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Application of SLAM in endoscopic imaging

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Abstract. This paper presents the utilization of Simultaneous Localization and Mapping (SLAM) technology in medical endoscopic imaging. The fundamental components, hardware configuration, and process of SLAM are introduced in detail, with a focus on sensor acquisition, data preprocessing, feature extraction and matching, state estimation and update, map construction, and optimization modules. The application of SLAM in the medical field is then discussed, specifically highlighting real-time localization and reconstruction of endoscopic imaging. The integration of SLAM technology can assist doctors in accurately identifying the site of lesions, thereby enhancing surgical precision and safety. Furthermore, the paper introduces various commonly used SLAM algorithms, including the Kalman filter, extended Kalman filter, particle filter, optimization algorithms, among others. It emphasizes the significance of algorithm selection and optimization tailored to different scenarios and requirements. In conclusion, the application of SLAM technology in medical endoscopy imaging holds immense potential, offering improved accuracy and visualization during surgical procedures. This technology provides valuable support for doctors in diagnosis and treatment, ultimately enhancing patient outcomes.

Keywords: SLAM technology, endoscopic imaging, medical application.

1. Introduction

The advancement in medical technology has paved the way for the development of the endoscope, a revolutionary device that provides a non-invasive way to visualize and explore the internal structures of the body. Originating from the rudimentary designs of Hippocrates in 460-375 BC, the endoscope has since undergone significant transformations, evolving from rigid tube constructions to more sophisticated designs incorporating fiber optics, and more recently, ultrasonic and electronic technologies [1].

Simultaneously, there has been a surge in interest in the application of Simultaneous Localization and Mapping (SLAM) technology in various fields, including robotics and artificial intelligence. Since its inception at the IEEE Conference on Robotics and Automation in 1986, SLAM has seen rapid development and widespread adoption due to its potential in areas such as computer vision, signal processing, geometry, graph theory, optimization, and probability estimation [2].

These two seemingly disparate fields of endoscopy and SLAM have begun to intersect, leading to a new frontier in medical imaging. The integration of SLAM into endoscopic procedures holds promising potential for enhanced navigation and imaging, particularly in the complex and intricate

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environment of the human body. With SLAM, the endoscope is not only a tool for visualizing the body's interior but also a sensor that can map its path, providing valuable spatial information and enabling more precise surgical interventions [6,9].

This paper aims to explore the application of SLAM in endoscopic imaging, examining its potential benefits, current limitations, and areas for future research. It draws upon recent studies and advancements in both the fields of endoscopy and SLAM, looking at how these two technologies can be integrated to improve medical procedures and patient outcomes.

Recent research has shown promising results in the use of SLAM for 3D reconstruction of the abdominal cavity [2], the creation of human body maps for endoscopic surgery [4,5], and the modeling of the intestinal environment for endoscopic surgical robot navigation [5,7]. Furthermore, the integration of SLAM with other technologies such as computed tomography [6] and deep learning [8] demonstrates the potential for further advancements in the field.

Despite these promising developments, there are still many challenges to be addressed, including the need for improved sensor calibration, system integration, and the development of reliable methods for dealing with the unique challenges posed by the human body's environment [10]. By addressing these issues, we hope to pave the way for the broader application of SLAM in endoscopic imaging, leading to improved medical procedures and patient outcomes.

2. Overview of relevant theories

2.1. Basic modules of SLAM

SLAM is Simultaneous Localization and Mapping, while SLAM is simultaneous localization and composition. The basic components include Landmark extraction, data association, system state variable estimation, observation-based system state variable update, and landmark update. SLAM for Dummies mainly describes map construction and robot positioning in 2D scenarios. The state variables here mainly refer to the coordinate position and direction Angle of robot x and y, as well as landmark x and y coordinate position, while the EKF algorithm is mainly used to estimate system state variables and update system state variables based on observed values.

2.2. SLAM hardware components

Typical slam system hardware consists of ranging sensor, odometry odometer, processor, IMU, motion robot, etc. The simplest structure is a mobile robot platform and contains at least one ranging unit. The process includes feature extraction, data association, state estimation, state update and feature update. For each of these parts, there are multiple implementations [2].

