A Study on Detection and Localization of Different Sensors in Surgical Robots

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Abstract. Today's surgical robotic systems are utilizing a wide variety of sensors (force sensors, acceleration sensors, electromagnetic sensors, Hall sensors, etc.). Different types of sensors serve different purposes, and they make the system of the surgical robot larger and more precise and also increase the amount of available information for the surgery to give the healer good surgical conditions. This paper aims to analyze the effectiveness of sensors in 8 surgical robots. This text concludes that the sensors enable the surgical robot to perform the function of force detection and function of localization. For pressure detection, there are not only piezo resistors that form a full-bridge circuit but also sensors that mix piezo resistors with optical fibers. For localization, there are not only stereo cameras but also localization methods that use external markers. The combination of the two key functions enables the surgical robot to provide feedback on the magnitude and exact position of the force, making the surgery more precise and complete.

Keywords: Surgical Robot, Sensor, Detection, Localization.

1. Introduction

Sensors explore various states of motion in the physical world by converting the measured values into corresponding electrical quantities. It plays an important role in the medical field, especially in surgical robotics. In recent decades, people's demand for medical technology has been increasing, and many researchers around the world have used multiple sensors in medical surgical robots to create advanced surgical conditions for healers and excellent medical environments for patients. Before the application of multimodal sensors in surgical robots, the surgical process mainly relied on the doctor's experience and visual observation, which not only increases the doctor's operation difficulty but also reduces the patient's success rate in difficult surgeries. Therefore, it is very important to perceive the internal results of the human body, which can be the second pair of “eyes” of the surgical performer, and this pair of “eyes” can cross the physical barriers, the human body's internal environment can be visualized and readable. For example, equipped with force feedback sensors, which can monitor and feedback on the force of surgical tools in real-time, robotic surgery can achieve higher precision and results when performing complex breast surgery [1]. Ophthalmic surgical assist robots utilizing an algorithm can update the 3D map of retinal vessels in real-time during surgery [2]. The application of different kinds of sensors is a key factor in the ability of surgical robots to achieve functionality that takes medicine a step further and improves the success rate of surgery.

The purpose of this paper is to generalize and summarize the application of different sensors for detection and localization in surgical robots, and to provide reference solutions and directions for other researchers.

2. Overview of sensors

First of all, there is no doubt that surgical robots will be developed in the future because manual skills have an upper limit and are very expensive to learn and dependent on experience, but with the help of surgical robots, we can simplify and optimize surgery and increase the success rate of surgery. Nowadays, the development of surgical robots is facing many challenges: stability of real-time monitoring, measurement range too small to be sufficient for surgical applications, accuracy of surgical execution, and degree of integration. Only with the application of sensors, a surgical robotic system is complete.

Sensor is a device that detects and responds to inputs from the external environment and converts these inputs into electrical signals or other forms of outputs, which senses changes in the external environment and detects them. Sensors used in the field of surgical robotics include temperature sensors, pressure sensors, vision sensors, flow sensors, etc. The use of sensors in the medical field has a number of advantages that can improve accuracy, enhance the safety of surgery, and navigation helps surgeons perform more precise surgical operations. The fusion of several different sensors in a single surgical robotic system constitutes a multimodal sensor, which is capable of simultaneously processing and integrating data information from different sensory modalities, thus improving the accuracy and safety of the surgery, and allowing the quality of the surgical environment to be further improved.

3. Application of sensors in surgical robots

3.1. Force detection (only)

Detection in the surgical field measures and senses physical quantities that need to be known and translates them into data, information that can be read by the surgeon and then negatively feeds back to the human brain, which then analyzes the next step in the behavior.

(1) Hybrid piezoresistive-optical tactile sensor

Naghmeh M's team's hybrid piezoresistive-optical fiber tactile sensor, when applied to a surgical robot, enables the measurement of biological tissue stiffness and the detection of hidden masses within the tissue. The piezoresistors of the pressure sensors measure the contact force directly, while the fiber optic sensors use the transmission properties of light to assist in the measurement of the contact force. When the gap between the optical fibers changes due to the deformation of the sensor, it will lead to a change in the coupling efficiency of the light, thus changing the intensity of the light. The coupling efficiency is obtained by calculating the output power of the output fiber and the input power of the input fiber, and the degree of bending of the part is detected by the formula related to the coupling loss so that the hardness of the human tissue and the location of the hidden mass can be obtained [3].

