Tactile Tracking Technology for Medical Robots: Tactile Sensing

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Abstract. Tactile tracking technology is the core support for the "perception interaction" of medical robots. This article focuses on its application in this field, reviews the current status and core scenarios of the technology, and focuses on three key directions. Firstly, by utilizing multimodal autoencoders, reinforcement learning algorithms, and other techniques, this paper aim to promote the deep integration of tactile, visual, and auditory senses, enhancing robots' perception and decision-making abilities in complex surgical environments and human tissue characteristics; Secondly, in response to the high-precision and high-sensitivity requirements of touch in medical scenarios, analyze the application of new materials and miniaturized structures in the design of tactile sensors, and explore the key issues of sensor integration; Thirdly, expand technology to remote medical and rehabilitation assistance scenarios, and solve problems such as remote operation signal delay and personalized tactile feedback for rehabilitation training. This article also analyzes the challenges faced by current technology, such as algorithm complexity, data synchronization, and scene adaptation, providing theoretical references and practical directions for the deep integration of tactile tracking technology and medical robots, in order to promote the improvement of surgical accuracy and optimize the patient rehabilitation effects of medical robots.

Keywords: Tactile Tracking, Medical Robot, Tactile Perception, Perceptual inTeraction.

1 Introduction

Tactile tracking technology is one of the core technologies for achieving a closed-loop control of "perception - decision-making - feedback" in the field of medical robots. Different from traditional static tactile sensing, it captures dynamic mechanical signals (such as contact force, pressure distribution, and sliding displacement) between the robot and human tissues and instruments in real time through multi-modal sensing units. Combined with signal processing algorithms, a dynamic haptic information model is constructed, ultimately achieving precise

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positioning, quantitative analysis and real-time feedback of haptic features during the interaction process, providing haptic dimensional support for the safety and accuracy of robot operations.

The technical principles can be divided into three layers: The perception layer adopts flexible piezoelectric sensors, fiber Bragg grating sensors or capacitive array sensors to achieve highly sensitive collection of micrometer-level displacement and millimeter-level force signals; The signal processing layer eliminates noise interference through Kalman filtering and deep learning (such as the CNN-LSTM fusion model), extracts key features such as contact position and force gradient, and constructs the haptic - spatial mapping relationship; The feedback layer converts the tracked tactile information into physical signals that medical staff can perceive through electrical stimulation, pneumatic drive or magnetorheological devices, forming a closed loop of human-computer interaction.

According to national statistics, by the end of 2024, the elderly population (aged 60 and above) in China will reach 310 million, accounting for 22.0% of the total population [1], with a year-on-year growth of 0.9% compared to 2023 [2]. This indicates that the degree of aging has reached a relatively high level. With the acceleration of the global aging process and the increasing demand for personalized medical services, a more accurate, reliable and complete sensing technology is particularly important in the medical field. Compared with traditional medical robots, tactile tracking, by analyzing and fitting human tactile perception, can make up for the judgment errors in tissue characteristics, wound location and surgical force caused by the poor flexibility of traditional medical devices and remote operation, thereby enhancing the safety and operational accuracy of medical robots, improving the human-machine interaction experience and avoiding tissue damage.

In recent years, under the rapid development of global technology, haptic tracking technology has made significant progress in the application of medical robots and has achieved breakthroughs in many aspects, such as multimodal fusion, algorithm combination, system integration and miniaturization, becoming a hot topic of cross-disciplinary research in robotics and medical science and technology. However, most of the above-mentioned studies have focused on multi-dimensional information recognition and collection, deep learning, and machine learning, while neglecting the load brought by perceptual conflicts, the universality and biocompatibility of algorithms. Therefore, the discussion of issues related to medical robots centered on haptic tracking is of crucial significance to technological progress in the medical field.

In conclusion, this paper provides a detailed overview and discussion of haptic tracking technology and its application research in medical robots. It also looks forward to the comprehensive development of medical robots using haptic tracking technology in the future by combining the latest development directions and a series of challenges faced, and draws a review conclusion.

