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Contact-Based Robotics: A Review of Tactile Sensing Applications

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Abstract. Robotic tactile and force sensing has emerged as a critical field for innovation, complementing traditional visual and radar systems to enhance a robot's ability to interact with its environment. This article offers a succinct summary of the last five years' developments in robotic touch sensing, grouping their uses into three main categories: improving object handling, allowing micro-scale jobs, and increasing movement agility. The review highlights how force sensors improve agility in legged robots and drones by providing direct physical information about terrain and surroundings, crucial for fast and complex movements. It also examines their vital role in micro-scale sensing, such as in robotic surgery and micro-assembly, where they offer essential force feedback that visual sensors alone cannot provide. The study concludes by outlining how these sensors—which are frequently paired with other sensory modalities—are essential to creating more complex object manipulation skills for applications like human-robot cooperation and household help. This overview aims to guide future research, underscoring the potential for tactile sensing to advance the capabilities of modern robotics further.

Keywords: Robotic tactile sensing, Force/torque sensor, Movement agility, Micro-scale sensing, Object manipulation

1. Introduction

With the development of robotics comes the increased use of sensors. It is a significant way for robots to gain information about their ontology status and surroundings [1,2]. Tactile/force sensors are still in their infancy. While visual sensors have become widely integrated into robots since the 1970s, advancements in tactile sensing have generally been achieved in the past thirty years [3,4]. The field of robotic tactile sensing continues to present significant opportunities for future innovation and development. This paper presents an overview of tactile sensing applications in robotics over the past five years, to offer guidance for future research. This paper divides tactile and force sensors into three significant categories: fast sensing for movement agility, micro-scale sensing and assisting manipulation of objects. It should be noted that this paper uses the terms interchangeably to highlight the broader role of contact sensing in robotics, even though tactile sensors and force/torque sensors are different—the former captures finer details like contact state and surface texture, while the latter measures overall force/torque magnitude and direction [5].

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2. Fast sensing for movement agility

One main reason for using force or tactile sensors in robotics is to gain sufficient information to support fast and agile terrain crossing [6]. Visual or radar sensors usually play a crucial role in robotic sensing. However, they have historically been best suited to obtaining a thorough overview of the whole environment rather than precisely detecting the physical characteristics of the terrain or the robot itself, such as hardness, roughness, pattern, and force distribution, among other things [7]. In comparison, force or tactile sensors can directly gain physical information about the interaction between the robot and the surroundings. Some of the most promising designs to achieve agile movement are legged automations and drones, which show many advantages compared to conventional wheeled robots [8, 9]. For this reason, the following section will focus mainly on these two types of robots.

Legs are the body sections of legged robots that experience the greatest force and contact information. Hoepflinger's invention incorporates force sensors into a legged robot's shanks [10]. His team arranged three force sensors to form an equilateral triangle. Through incurring small-scale oscillations, they successfully attained the force distribution in the shanks, which can be directly used to obtain the ground contact force distribution. In addition, since the sensors' upper and lower parts were secured with a fixed bolt, compressive and tensile forces can be attained. Researchers were able to distinguish between various surface materials and precisely estimate the terrain's form and concavity by examining the data obtained from the force sensors. Considering the limited training data and the poor quality of their sensors, using force sensors to improve terrain sensing shows much promise. In a much later investigation, Xu et al. recognised the advantages of Hoepflinger and his team's lightweight force-sensing resistors [11]. He noted that this type of sensor can be integrated into a robot without too many changes to the mechanical design. Although adding force/torque sensors at robotic joints can provide a fuller comprehension of all-directional forces, it will result in exceptionally high impact and inertia at the joints. Therefore, they designed a flexible multi-modal sole sensor, combining a piezoresistive sensor, a piezoelectric sensor and a triboelectric sensor. Specifically, they used different tactile sensors for different data sensing according to their distinct characteristics. For example, piezoelectric sensors sense the contact state due to their responsivity and signal decay. In contrast, triboelectricity sensors detect terrain information through the charge transfer process. They experimented with their sensor on surfaces of different slopes, surface materials, textures, and hardness, and found it showed excellent performance.

