machine learning technology can be introduced to solve the negative impact of surface deformation on visual recognition. The model can also be further optimized to reduce the error caused by long-distance path application and improve FSR.

4. Strategic recommendations

CT navigation technology has been widely used in complex thoracic, spinal and lung surgeries because it provides accurate three-dimensional anatomical image guidance [12-14]. However, traditional CT navigation often relies on a static reference frame and cannot reflect the patient's physiological changes such as breathing and heartbeat in real time. The positioning accuracy is limited by the accuracy of the reference coordinate system. When there is a certain distance between the reference frame and the surgical site, errors are prone to occur [15]. In addition, when dealing with unobservable states, it cannot respond to environmental changes in real-time, resulting in information lag. Therefore, this paper proposes a new system that integrates extended Kalman filter simultaneous localization and mapping (EKF SLAM) and CT navigation technology. After the CT scan image is processed, the system uses the right-invariant extended Kalman filter (RI-EKF) SLAM algorithm for image analysis and navigation positioning. The real-time position of the surgical instrument or patient is obtained through posture estimation. Then, the system constructs a map to generate the patient's anatomical structure map. Then, the system identifies key anatomical structures to ensure navigation accuracy. At the same time, the system also tracks the surgical instrument, monitors the position of the instrument in real time, and performs dynamic path planning based on the latest data to provide real-time path guidance for surgical operations. The workflow diagram of the CT navigation system integrated with RI-EKF SLAM is shown in Fig. 2.

EKF SLAM allows robots to achieve the dual functions of self-localization and map construction in unknown environments. On this basis, the existing RI-EKF algorithm shows significant advantages over the standard extended Kalman filter (Std-EKF). The observability analysis of the RI-EKF algorithm shows that it can automatically maintain a correct, unobservable subspace to consistently handle object postures, rather than relying solely on point features [16]. This feature significantly improves the system's ability to adapt to complex environments. Applying this integrated technology to surgical operations can effectively identify and track the complex anatomical structures involved (such as organs and blood vessels) and the postures of surgical tools. This dynamic tracking capability enables more accurate positioning and path planning during surgery, which helps reduce surgical risks and improve surgical success rates.