2 Tactile Feedback

The primary method for combining digital signals with human tactile awareness is haptic feedback technology. Its core mechanism is to utilize various physical effects to precisely reproduce the multi-dimensional tactile experiences of human beings. The connotation of this technology is far richer than that of fundamental vibration. It is dedicated to simulating complex tactile attributes ranging from fine surface features to overall mechanical feedback, thereby expanding the boundary of human-computer interaction from the audio-visual field to a multi-dimensional integrated perception space.

The application prospects of this technology in many cutting-edge fields are essentially due to the fact that it provides a sensory communication method with high bandwidth and low cognitive load. Whether it is to restore the mechanical properties of tissues in remote interventional surgery or to provide precise force guidance in simulation operations, this simulation of "direct touch" fundamentally enhances the authenticity of interaction and the efficiency of task completion.

Regarding the construction of its technological spectrum, the main classification criteria are based on its working principle and the perception modes it generates. It specifically covers the following aspects:

2.1 Piezoresistive Tactile Feedback

Piezoresistive tactile feedback is a technology that achieves tactile signal perception and feedback through the piezoresistive effect. Its core principle involves utilizing the piezoresistive properties of materials to convert external forces (such as contact or pressing) into measurable resistance changes. Through circuit processing and signal interpretation, it ultimately enables the perception and feedback of tactile information. In the medical field, minimally invasive surgical robots can avoid organ damage by perceiving the grasping force of tissues [3]. Remote surgical robots utilize piezoresistive tactile feedback technology, enabling doctors to accurately sense the contact force between surgical instruments and tissues [4], thereby precisely controlling surgical operations and improving surgical success rates. Rehabilitation nursing robots can measure the pressure on contact surfaces, dynamically adjusting and distributing surface pressure to effectively prevent pressure ulcers [5].

2.2 Capacitive Tactile Feedback

Capacitive tactile feedback is a technology that utilizes the principle of capacitive induction to achieve tactile signal perception and feedback. Its core principle is to use the characteristics of parallel plate capacitors to identify external forces (such as contact and pressure) by detecting changes in capacitance values between electrodes, and then convert capacitance changes into electrical signals for interpretation, ultimately achieving tactile perception and feedback. Capacitive tactile feedback, with its high sensitivity, fast response, and long lifespan, can accurately adapt to the needs of minimally invasive, fine operation, and human-machine safety collaboration in medical robots. For example, in medical scenarios where doctors need to work together with robots, capacitive sensors can be integrated into the robot's shell or working arm surface. When the doctor's body accidentally approaches or touches the robot, the sensor can quickly detect a sudden change in capacitance value, causing the robot to decelerate or stop urgently, ensuring the safety of personnel during human-machine cooperation. Erickson et al. used multi electrode capacitive sensors installed on robot end effectors to estimate the relative position and direction (posture) of human limbs, which can accurately perceive the human body, track the trajectory around the body, and track human motion [6].

2.3 Force Feedback Tactile Feedback

Force feedback tactile feedback, also known as "force feedback", is a tactile interaction technology that allows users to truly perceive physical forces. Its core principle is to actively apply physical reaction forces related to operations to users through a closed-loop process of "perception - calculation - execution", simulating the force sensation in the real environment and allowing users to obtain an immersive tactile experience. It is widely used in the field of medical surgery. For example, Jin et al. developed a passive robotic arm with collaborative surgical guide wire and catheter functions, which is used as a tactile sensing robot assisted system for vascular intervention surgery [7]. The system achieves tactile force feedback by generating tactile force acting on the doctor's hand, replacing the doctor's operation in the operating room; Xu et al. constructed a master-slave CMF (Cranal Maxillofacial Robot) surgical robot system based on force feedback [8]. The surgical robot adopts a model-based main robot gravity compensation and force feedback mechanism, which can assist surgeons in completing accurate mandibular osteotomy surgery. Through the force feedback mechanism, the interaction between surgeons and robots can be improved to achieve tactile trajectory motion.

