Force Feedback and Control Theory Applications in Haptic Interaction Systems

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Abstract. With the rapid development of virtual reality, augmented reality, and remote operation technologies, force feedback-based tactile interaction has emerged as a key pathway for enhancing immersion and precision in human–computer interaction. This paper investigates the principles, implementation mechanisms, and practical challenges of force feedback systems from the perspective of robot control theory. Drawing on core concepts such as impedance control and hybrid force-position control, the study explores how these theoretical models underpin the design of stable and responsive haptic systems across application domains including telemedicine and industrial robotics. Through literature review and case analysis, this research reveals that while existing systems achieve impressive levels of realism and operability, they often lack robustness under real-world conditions such as network delay and dynamic environments. The study concludes by identifying limitations in current research, notably the absence of experimental validation, and calls for future development of adaptive algorithms, interdisciplinary approaches, and standardized evaluation frameworks to advance the effectiveness and reliability of force feedback technologies.

Keywords: Force feedback, tactile interaction, robot control theory, impedance control.

1. Introduction

In recent years, with the rapid development of technologies such as virtual reality, augmented reality, and remote operation, tactile interaction systems have gradually become an important research direction in the field of human-computer interaction[1]. Among them, tactile technology based on force feedback, as a key means to connect human perception with virtual environments or robot systems, can provide users with a real force experience, thereby significantly improving the immersion of interaction and the accuracy of operation [2]. Although the current force feedback technology has achieved initial results in hardware equipment and application practice, it still faces many challenges in control strategy and system stability. Current research is mostly focused on improving device performance or optimizing user experience, and rarely systematically explores the principles and implementation mechanisms of force feedback interaction from the perspective of robot control theory.

Core concepts in control theory, such as impedance control, hybrid control of force and position, and the stability of human-machine interaction systems, are essential for understanding the dynamic characteristics of tactile interaction and for guiding the development of effective and reliable systems. These theoretical principles contribute to the accurate modeling and regulation of tactile feedback, helping to ensure responsiveness, precision, and safety in various interaction contexts. Their practical importance is particularly evident in complex application scenarios, including remote medical procedures, collaborative robotics in industrial environments, and tasks that require high levels of accuracy and control. Building on this theoretical foundation, the present study adopts a combined approach of literature review and case analysis to explore how force-feedback-based tactile interaction technologies are applied within the framework of robotic control theory. The aim is to clarify the underlying application logic, trace the current state of development, and identify the key theoretical and practical challenges that remain.

2. Principles and Foundations of Force Feedback Haptic Technology

2.1 Basic Physical Principles

The essence of force feedback tactile interaction is rooted in Newton's third law of classical mechanics, that is, every action corresponds to an equal and opposite reaction force [3]. In the process of human-computer interaction, the user applies force to the virtual or real object through the force feedback device, and the system needs to generate corresponding reverse feedback in real time to make the user have the same physical perception as the real world. This process is the theoretical core of achieving realism and interactive immersion.

There are two commonly used control models in force feedback systems: the impedance model and the admittance model [4] . The impedance model takes the user's motion inputs—such as displacement, velocity, and acceleration—and computes the corresponding reaction force. For instance, when a user pushes against a virtual door, the system calculates and applies a force opposite to the pushing direction based on the simulated "virtual stiffness" and "damping" properties of the door, thereby mimicking the door's physical behavior. In contrast, the admittance model uses the force applied by the user as the input to determine the system’ s motion output (e.g., position or velocity). This model is better suited for systems with high mechanical inertia or lower back-drivability, such as large-scale teleoperation manipulators. These two models can be flexibly chosen based on specific application needs. Regardless of the model used, system stability remains the top design priority. In real-world applications, issues such as time delay, sensor noise, or limited control loop bandwidth can cause unnatural oscillations or even instability in the virtual interaction. To ensure safe and consistent user experiences—especially in complex environments—modern haptic systems integrate not only accurate physical modeling but also techniques such as virtual damping and delay compensation within the control algorithms.

2.2 Overview of Tactile and Force Interaction Types and System Composition

Tactile interaction systems are mainly divided into two categories: tactile and kinesthetic [5]. Tactile interaction relies on nerve endings on the surface of the skin, which can sense details such as surface texture, small vibrations and temperature changes. It is usually achieved through high-resolution vibration motors, micro airbag arrays or piezoelectric materials. This type of feedback allows users to experience delicate touch such as key clicks and material roughness. The vibration feedback of the virtual keyboard of a smartphone is a typical application. Force interaction relies on deep tissues such as muscles and joints to sense movement and resistance, and reflect the macroscopic physical properties of objects such as weight, hardness, and elasticity. Through feedback on motion impedance or force, users can experience real interactive feelings such as pushing heavy objects, stretching springs or encountering obstacles. Force feedback is mostly achieved through a force feedback device at the end of a robotic arm, and is widely used in scenarios such as remote operation, surgical simulation, and virtual assembly. The combination of tactile and force is the key to achieving a highly immersive human-computer interaction experience.