(2) Piezoelectric Tactile Sensor

Yingxuan Zhang's team developed a piezoelectric tactile sensor for detecting tissue stiffness in robot-assisted minimally invasive surgery. The sensor's piezoresistor circuit input is given a natural resonant frequency by applying an AC voltage, and the impedance of the sensor changes when the sensor is in contact with the tissue. This results in a shift in the resonant frequency and this change in frequency is known as the frequency shift (Δf), which is related to the stiffness of the tissue. By measuring this frequency offset, researchers can infer the mechanical properties of the tissue under test and thus assess its stiffness. This results in the detection of strength. The team also made a new detection model through theoretical analysis and optimized the parameters of the sensor so that it can effectively detect the hardness of tissues at different contact angles. The superiority of piezoelectric tactile sensors lies in the ability to accurately determine tissue hardness through the resonant frequency change of the sensing system without damaging the tissue, thus effectively distinguishing between normal tissue and mass, reducing the misdiagnosis rate, and enhancing the success rate of the surgery [4].

(3) Modular 3-Degrees-of-Freedom Force Sensor

Zonghe Chua and Allison M. Okamura applied a 3-Dof sensor to robot-assisted minimally invasive surgery, capable of sensing manipulation forces such as grip. Its main part is the HSFPAR003A load sensor (a piezoresistive effect-based sensor with a full Wheatstone bridge design (full bridge circuit), which is mainly used to measure compressive forces.) By listing the x and y axis moment balance equations and the z-axis force balance equation, it is able to calculate the change in force along the x, y and z directions. The voltage output of each transducer is linearly related to the applied force, and the output voltage is converted to the applied force using the transducer's sensitivity matrix. It is capable of providing real-time feedback of force information during the grasping and manipulation of tissues, which helps the operator perform delicate maneuvers in order to avoid damage to the tissues [5].

(4) Piezoresistive-based 3-axial MEMS tactile sensor

Cheng Hou's team's piezoresistive sensor, together with an elastic force-transfer layer and a flexible circuit board (FPCB), forms a compact three-axis (X, Y, Z) haptic sensor capable of providing real-time force feedback during minimally invasive surgery. When an object is clamped, the top and bottom sides of the fixture are closed and the force applied to the elastic layer causes the sensor's cantilever beam to deform. This deformation causes a change in the resistance of the piezoresistive element, which breaks the equilibrium of the bridge, which in turn generates a signal of voltage difference. These signals are amplified and digitized and transmitted to a computer for real-time analysis. When a surgical instrument grasps or applies force during an operation, the cantilever beam changes resistance due to deformation, allowing the sensor to sense the magnitude and direction of the force. This sophisticated force sensing capability allows the surgeon to obtain real-time feedback when performing complex operations, thus better controlling the surgical effort and ensuring a smooth operation. In addition, the compact design and high integration of the sensor ensure its use in minimally invasive surgery [6].

3.2. Localization (only)

In traditional surgeries, there are many problems in field of view and tissue occlusion, but the application of multimodal sensors provides real-time and intelligent support for precise localization. Localization of the target during surgery not only provides important information to the surgeon to avoid redundant surgery but also determines the degree of safety of the surgery and the extent of the condition.

(1) Bio-inspired multimodal 3D endoscope

The research team of LIU has developed an endoscopic surgical robot that uses a multi-band sensor based on a structure that mimics the compound eye of the mantis shrimp. This sensor combines the stereo vision characteristics of the human eye with the high polarization sensitivity of the mantis shrimp, enabling the acquisition of both color and near-infrared (NIR) fluorescence images. It is specifically divided into a left eye sensor and a right eye sensor. The sensor utilizes dichroic filters, which are capable of selectively transmitting specific wavelengths of light and is divided into four channels of visible (red, green, and blue) and NIR light.

First, the sub-images from the red, green, and blue (R, G, and B) channels are processed by a demosaicing algorithm to obtain a high-resolution color image. This process merges the three sub-images to form a complete color image. The acquired color image is paired with a near-infrared fluorescence image (NIR) to form a pair of left and right images. A 3D coding algorithm in red and blue format replaces the red channel of the right eye image with the green channel of the left eye image so that when viewed, the red portion provides the right eye's perspective and the blue portion provides the left eye's perspective, resulting in stereoscopic sensation and generating a 3D image with parallax. With this high-performance sensor, real-time feedback can be provided to surgeons to help them identify tumors and their boundaries during surgery, and tumor tissues and lymph nodes can be accurately localized during surgery, which significantly improves the safety and success rate of surgical procedures [7].