2.4 Optical Haptic Feedback

By integrating optical technology with haptic feedback, optical-haptic feedback technology has greatly enhanced the sense of reality and immersion in human-computer interaction. This technology conveys tactile information to users through optical means and often works in synergy with visualization and sensor technologies to enhance users' perception of object mass, surface texture or environmental conditions [9]. In the field of tumor treatment, Li et al. fabricated a three-axis tactile sensing probe (Fig.1) based on a fiber Bragg grating (FBG) by using five optical fibers engraved with FBG and a force-sensitive 3D printed variable body [10]. The team adopted a linearized difference model and endowed it with the ability to reconstruct the surface profile of non-planar tissues to calibrate triaxial force detection and enhance resistance to nonlinear interference, thereby effectively 3D positioning hard blocks.

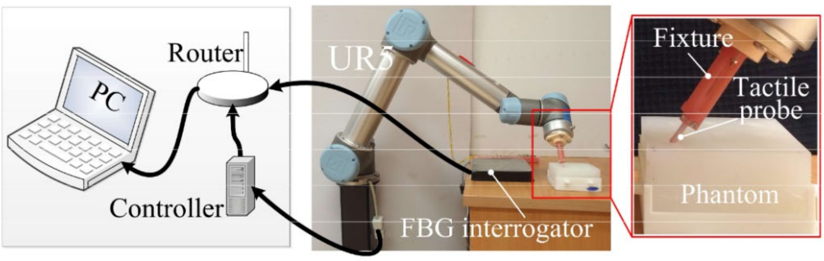

Fig. 1. Robotic integrated with the tactile probe to implement palpation [10]

2.5 Magnetic Contact Feedback Technology

Magnetic touch feedback technology utilizes magnetic fields and magnetic materials to endow users with tactile perception, thereby enhancing the experience of human-computer interaction. This technology precisely modifies the force or vibration experienced by the user by changing the intensity, direction or position of the magnetic field, thereby achieving extremely fine haptic feedback. Its basic function is to generate observable vibrations and tactile sensations using magnetic devices (such as permanent magnets or magnetic shape memory alloys (SMA)) [11].

3 Tactile Positioning

3.1 Self-healing Material

Self-healing materials are a new type of material that has the special ability to take a series of measures to promptly repair the damaged tissue structure and corresponding functions when they are worn by imitating the biological self-healing mechanism. With its unique bionic self-healing function, self-healing materials play a crucial role in application fields such as surgery, diagnosis, and rehabilitation. Compared with the reliability bottleneck of traditional tactile sensors caused by material aging and other factors, self-healing materials not only can withstand mechanical damage but also achieve dynamic repair, providing a new path to solve core challenges such as equipment durability, thereby significantly improving their long-term stability under harsh working conditions. For instance, the team led by Academician Zhonglin Wang from the Chinese Academy of Sciences and the Georgia Institute of Technology has developed an electronic skin (e-skin) with self-healing ability, high transparency, ultra-thinness and excellent mechanical properties [12]. This electronic skinachieves self-healing of the material through an elastomer with dynamic disulfide bonds and uses this elastomer as a friction layer. Through the coupling effect of contact charging and electrostatic induction, mechanical energy is converted into electrical energy, thereby realizing self-powered tactile and non-contact sensing. The mechanical durability of this product has been effectively verified through experiments. Its performance remains unchanged after 45,000 bends (with a radius of curvature of 0.5mm) and 146,000 operation cycles. In the future, thanks to a profound understanding of self-healing mechanisms and the development of materials engineering, the new generation of self-healing materials will become a key driving force for the long-term stable operation of tactile perception and medical robots and the expansion of their application boundaries.