2.3. The process of SLAM

The SLAM process is shown in Figure 2. Based on the changes of the odometer, EKF is used to update the system state variables, landmarks are extracted based on laser scanning data, and data association is carried out to complete the association between the observed landmarks and the previously observed landmarks. According to the results of data association, namely the observation process, EKF is used to update and revise the system state variables predicted based on the odometer. At the same time, update the landmark information to add that no landmark was observed before.

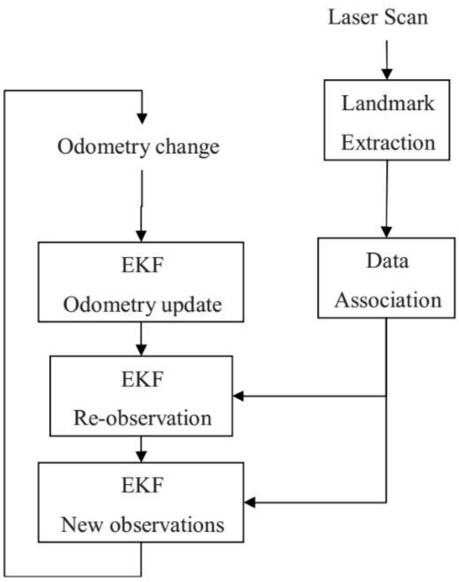

Figure 1. The process of SLAM.

3. Medical application of SLAM, endoscope

Phillip Bozzini, a German, invented the world's first hard tube endoscope in 1804, also known as photoconductor endoscope, which can directly observe internal organs, including urethra, oral cavity, nasal cavity, etc. The difficulties in the design of hard tube endoscope mainly lie in optical processing. The hard-tube endoscope consists of optics, lighting and mechanical components that can be changed to fit different body anatomy. The device was first used on a human in 1806, a professor at the Vienna School of Medical Surgery [3].

In 1932, German Schindler and instrument maker Wlf jointly designed a semi-curved metal gastroscope named WolfSchindler. The proximal end of the gastroscope is a hard tube, and the front end is a hose. The hose part can bend freely at 30 to 40 degrees, which can well solve the disadvantage that the hard tube endoscope cannot bend, and is more suitable in the complex human environment. Later, many researchers upgraded the structure of Wolf-Schindler's semi-curved metal gastroscope and designed a more complete semi-curved endoscope. In 1930, Lamm, a German, proposed that optical information could be transmitted through optical fiber bundles, which laid a theoretical foundation for the later development of fiber optic endoscope. In 1957, Hirschowitz led his team to develop the world's first fiberoptic endoscope for examining the stomach and duodenum using fiber optic technology. They packed bundles of fibers tightly into the endoscopic catheter to transmit light and images, which made the catheter softer and easier to bend. Since then, instrument channels have been added to the optical fiber endoscope, which can be used for monitoring and observing internal organs and tissues and for minimally invasive operations such as laser therapy and gastrointestinal hemostasis. However, because the optical fiber inside the catheter is easy to be broken in the bending process, the longer the use time, the more bad spots in the image, resulting in a short service life [4].

In 1983, Welch Allyn Company of the United States successfully developed the photoelectric image sensor (Charge CoupledDevice, CCD) and applied it to the endoscope, announcing the birth of electronic endoscope. Many photodiodes are arranged inside the image sensor, through which the optical signals are converted into electrical signals and transmitted through metal wires. The size of the electrical signals represents the strength of the optical signals. The photodiodes' electrical signals are collected externally and a complete image is formed. The appearance of CCD completely replaces the optical fiber image transmission technology of endoscope, and its application makes image storage and playback more convenient. Compared with the fiber endoscope, the electronic endoscope has

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more sensitive pixels per unit volume, and the image obtained by the electronic endoscope has higher resolution, more vivid color, higher resolution, and has the characteristics of wide dynamic range and low distortion, which many people can view at the same time.