The force feedback system that realizes these interactive experiences usually consists of three parts: sensors, drivers, and controllers [5]. The sensor is responsible for real-time acquisition of physical quantities such as force, displacement and speed, such as strain gauge force sensors and position encoders; the driver applies mechanical force to the user according to the control signal, usually using a motor or pneumatic device, whose performance affects the system response speed and force output accuracy; the controller, as the center of the system, processes sensor data in real time, adjusts the driver through algorithms such as PID and impedance control, and realizes closed-loop control. The three work together to enable users to obtain a stable, timely and realistic force experience in a virtual or remote environment. The deep coupling of software and hardware is the technical guarantee for modern force feedback systems to achieve high performance and immersion.

3. Analysis of the Correlation between Robot Control Theory and Force Feedback

3.1 Overview of the Basic Control Theory

Robot control theory provides a systematic theoretical framework for the design and optimization of force feedback tactile interaction systems. According to different control objectives, robot control strategies are mainly divided into three categories: position control, force control and hybrid control [6]. Position control takes the spatial position of the end effector as the main control target, and uses closed-loop feedback to make the robot trajectory accurately follow the preset path. This strategy is suitable for non-contact or weak contact scenarios, such as automated handling, point-to-point positioning, etc. Its advantages are high precision and fast response, but its flexible adaptability to complex environments is limited. Force control takes the interaction force between the robot and the external environment as the main control object, and achieves safe contact and force adaptation with the environment by adjusting the actuator output in real time. Typical scenarios include precision assembly, surface polishing and medical surgery. Force control has extremely high precision requirements for sensors and control algorithms, and can effectively prevent excessive squeezing or damage to sensitive targets. Hybrid control takes into account the dual goals of position and force, and usually uses position or force control in different spatial directions. For example, in assembly tasks, force control is used in the direction perpendicular to the assembly surface to protect the workpiece, and position control is used in the parallel direction to ensure positioning accuracy. These control theories not only ensure the accuracy and safety of the robot's body movement, but also form the basis for the force feedback tactile interaction system to achieve a high degree of realism and immersive experience. With the increase in environmental complexity, more and more high-end interactive systems tend to adopt multi-sensor fusion and adaptive hybrid control to achieve flexible and stable interaction in complex scenarios.

3.2 The Role of Force Feedback in the Master-Slave Control System

The master-slave control system, also known as the Master-Slave System, is widely used in applications such as remote operation and virtual reality and is one of the most representative force feedback technologies. The system consists of a master operation end, which is the user interface, and a slave execution end, the remote robot, and these two ends communicate with each other via network connections. In practice, the user issues commands through the master device, for example a force feedback joystick or handle, and the master’s motion data is transmitted to the slave in real time [7]. The slave robot then performs tasks such as remote surgery or operations in hazardous environments. Meanwhile, physical interaction forces such as tissue resistance or object collision forces experienced by the slave robot are sensed and sent back to the master device. The master-end force feedback device applies these forces to the user's hand, providing a tactile experience that feels "just like on-site operation."

Force feedback plays multiple key roles in the master-slave system. It greatly improves the remote operator's perception sensitivity and operation accuracy of the environment, especially in high-risk scenarios such as minimally invasive surgery and precision assembly, which helps to reduce operation errors and accidental injuries. Force feedback enables users to experience an immediate and natural interaction loop, significantly enhancing both immersion and control accuracy. However, in master-slave systems, issues such as network latency and packet loss can compromise the stability and safety of the force feedback loop. To address these challenges, researchers have developed a range of control strategies, including bidirectional impedance matching and delay compensation, aiming to maintain high-quality haptic interaction even under complex and unreliable communication conditions.

3.3 Impedance Control and Human-Robot Collaboration

Impedance Control is one of the core control strategies for achieving safe and efficient collaboration between humans and robots. The theory was proposed by Hogan in 1985, emphasizing the modeling of the physical interaction between the robot and the environment as "impedance", that is, the dynamic relationship between the applied force and the generated motion [8]. In practical applications, impedance control sets appropriate mechanical stiffness, damping and mass parameters to make the robot end show ideal elasticity or flexibility to external disturbances. For example, in collaborative assembly or co-operation and handling tasks, when humans and robots hold objects at the same time, the robot can adapt to the changes in human strength, automatically adjust its own movement, and achieve smooth and natural force-motion coordination.