3.2 Stretchable Conductor

In conventional materials, electrical conductivity and stretchability are often not achievable simultaneously. Metallic materials such as copper and copper alloys have excellent electronic transmission capabilities, but they have poor mechanical ductility and are prone to being pulled apart; While elastomers like TPU have high elasticity, they are usually non-conductive. The stretchable conductor is a product developed to balance these two capabilities. Thanks to the deep integration of stretchable conductors and advanced tactile sensing technology, medical robots have achieved significant improvements in control accuracy, surgical efficiency, minimally invasive level and operational safety. A team from the Chinese Academy of Sciences developed a stretchable conductor (Fig. 2) based on liquid metal nanoparticles and used it to construct an energy-harvesting tactile interaction interface [13]. This interface simultaneously achieves self-powered pressure sensing and mechanical energy collection through a triboelectric generation mechanism. Experiments show that it still maintains excellent electrical performance under 260% tensile conditions, providing a new solution for the development of highly stretchable self-sustaining wearable systems.

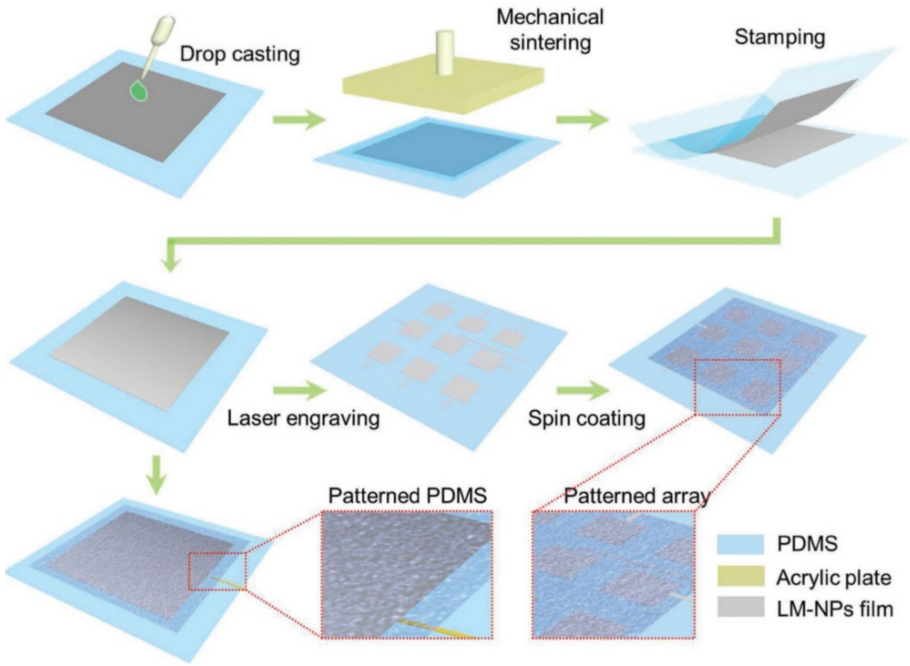

Fig. 2. Schematic illustration of the fabrication process of the tactile interactive interface [13].

4 Application

4.1 Surgical Robot

In the field of minimally invasive surgical robots, tactile tracking technology is the core solution to compensate for the lack of tactile sensation in doctors' operations. It provides critical perceptual support for complex intracavitary operations by accurately capturing the dynamic mechanical interaction between instruments and tissues. The core challenge of this technology is to achieve high sensitivity and anti-interference force signal acquisition and real-time feedback within the limited space of minimally invasive instruments.

The current mainstream technological path presents a parallel development trend of multi-sensor principles. The FBG fiber Bragg grating sensor developed by Shenzhen Advanced Institute effectively decouples strain and temperature cross interference through a dual grating element design, achieving a force sensing accuracy of 0.8mN within a 1N range and compatible with imaging environments such as MRI. It has achieved precise localization of tumors in pig liver tissue palpation experiments. The flexible PZT piezoelectric film, with its advantage of micrometer level thickness, achieves adhesive integration on the surface of surgical instruments. Its micro level detection capability is suitable for ultra fine operation scenarios such as ophthalmology and neurosurgery, and it also has the advantages of high temperature resistance, disinfection, and biocompatibility [14].