In terms of sensor, the endoscope image sensor can be divided into CCD (charge combination element) and CMOS (complementary metal oxide semiconductor) two kinds. Although CCD image sensors have higher sensitivity and better imaging effect, in the process of signal transmission, a single pixel transmission interruption will lead to a whole line of images cannot be transmitted, its rejection rate is higher, manufacturing is more difficult, and the cost is relatively higher. With the continuous improvement of the output image quality of CMOS image sensor, its advantages of small size, low noise, low power consumption, low cost and high system integration make it become the mainstream technology of endoscope sensor. Most endoscope manufacturers are making the transition from CCD to CMOS sensors.

Countries such as the United States, Japan and Europe lead the world in medical endoscopes, and medical endoscopes are also more common in these developed countries. Japanese and German manufacturers monopolize Chinese endoscope market, and the market share of domestic manufacturers is about 5%. Japanese enterprises with high core technology barriers promote the photosensitive components industry of traditional soft endoscope. Olympus, Fujinon, Pentax and other Japanese manufacturers basically monopolize the soft endoscope market. German companies have the most advanced technology in the field of rigid endoscopes, far ahead of other countries, such as KarlSTORZ company, which was the first to apply cylindrical lens technology in rigid endoscopes. At present, the main companies designing medical endoscopes in China are Mindray Medical, Auhua Endoscopy, Open Medical and other companies. Their products are mainly used in secondary hospitals and below, and they cannot compete with imported endoscopes in the high-end market. In the hospitals that have entered, few can take the place of main endoscopes.

In the ultra-fine diameter electronic endoscope field, some foreign manufacturers have developed relatively mature ultra-fine diameter series of endoscope products. 0lympus has developed a new electronic ureteroscope URF-V based on a CCD image sensor. The outer diameter of the insert tube is 3.3mm, the outer diameter of the end is 2.8mm, and the rotation Angle can reach 90°. Its narrow-band imaging capability improves mucosal visualization and contributes to the early diagnosis of Ureter Transitional Cell Carcinoma cancer. The URF-P6 catheter, another fiber ureteroscope developed by 0lympus, has an external diameter of 2.6Smm and can be freely bent at 275°. The diagnostic nasopharyngeal endoscope ER-530S2 developed by Fujinon adopts Fujifilm's new Super CCD technology. The outer diameter of the head is 2.9mm and the outer diameter of the bending part is 3.2mm. The output image resolution is higher than that of the traditional electronic nasopharyngeal endoscope. ER-530S2 makes use of better optical lighting system to make the image brighter, which can better help doctors find small lesions and improve diagnosis and treatment efficiency. The electronic ureteroscope 11278 developed by KarlSTORZ, a German manufacturer, has a head outer diameter and catheter diameter of 2.5mm, and a bending Angle of up to 285°. Many foreign researchers have also developed micro-image sensors. The IVP project team designed an image acquisition probe with a diameter of 3.5mm and an image resolution of 36,000 pixels using an image sensor with a size of only 1.7mm×1.3mm [5, 6]. Covi et al. designed a CMOS image sensor module, which could be used as an electronic endoscope in minimally invasive surgery. The module size was 5.0mx82mmx7.0mm, and the image resolution reached 640×480 pixels. Andrew Catanzaro developed a 4mm diameter CCDI to test the esophagus. KamiuchiH proposed a 3D electronic endoscope based on a CCD and a pneumatic vibration mechanism with a size (diagonal distance) of 1/10 of an inch [7].

Some domestic researchers are also exploring the micro image sensor. Wang et al. designed an endoscopic image acquisition module using a CMOS image sensor with a 1/18 inch (diagonal distance) image resolution of only 320x240 pixels. Ye Wei et al. proposed an electronic endoscope based on a CMOS image sensor with a 90° field of view Angle and a 1280x800 image resolution. The sensor package size is 43mmx3.5mm. Xu Zhong et al. used CMOS image sensor GC309 from Gkwe to design a high resolution ultra-fine endoscope system. The diameter of the front catheter of the endoscope was 5mm and the resolution reached 300,000 pixels [8].

