Tactile Sensing for Extreme Environments

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I. Introduction

From space to surgery to agriculture, in-the-wild robots must contend with unstructured environments and safety-critical situations. When visual perception alone falls short, tactile sensing is indispensable for successful contact-rich manipulation [1]–[3]. However, deploying touch sensors remains a major challenge—while new tactile sensors are proposed each year, few achieve widespread use outside the lab.

My research investigates **mechanically intelligent tactile sensing** for in-the-wild robots with an ambition to test them in a wide variety of field settings. My current work seeks to define design methods and principles that achieve: (i) environmental resistance to extreme conditions, (ii) compact and minimally intrusive for constrained spaces, and (iii) functional multimodal tactile perception for delicate field operations. This research spans hardware and software and is grounded in both theoretical modeling and real-world experiments. The following sections detail the related work and scientific contributions.

II. Resistant Designs for Extreme Environments

Space is one of the harshest environments for modern electronics—from extreme temperature swings ($-150°$ to 60°C in orbit), to radiation and electromagnetic interference, to intense vibrations at launch. In such conditions, robustness is not just a desirable feature but a necessity. However, for current tactile sensor designs, "robustness" is often ill-posed as solely material durability (e.g. how many cycles can a sensor pad withstand?). As a result, many current tactile designs fail to translate well to extreme field settings.

How can tactile sensors have inherent environmental resistance by design? By analyzing a tactile sensor by its transduction methods, we can study and therefore reduce potential points of failure in real-world deployments.

Many common methods exist to convert mechanical tactile stimuli into measurable signals. Capacitive and piezoresistive sensors [4]–[6], although sensitive and capable of direct measurements of mechanical deformation, need multiple sensing elements to measure both normal and shear forces increasing the complexity, number of interconnections, and fabrication process. Vision-based tactile sensors [7]–[10] have high spatial resolution, enabling the capture of textural information, but suffer from relative bulkiness and the potential degradation of the elastomer gel during data collection for the machine learning models. Tactile sensors based on magnetism [11]–[13] have recently gained attention for sensing simplicity and durability, but can suffer from strong cross-talk with complex recalibration processes as a result.

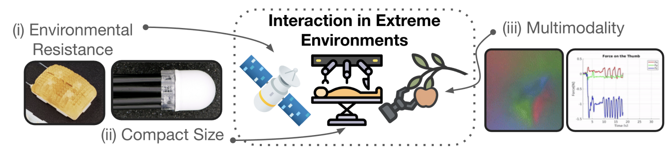

Fig. 1. Mechanically intelligent tactile sensor designs enable contact-rich interaction in extreme environments, from space to surgery to agriculture. Inset are tactile sensor designs towards those application areas: (i) FBG-based tactile sensor with inherent environmental resistance in space; (ii) fiber-based tactile sensor that achieves a compact size for endoscopic procedures; and (iii) multimodal output of visual-capacitive sensor for agricultural robotics.

Current Work: Our approach explores design principles that complement tactile transduction methods. In this case study, we explore a design principle of decoupling mechanical and electrical components to achieve passive sensing, eliminating the need for onboard wires or electronics and directly embedding robustness into the sensor design. For the motivating space application, we have developed a multiaxial sensor based on optical Fiber Bragg Gratings (FBGs), a well-established strain sensing technology in structural health monitoring and biomedical applications but with relatively unexplored potential in tactile sensing [14]. Unlike the prevalent transduction methods in robotic tactile sensing (i.e. capacitive, piezoresistive, magnetic, and optical transducers based on imaging), which are vulnerable to electromagnetic interference, radiation, and temperature, our sensor exploits FBG technology to be environmentally resistant by design. The sensing element is passive, with all processing electronics mechanically separated with negligible signal loss, leading to inherent robustness to extreme temperatures, radiation, and electromagnetic interference. While most fiber-based designs are single-axis strain sensors, for the tactile use case we achieve a multi-axis sensor using multiple FBGs on a single fiber through a three-dimensional routing scheme for high sensitivity. We were able to prototype and demonstrate a simple force-torque sensor design that performs with 96% accuracy compared to a commercial multiaxial force-torque sensor, while remaining lightweight, rugged, and adaptable to extreme environments. By design, this sensor can operate underwater and in space without modification. A version of the sensor is scheduled to launch to the International Space Station, a step towards space-ready tactile sensors.

III. Miniaturization for Constrained Spaces

Because camera technology has improved significantly (smaller, cheaper, and higher in resolution), new vision-based tactile sensors now match or even exceed the spatial resolution of a human fingertip [8], [10], [15] and are gaining in popularity. While significant progress has been made in enhancing reliability and durability, bulkiness remains a persistent challenge. Many existing designs result in oversized robotic fingertips, making them too cumbersome for the fine, precise interactions where tactile sensing would be most beneficial.