At the signal processing level, deep learning algorithms have become the key to breaking through bottlenecks. Feedforward neural networks are used for sensor calibration, significantly improving the accuracy of force wavelength mapping. By combining the CNN-LSTM fusion model, real-time analysis of tissue hardness distribution can be achieved, enabling differentiation of mechanical properties between tumors and normal tissues. The feedback mechanism can be divided into two modes: direct feedback transmits contact force in real-time through force sensors, while indirect feedback predicts potential risks through motion state analysis. However, the latter has a disadvantage in response speed [15].

Clinical applications have covered key scenarios such as vascular protection and tumor palpation in laparoscopic surgery. By precisely controlling the operating force within 0.01 Newtons, the risk of tissue damage is significantly reduced. However, the implementation of technology still faces challenges: sensors need to balance durability and flexibility, and existing solutions are prone to deformation delays after 2000 cycles; The synchronization and feedback delay issues of multimodal feedback, such as visual tactile fusion, still need to be optimized. In the future, the integration of distributed sensing and wireless sensing technology for flexible electronic skin will promote the development of this field towards more natural human-computer interaction [16].

4.2 Rehabilitation Robot

A variety of assistive functions related to tactile tracking technology are also one of the key countermeasures to improve the treatment speed in the field of rehabilitation medical robot research. One of its core mechanisms is to capture the patient's body language and corresponding tactile movement information, analyze and compare them with the set rehabilitation actions, thereby correcting the patient's rehabilitation movement behavior and improving the rehabilitation efficiency.

In terms of immediate and reliable perception, by using flexible sensors to assist external sensing feedback loops, rehabilitation robots can conduct real-time quantification and high-precision synchronous monitoring of kinematic and dynamic parameters of rehabilitation training. Thanks to this enhanced perception ability, rehabilitation robots can achieve dynamic monitoring of patients' movement trajectories and interaction forces, which is an important prerequisite for building an adaptive closed-loop control system. By combining soft matter logic, electro-fluid sensing and SMA driving, a multidisciplinary team from the University of Bristol in the UK has developed a flexible smart Glove (B: Ionic Glove) [17]. This glove (Fig. 3) provides haptic feedback for the upper limb prosthesis by sending a squeezing sensation to the arm. The effectiveness of its communication of contact information has been verified through user surveys, in which the correct rate of participants distinguishing the location of stimuli was as high as 81%. Not only that, the task verification of this glove in grasping a Rubik's Cube shows that it can still have the ability to perform grasping activities without the need for visual AIDS. This provides a new reference direction for reducing the abandonment rate of prosthetic limbs.

In terms of medical rehabilitation, its application has become quite extensive, covering numerous typical use cases such as stroke rehabilitation, upper limb rehabilitation, Parkinson's disease treatment, and spinal cord injury. It is worth noting that the current technology still has a series of complex problems such as the biological adaptability of materials that need to be solved urgently.