The biggest advantage of impedance control is that it can take into account both operational flexibility and system stability. Compared with traditional rigid position control, impedance control allows a certain range of "errors" to better absorb the impact of environmental changes and user actions, thereby improving interaction safety. Studies have shown that impedance control has outstanding performance in reducing collision risks, preventing equipment damage, and enhancing collaborative experience, and has become the mainstream solution in modern collaborative robots (Cobot) and medical robots [9]. In recent years, intelligent methods such as adaptive impedance control and learning-based impedance adjustment have emerged, further improving the system's ability to adapt to complex and unknown environments, enabling robots to collaborate with humans more naturally and efficiently. Therefore, impedance control is not only a key support for theoretical innovation of force feedback tactile systems, but also an important direction for the development of future intelligent interactive robots.

4. Typical Application Scenarios and System Status

4.1 Force Feedback in Medical Robots

In the medical field, force feedback technology has become an indispensable key module for surgical robot systems and virtual surgical simulators. Remote minimally invasive surgical systems represented by the da Vinci surgical robot integrate high-precision force feedback devices on the main console[10], allowing surgeons to sense the interaction between instruments and tissues in real time when manipulating the robotic arm to perform tissue cutting, suturing and other operations, thereby greatly improving the safety and accuracy of the operation. Force feedback not only helps doctors distinguish tissue hardness and perceive unexpected resistance in complex operations, but also effectively prevents tissue damage caused by visual delay or misoperation [10]. Research on surgical simulators with force feedback can significantly improve the efficiency of doctors' surgical skill training, help beginners accumulate real tactile experience in a risk-free environment, and reduce the error rate of actual operations.

With the development of minimally invasive surgery and telemedicine, the demand for fine force perception continues to grow. Modern medical robot systems are constantly improving sensing and driving resolution, and introducing intelligent force control algorithms to support more complex and fine tissue operations. For example, flexible laparoscopic robots and neurosurgery robots rely on high-performance force feedback modules to ensure sensitive identification and safe intervention of tiny tissue structures. The introduction of force feedback technology has not only broadened the scope of application of remote and minimally invasive surgery, but also become the core driving force for the improvement of medical robot intelligence and human-machine collaboration capabilities.

4.2 Industrial Robots for Precision Assembly and Collaboration

In the fields of modern manufacturing and industrial automation, force feedback systems provide a solid technical foundation for the application of robots in tasks such as precision assembly, flexible grasping and human-machine collaboration. Compared with traditional pure position control, industrial robots with integrated force feedback can sensitively perceive and adjust the contact force between themselves and the workpiece, greatly improving assembly accuracy and product consistency. In high-precision fields such as electronic products or automobile manufacturing, operations such as plug-in and thread locking of tiny parts require robots to be highly adaptable in insertion force, position fine-tuning and anomaly detection. Robots using force/position hybrid control can adjust assembly actions in real time, effectively preventing damage and misassembly caused by part tolerances or position errors. In addition, industrial collaborative robots (Cobots) based on impedance control are widely used in collaborative handling or flexible production lines with people, which not only ensures operational safety, but also improves production efficiency and process flexibility [9]. In recent years, with the promotion of intelligent manufacturing and the concept of "Industry 4.0", industrial robots are gradually developing towards high-resolution multimodal perception, high dynamic response and intelligent self-adaptation. The force feedback system has become the core of achieving these goals, enabling robots to collaborate more naturally with complex environments and human workers to meet the personalized production needs of small batches and multiple varieties. As a result, force feedback technology has become the key support for high-end industrial robots to achieve precise operation and safe collaboration.

5. Conclusion

This study highlights the pivotal role of force feedback haptic technology in enhancing immersion, safety, and precision across various human-computer interaction scenarios. By integrating control theory, especially impedance control and hybrid force-position strategies, into the design of tactile systems, researchers and engineers can achieve stable, responsive, and natural interaction experiences in complex environments such as telemedicine, collaborative robotics, and precision assembly. The exploration of system composition, control strategies, and application cases emphasizes the importance of a solid theoretical foundation for advancing force feedback technology.

However, the current study is primarily conceptual and theoretical in nature. It does not include empirical validation through experimental testing or quantitative performance comparisons between different control models. In addition, most existing research is based on ideal or controlled environments, while real-world applications often involve unpredictable variables such as network delays, sensor noise, or user-specific behavioral factors. Future research should focus on developing adaptive control algorithms that respond dynamically to changing task conditions and user interactions. Furthermore, collaboration across disciplines such as robotics, neuroscience, and machine learning could contribute to more intelligent and realistic haptic systems. Establishing standardized benchmarks and practical evaluation frameworks will also be essential to support the broader application of force feedback in medical, industrial, and consumer contexts.

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