Force sensors are not as widely applied in drones as in legged robots. But in some situations, employing force sensors offers a number of benefits over relying just on radar or optical detection systems [12]. One prominent instance would be in congested spaces or in situations when sensors are blinded by low light or smoke [13,14]. It can also benefit several applications, such as environmental interaction and terrain mapping [12]. In a 2019 paper, Papachristos et al. provided a possible way to implement force sensors into drones [15]. His team created robotic antennae using force-bend sensors to sense their surroundings when they come into touch with them, drawing inspiration from biological characteristics such as bug antennas and cat whiskers. They successfully built a drone that can navigate in an unknown, confined environment while only relying on its IMU and antennas' feedback. This design is handy when drones encounter camera/LiDAR sensor failure. In 2025, Aucone et al. designed a drone with force-sensing abilities, using a different approach [12]. In their study, they need the drone to gain information about contact locations and interaction forces occurring over a large surface of their body. To achieve this, the team implemented a visual force sensor with a hollow arc-shaped design, an acrylic substrate, a silicone material membrane, and a USB camera with color filters. In addition to maintaining a low mass, this sensor can provide

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information about the drone's surroundings with an accuracy of 1.5mm and 0.17N. It can perform tasks such as detection and obstacle mapping.

Force sensors can be combined with machine learning in future studies. They will also play a crucial role in the multi-sensor automation system to enhance environmental sensing [16].

3. Micro-scale sensing

Force sensors also play a pivotal role in small-scale sensing. This is mainly because traditional visual sensors usually cannot guarantee micro-scale manipulation accuracy solely, and often rely on tactile sensors to ensure that the exerted force is within range [17].

One such application is in robotic-aided surgery. Many medical robots have aided surgeons with delicate tasks, such as the Da Vinci Robotic Surgical Systems and the KangDuo Surgical Robot [18]. However, these robots cannot direct the operators to respond directly to the contact state, force and texture. These instantaneous reactions are essential for doctors using surgical robots [19]. Research has shown that a lack of force feedback can increase the maximum exerted force on surgical instruments by approximately 40% [20]. In order to quantify the contact force without impairing surgical performance, Ebrahimi et al. developed a robotic surgical tool with a thin layer of Fiber-Bragg Grating force sensors on its surgical instrument [21]. They also designed two force controlling schemes that complement it. The researchers asked doctors to perform stimulated eye surgeries with the medical robot. These force controlling schemes, like free-hand surgery, can significantly reduce operational damage while maintaining user satisfaction.

Another important application is micro-scale assembling. In his 2004 paper Development of a tactile low-cost microgripper with integrated force sensor, Kemper noted that most traditional manipulation robots cannot conduct microscale work successfully, while most micro manipulation robots are only designed for specific tasks, due to their structural design [22]. He and his team designed a micro robot that is both highly accurate on a microscopic scale and satisfies a macroscopic workspace's requirements. They used a piezo stack as the actuator and measured the applied force from the input voltage and the resistance of the piezo stack. The small robotic gripper can manipulate tiny objects without damage and determine the contact state and force. In addition, these data can be used to calculate the object's size and elastic parameters. Experiments show that "it provides a resolution sufficient for most micromanipulation tasks". Approximately two decades later, Ma et al. designed a robotic system for micro assembling [23]. In contrast to Kemper's approach, their methodology incorporated a sensor fusion system that synergized visual and tactile modalities. The robotic system employed a dual micro-camera configuration to facilitate visual servoing during the assembly process, complemented by a six-axis micro force sensor for precise contact force measurement. They conducted simulations of real life and found that this design can satisfy microscale and macroscale assembly while maintaining high efficiency. Although the accuracy and structural design are not ideal, this robotic system is promising for future micro-scale assembling.