How can vision-based tactile sensors be compact by design? To address this problem, several designs have attempted to reduce the sensors to the size of a human fingertip. For example, dome-shaped, three-dimensional sensors such as OmniTact, GelSight360, and Insight have base diameters of $30\,\mathrm{mm}$, $28\,\mathrm{mm}$, and $40\,\mathrm{mm}$ respectively [16]–[18]. At the size of a large adult thumb or toe, they are not quite comparable to a slim fingertip. More importantly, the constraints on their designs preclude further miniaturization: an integrated base must package the associated electronics while maintaining compatibility with the optical path of the camera, or feature an arrangement of mirrors or prisms for directing light to an internal camera located a short distance away. However, similar to our previous sensor design, what if we were to remove all the electronics entirely? In this investigation, by decoupling optical elements from their electrical components, we can significantly shrink vision-based sensors.

Current Work: Extending our design principle of mechanical decoupling to visual transduction, we have constructed a new vision-based tactile sensor [19] that uses optical fiber bundles to invalidate the limitations on sensor size imposed by the camera optical path. With this design paradigm, we achieve a fingertip sensor about the size of an average woman's index finger, shown in Fig. 1, enabling new tasks that cannot be done with bulkier sensors. We characterize the sensor performance, achieving $5\,\mathrm{mN}$ minimum resolution in normal and shear force prediction and $0.22\,\mathrm{mm}$ spatial resolution. Moreover, we report cancer detection results on phantom and *ex vivo* biospecimens in-situ in the operating room, demonstrating the potential of ultra-slim tactile sensors inside anatomically constrained spaces. This technology could lead towards the robotic automation or remote teleoperation of surgical or in-body examinations performed by clinicians today.

IV. Multimodal tactile perception for soft delicate field operations

Soft fruit harvesting presents a unique challenge for robotic manipulation and tactile sensing. Unlike rigid industrial objects, delicate crops such as strawberries, require precise force control to prevent bruising while ensuring a firm grasp for successful picking. Despite active research in tactile-enabled fruit handling [5], [20], [21], most existing solutions rely on single-modality sensors. Real-world environmental variability—such as heat, wind, rain and sunlight—compounds the complexity.

How can modality design enable delicate field operations? Multimodal tactile sensors have seen rapid advancements, providing visual, temperature, and even audio, with encouraging improvements in robotic manipulation performance [9], [22]–[25]. For soft fruit handling, multimodality serves to add flexibility and safety factors. However, it is not yet conclusive which combination of tactile modalities provides the most useful information, or is most practical. Moreover, many of these sensors are limited to the lab due to their reliance on delicate elastomers and fragile electronics.

Current Work: From manipulation theory, knowledge of the contact force, location, and patch size produces kinematically force-closed grasping in dexterous manipulation [1]. Based on this understanding of a minimalist set of necessary tactile information, we have designed and developed a multimodal tactile sensor that integrates vision-based sensing with direct high-frequency force/torque measurements [26]. This approach to multimodality is suited for berry harvesting where high-frequency, direct force feedback ensures an adaptive grasp while visual feature extraction gives information on contact patch size, location, and fruit ripeness.

As with the previous two sensors, careful attention is paid to material and construction. Here, we combine the principle of mechanical decoupling with signal multiplexing to simplify this visual-capacitive sensor: only two PCBs are needed for normal and shear forces (as opposed to three normally), and one PCB for the camera [27]. This design is compact, lightweight ($30\,\mathrm{g}$ overall), and has simple wire routing (one USB cable routed internally).

Additionally, the sensor's fully-enclosed capacitive construction minimizes the need for bulky electronics and wiring, making it less vulnerable to moisture, vibrations, or debris, common in agricultural settings. Preliminary studies indicate that the sensor delivers highly accurate force readings, with a resolution of $0.002\,\mathrm{N}$, and can accurately classify object hardness, which is crucial for differentiating between ripe and unripe fruits. Field tests are planned for strawberry harvesting at a local farm, where we will assess the sensor's performance in a real-world agricultural environment.

V. Future Work

I envision a future where robots seamlessly and autonomously interact in the most extreme of environments. Mechanically intelligent tactile sensor design underpins this vision of robotic manipulation in extreme environments. Several challenges remain, and future work will focus on scaling and integration with intelligent processing.

One key future direction is to expand to other **translational research**, such as clinical trials during MRI scans and surgeries, or for nuclear disaster relief. These applications harness the unique capabilities of our sensors for environmental resistance (e.g. radiation exposure during MRI) and multimodality. Another key research direction is to study **low-data methods for tactile perception**—for years, the lack of robot data has been a bottleneck, and in many of these extreme environment applications, it is prohibitively expensive or even impossible to collect in-situ data. Areas of active effort include investigations in digital twins and mid-level features and representations that bridge the sim2real gap. Finally, before fully autonomous robots are possible, intermediate human-robot teaming is likely and necessary in several of these extreme applications. We wish to investigate **integrated visual-tactile-language models** for **human-collaborative** tasks like fruit handovers to farm workers or tool handovers to astronauts.

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