4. Understanding and application of specific algorithms such as Kalman filtering

State estimation in SLAM technology refers to the estimation and updating process of attitude, position, speed and other states of robot/equipment in unknown environment. Kalman filtering is one of the commonly used algorithms. This paper introduces the basic principles and application scenarios of Kalman filtering and the algorithms commonly used in SLAM such as extended Kalman filtering and particle filtering.

Kalman filter is an optimal linear unbiased estimation algorithm that constantly predicts and updates the robot/device state and revises the estimated value of attitude, position, and other states. The basic idea of the Kalman filtering algorithm is to use the past and current observation information to predict and update the current state through the state transition equation and observation equation to get the optimal state estimate. Kalman filtering algorithm is widely used in SLAM because of its advantages of small computation, high precision, and fast convergence [9].

In SLAM, Kalman filtering algorithms are often used to estimate robot/device states such as position and attitude, and update the map based on these states. When the robot/device moves, the Kalman filtering algorithm can predict the position and attitude of the robot/device through sensor data such as IMU. When the robot/device perceives, the Kalman filter algorithm updates the position and attitude of the robot/device through sensor data such as Lidar and camera. Through the process of prediction and update, the Kalman filter algorithm can gradually correct the robot/device state and improve the accuracy and robustness of SLAM.

However, Kalman filtering algorithm has limitations when dealing with nonlinear systems. Therefore, nonlinear filtering algorithms such as extended Kalman filter and particle filter are widely used in SLAM. The extended Kalman filter linearizes nonlinear problems by Taylor series, so that it can be applied to Kalman filter algorithm, thus extending the application range of Kalman filter algorithm. Particle filter generates a group of particles, simulates the robot/device state distribution, and calculates a posteriori probability distribution through importance sampling to realize nonlinear filtering.

In addition to the above algorithms, optimization algorithms such as nonlinear least square method and Bundle Adjustment are also commonly used in SLAM. The optimization algorithm optimizes state estimates by minimizing residuals, thus improving the accuracy and robustness of SLAM. Among optimization algorithms, the nonlinear least square method is a widely used algorithm that optimizes state estimates by minimizing the residuals of nonlinear equations. Bundle Adjustment algorithm is a global optimization algorithm that optimizes camera position and map point position in all images to achieve global optimization [10].

In short, Kalman filtering algorithm is a commonly used algorithm in SLAM, which can improve the accuracy and robustness of SLAM by predicting and updating the status of robots/devices. Nonlinear filtering algorithms such as extended Kalman filter and particle filter and optimization algorithms are important for solving nonlinear and global optimization problems. In practical application, according to the specific problems and different scenarios, it is necessary to select and optimize the algorithm according to its characteristics and merits to achieve the best effect.

5. Conclusion

In conclusion, SLAM technology has evolved significantly since its inception, and has become increasingly relevant in many fields, particularly in the medical industry. Endoscopes have benefited from advancements in SLAM technology, resulting in improved imaging quality and minimally invasive procedures.

SLAM technology encompasses various theories and hardware components, including landmark extraction, data association, state variable estimation, and sensor systems such as ranging sensors, odometers, processors, and IMUs. The SLAM process involves updating system state variables based on observed values, while landmark information is updated simultaneously.

Medical endoscopes have come a long way since the invention of the first hard tube endoscope by Phillip Bozzini in 1804. The introduction of fiber optic and electronic endoscopes significantly improved imaging quality and provided greater flexibility in diagnosis and treatment. Japanese and German manufacturers dominate the medical endoscope market, with domestic manufacturers lagging in terms of technological advancement.

Kalman filtering algorithm is a widely used algorithm in SLAM, which predicts and updates the status of robots/devices. Nonlinear filtering algorithms such as extended Kalman filter and particle filter, as well as optimization algorithms such as nonlinear least square method and Bundle Adjustment, are also commonly used in SLAM to solve nonlinear and global optimization problems.

In practical applications, the selection and optimization of algorithms depend on the specific problems and different scenarios to achieve the best effect. The continued development and application of SLAM technology in the medical field will undoubtedly lead to further improvements in diagnosis and treatment, benefiting both patients and medical practitioners.

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