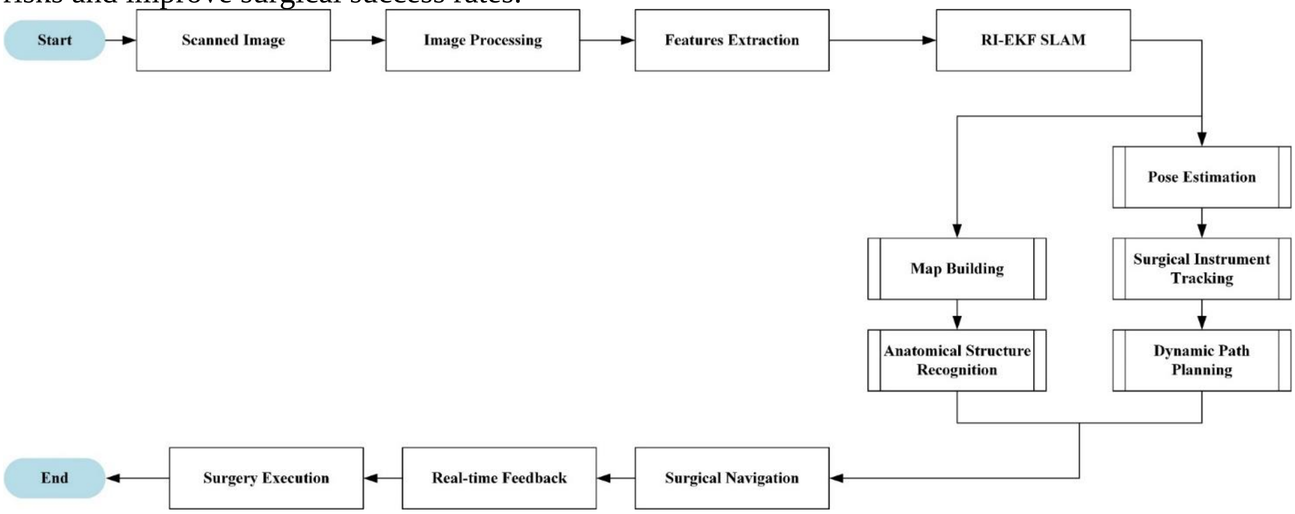

Fig. 2 Workflow diagram of the integrated RI-EKF CT navigation system

5. Conclusion

This paper reviews the existing literature and deeply analyzes various optimization strategies of CT navigation systems. Based on the existing research, a new optimization strategy integrating RI-EKF and CT navigation systems is proposed to address the current deficiencies in predicting unknown environments and building intraoperative maps. Numerous existing studies have developed algorithms to enhance CT imaging resolution and improve intraoperative positioning accuracy. These include image processing-based enhancement technologies and advancements in surgical path planning.. These technologies have improved the responsiveness of the navigation system to varying degrees, reduced intraoperative operation delays, and significantly improved the safety and success rate of surgery. However, the current response strategies for unknown risks and emergencies during surgery are still relatively limited. Therefore, artificial intelligence (AI) and machine learning algorithms can be introduced in the future to give the CT navigation system adaptive learning capabilities. By autonomously learning a large amount of intraoperative data, the system can update CT images in real-time during surgery and dynamically plan the operation path, enabling it to make adjustments faster and more accurately in complex environments. In addition, the introduction of AI technology can also help the navigation system identify potential risks in advance, thereby responding to emergencies within a limited intraoperative time, and further improving the success rate and safety of surgery. This integrated strategy not only provides a new direction for the optimization of navigation technology, but also lays the foundation for the intelligence and automation of future surgical operations.

References

[1] Kim Y, et al. Telerobotic neurovascular interventions with magnetic manipulation. Sci Robot. 2022; 7: eabg9907.

[2] Huang B, Wei Y, Zhang B, Chen J, Guo R, Zhou SZ, Lin Z, Lin Z. Investigating the accuracy of machine vision and augmented reality in percutaneous computed tomography-guided interventions: A phantom study. J Cancer Res Ther. 2024; 20(4): 1338-1343.

[3] Hu W, Jiang H, Wang M. Flexible needle puncture path planning for liver tumors based on deep reinforcement learning. Phys Med Biol. 2022; 67(19): 1-14.

[4] Peltonen JI, Kaasalainen T, Kortesniemi M. Metal artifacts in intraoperative O-arm CBCT scans. BMC Med Imaging. 2021; 21: 2.

[5] Benn BS, Romero AO, Lum M, Krishna G. Robotic-assisted navigation bronchoscopy as a paradigm shift in peripheral lung access. Lung. 2021; 199(2): 177-186.

[6] Rivero-Moreno Y, et al. Robotic surgery: A comprehensive review of the literature and current trends. Cureus. 2023; 15(7): e4400.

[7] Tonetti J, et al. Role of 3D intraoperative imaging in orthopedic and trauma surgery. Orthop Traumatol Surg Res. 2020; 106(1): S19-S25.

[8] Privalov M, et al. Evaluation of software-based metal artifact reduction in intraoperative 3D imaging of the spine using a mobile cone beam CT. J Digit Imaging. 2020; 33(5): 1136-1143.

[9] Touchette M, et al. The effect of artificial X-rays on C-arm positioning performance in a simulated orthopedic surgical setting. Int J Comput Assist Radiol Surg. 2021; 16: 11-22.

[10] Chao YK, et al. Preoperative versus intraoperative image-guided localization of multiple ipsilateral lung nodules. Eur J Cardiothorac Surg. 2020; 57(3): 488-495.

[11] Han R, et al. Multi-body 3D–2D registration for image-guided reduction of pelvic dislocation in orthopedic trauma surgery. Phys Med Biol. 2020; 65(13): 135009.

[12] Shidei H, et al. Mediastinal paraganglioma successfully resected by robot-assisted thoracoscopic surgery with en bloc chest wall resection: A case report. BMC Surg. 2020; 20: 1-5.

[13] Wang TY, et al. Operative time and learning curve between fluoroscopy-based instrument tracking and robot-assisted instrumentation for patients undergoing minimally invasive transforaminal lumbar interbody fusion (MIS-TLIF). Clin Neurol Neurosurg. 2021; 206: 106698.

[14] Kemp SV. Navigation bronchoscopy. Respiration. 2020; 99(277-286.

[15] Otomo N, et al. Computed tomography-based navigation system in current spine surgery: A narrative review. Medicina. 2022; 58(2): 241.

[16] Song Y, et al. A right invariant extended Kalman filter for object-based SLAM. IEEE Robotics and Automation Letters. 2021; 7(2): 1316-1323.