(2) Electromagnetic sensors

The surgical robot studied by the team of Oleksandra V. Ivashchenko et al. is an integrated surgical navigation system that incorporates electromagnetic tracking technology. The team used a variety of electromagnetic sensors and trackers, including two 5-degree-of-freedom radio-magnetic sensors (Calypso) and a 6-degree-of-freedom miniature electromagnetic sensor. These sensors are immobilized inside the patient during surgery, e.g., the 6-degree-of-freedom miniature EM sensor is placed near the surface of the liver, and an EM field transmitter is placed externally to track changes in the position of the liver and tumor in real-time [8].

3.3. Integrated Functions for Multimodal Sensors: Localization and Force Detection

Li Qianqian has developed a robotic system for orthognathic surgery that can simultaneously detect, image, and localize three functions. For the detection function, a six-dimensional force sensor is integrated into the wrist of the robotic arm, in which the force sensor force can sense changes in the force applied to the surgical tool in real-time and provide precise haptic feedback. This feedback helps the robot recognize the contact with surrounding tissues and adjust the operation in time to avoid damaging important structures, thus improving the safety and accuracy of the surgery.

In terms of imaging and localization functions, the stereo camera, which utilizes the principle of binocular stereo vision, can accurately acquire the coordinates of the target object in three-dimensional space through an algorithm. Secondly, the stereo camera, by acquiring images of the surgical area in real time, together with the contact point information obtained by the force sensor, helps the navigation system to calculate the relationship between the preoperatively designed spatial coordinates and the coordinate system of the surgical robot, so as to ensure the precise execution of the surgery [9].

NingFan's team developed a robot-assisted system for transforaminal PELS. In the Foraminoplasty System, the robot uses a high-speed grinding head to perform foraminoplasty while providing real-time feedback on the working status of the grinding head through multimodal sensors, including force sensors to monitor force information and acceleration sensors to monitor the acceleration and direction change of the robot's movement. However, the role of the force sensors and acceleration sensors is not to provide tactile feedback, but to detect the current data to determine the working status. Automatic tracking system: External markers are placed to provide the robot with localization information to help it track and adjust accurately during surgery. The robot acquires the position of the external markers in real-time through the vision system and thus establishes a spatial relationship with the surgical target [10].

4. Discussion

In the above 8 studies, the types of sensors used are mainly categorized into two types: detection and localization. 6 of the studies have a force detection function and 4 of them have a localization function. For detection, many of the researchers used piezoresistors, which cause a change in piezoresistor resistance through a change in pressure, and then the voltage of the circuit is tracked and the contact force is measured.For example, the 3-Dof sensor applied by Zonghe Chua and Allison M. Okamura on a surgical robot is able to detect the magnitude of the force in the x, y, and z axes, but the measurement limit is small, and the measurement error increases when there are simultaneous forces acting in all three axes' directions, and it may show nonlinearities [5]. Piezoresistive sensors are susceptible to high or low temperatures, but it's a surgical robot application, so there is little impact in terms of temperature.

In terms of localization capabilities, the researchers in all three articles used vision systems. The endoscopic surgical robot developed by the research team of L IU et al. is small in size, which makes it ideal for endoscopic applications, and the dichroic multiband sensor it uses provides comprehensive 3D information that enables real-time imaging and helps surgeons localize target tissues. However, this integrated sensor involves complex optics, is costly, and is highly dependent on ambient light, which can have an impact on the image quality even when laser illumination is used [7].

Li Qianqian's robotic system for orthognathic surgery uses a stereoscopic camera to achieve localization, which has a high localization accuracy but is easily affected by ambient light and occupies a large space [9].

The localization function in the transforaminal PELS robot-assisted system by NingFan's team relies on external markers to track and localize, which is highly accurate and uncomplicated in the surgical process; however, it is highly dependent on the position of the markers, and the external markers move according to the patient's movement, which affects the accuracy of the surgery [10].

5. Conclusion

This paper summarizes several current methods of applying sensors in surgical robots and describes the functions they implement in the robotic system. It can be concluded that the use of sensors implements the force detection function and the localization function of the robot. Pressure detection in today's surgical robots, most of which use piezoresistors, are very sensitive to pressure changes, very sensitive to pressure changes, can detect small changes in force, and the contact force during surgery can be measured with high precision. However, they often require complex circuits to establish a relationship between the output voltage and pressure and will show non-linearity under certain load conditions. Positioning aspects they undoubtedly provide a good environment and precise information for the execution of surgery. Through tactile sensors, they can provide timely feedback on the size of the contact force and the abnormalities of the tissues; through visual sensors, they can localize the target object, image it, and obtain positional information before surgery. A variety of sensors are used in the surgical robot system, so that the robot obtains more functions, making it more intelligent and informative. The application of high-precision sensors reduces the work pressure of surgical executives so that the success rate of robotic surgery is greatly improved.

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