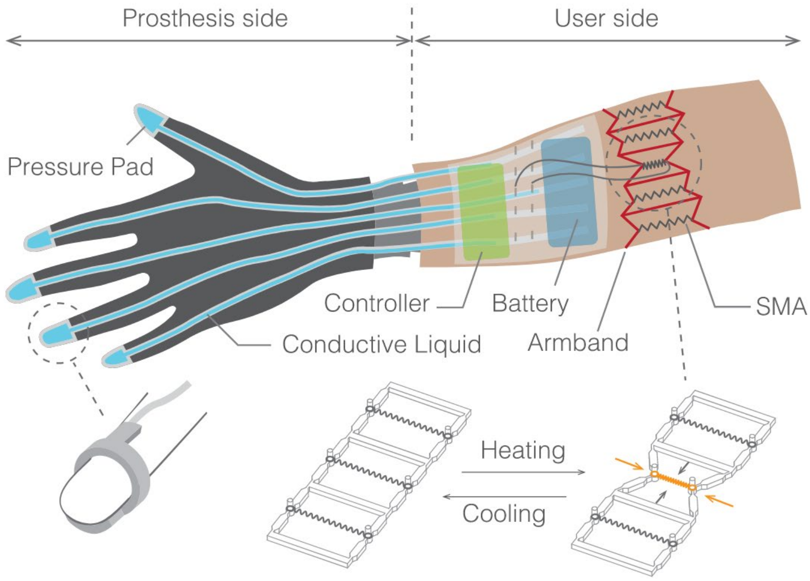

Fig. 3. Illustration of the B: Ionic glove, consisting of pressure pads containing conductive fluid wrapped around the fingertip of a prosthesis, an electro-fluidic control unit including the battery, and an armband actuated by shape memory alloys (SMAs) by way of heating and cooling, generating axial, radial and circumferential forces on the user's arm. [17]

5 Frontier Field

5.1 Multimodal Fusion and Algorithm Optimization

The tactile tracking medical robot integrates various sensors such as force, touch, vision, and hearing to comprehensively perceive the patient's condition. For example, rehabilitation robots can monitor the force on limbs through force tactile sensors, capture motion postures with visual information, and use auditory sensors to interpret voice commands, in order to achieve multimodal information fusion. Topini et al. developed a Hand Exoskeleton System (HES) that combines force feedback with tactile feedback, providing force feedback in virtual interaction to enhance rehabilitation outcomes and patient engagement [18]. In addition, inspired by the integration of multiple human senses, multimodal tactile information such as vision, hearing, motion, and pressure can be integrated, combined with self supervised learning to construct a universal tactile representation system, enhancing the performance of robots in complex tasks.

In terms of algorithms, deep learning can be used to process multimodal data, such as Luo et al. integrating visual and tactile information into ultrasound robot systems, and achieving autonomous imaging through a multimodal deep reinforcement learning framework [19]. Secondly, force tactile control algorithms such as impedance control and force position hybrid control can adjust the robot's motion impedance or flexibly switch control modes to achieve smooth and accurate interaction.

5.2 Sensor Integration and Miniaturization

Sensor integration and miniaturization are key technologies, focusing on process innovation, cost control, and stability improvement. In terms of manufacturing process, MEMS on CMOS and other integrated technologies have achieved ultra miniaturization. The Peking University team has developed a flexible modular sensor that can decouple and measure various forces and temperatures [20]. In terms of cost, new materials such as 3D printing and conjugated polymers have reduced manufacturing complexity and power consumption [21]. In terms of stability, new sensors such as conjugated polymer sensors remain stable after multiple loading cycles, FBG fiber sensors maintain high accuracy in complex environments, and modular design enhances durability [22].

6 Conclusion

This article provides a systematic review of the research progress of tactile tracking medical robots, clarifying that the current research progress in this field mainly focuses on technological integration and performance breakthroughs, including their applications in minimally invasive surgery, medical rehabilitation, and new materials. At the same time, it summarizes the latest research directions and challenges that currently exist, providing a clear context for understanding the overall situation of this field, and providing reference for researchers to clarify the direction of technological iteration and for enterprises to layout product development.

Through analysis, it was found that there are still problems in the current field, such as insufficient synchronization of multimodal fusion and insufficient real-time collaboration of feedback processing; the stability of the sensor is insufficient, which is prone to deformation delay; There are also many safety risks associated with biocompatibility, which restrict its large-scale application. These shortcomings have also become key factors restricting its further development.

The limitation of this article is the lack of in-depth comparison of the differences in tactile tracking medical robot technology for specific segmented scenarios. Based on the existing problems, two major research directions can be focused on in the future: on the one hand, it is necessary to develop high biocompatibility and high stability integrated sensors, striving to achieve scale and miniaturization; On the other hand, it is necessary to strengthen the multimodal signal fusion algorithm, further enhance the real-time performance and anti-interference ability of tactile tracking medical robots, and ultimately promote their development towards safer and more efficient practical fields, providing technical support for minimally invasive surgery, medical rehabilitation and other fields.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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