4. Manipulation & control

Force sensors are also widely used in the manipulation and control of objects. It is also a much simpler and easier way to detect contact [24]. Mao et al. discussed how the combination of force and visual sensors will play an important part in future domestic robots [25]. They point out that force sensors can no longer effectively locate objects when faced with increasingly difficult tasks. In contrast, visual sensors may be affected by light distraction or objects with similar shapes. By

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integrating force and visual perception into a cohesive system, the research team aims to showcase the potential of domestic robots to nimbly adjust to diverse tasks within future residential environments. They designed a flexible tactile sensor based on thermosensation, which can determine a wide range of information such as pressure, temperature, conductivity, slippage and pattern. In particular, the micro disturbances represent the surface patterns of the items, whilst the macro features of the sensor signals are utilised to ascertain the slippage condition and velocity. The stabilized voltage of the sensors can be used to determine the conductivity. Combined with visual sensors, they devised an autonomic manipulation system that enables the robot to locate, grasp and identify objects independently. During a stimulated task of cleaning a tabletop, it successfully determines objects with an accuracy of 94.3%. This design shows a promising application for future housework assistance.

In a 2022 paper, Gracia et al described how force sensors can assist human-robotic interference in surface treatment tasks [26]. Their primary concept is Human-Robot Interaction, which is helpful in situations when human intelligence is essential but direct human operation is not possible.The system they built contains active constraints to assist the human operators, and some parts are automated. To achieve this, researchers attached a force/torque sensor to the end effector of the surface treatment robot arm, and its information is used to ensure the contact angle and pressure are within range. By combining human operators and a robotic operation system, safety and efficiency can be assured.

Force sensors are also crucial in determining objects' physical characteristics. Previous robots usually used visual sensors to ensure that the shape was known at every moment to manipulate a deformable object. This works well in specific scenarios, but will malfunction when the environment is not suitable for visual sensing, such as when the object has a similar color to the background, or when the lighting is not sufficient. Sanchez et al. designed a system that compacts force sensors with a robotic manipulator [27]. This technology can estimate the characteristics and motions of a soft body while actively sensing its deformation. This, in turn, is used to assist the arm when manipulating the object. In their experiment, the sensor they used achieved an accuracy of centimeters. Table 1 shows that overview of tactile sensing use cases, basic principles, and representative robot applications.

Table 1. Overview of tactile sensing use cases, basic principles, and representative robot applications

Usages	Reasons	Applications
Fast Sensing for Movement Agility	Direct and instantaneous physical responses. Boost agility in visually impaired environments.	Legged robots with terrain analysis [10] Multi-modal sole sensor for walking surface data [11] Antenna force-bend sensors for drone navigation in confinement [15] Visual force sensors for drone obstacle mapping [12]
Micro-scale sensing	Precise force feedback beyond visual limits. Prevent damage in delicate operations.	Robotic surgical tools with force feedback [21] Microgrippers with piezo actuators for tiny object handling [22] Visual-tactile systems for micro/macro assembling [23]
Manipulation & Control	Accurate force control and contact detection. Human-robot collaboration.	Domestic robotic hand for grasping/cleaning [25] Force/torque sensors in arms for accurate surface treatment [26] Active force systems for deformable object manipulation [27]

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5. Conclusion

This paper reviews key innovations in robotic tactile sensing over the past five years, organized into three categories: rapid sensing for enhanced movement agility, micro-scale sensing, and sensing techniques that assist in object manipulation. This work aims to provide an overview rather than an exhaustive analysis of all existing developments. Consequently, it addresses only a subset of recent innovations. It does not offer in-depth evaluations, such as detailed structural data or systematic comparisons of the advantages and disadvantages of each design. Future studies can broaden tactile sensor applications across diverse settings, improve multi-modal integration, and use machine learning to refine tactile perception.

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