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REVIEW

A comprehensive review of tactile sensing technologies in space robotics



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Optical sensors;
Space robotics

Abstract This review explores the current state and future prospects of tactile sensing technologies in space robotics, addressing the unique challenges posed by harsh space environments such as extreme temperatures, radiation, microgravity, and vacuum conditions, which necessitate specialized sensor designs. We provide a detailed analysis of four primary types of tactile sensors: resistive, capacitive, piezoelectric, and optical, evaluating their operating principles, advantages, limitations, and specific applications in space exploration. Recent advancements in materials science, including the development of radiation-hardened components and flexible sensor materials, are discussed alongside innovations in sensor design and integration techniques that enhance performance and durability under space conditions. Through case studies of various space robotic systems, such as Mars rovers, robotic arms like Canadarm, humanoid robots like Robonaut, and specialized robots like Astrobe and LEMUR 3, this review highlights the crucial role of tactile sensing in enabling precise manipulation, environmental interaction, and autonomous operations in space. Moreover, it synthesizes current research and applications to underscore the transformative impact of tactile sensing technologies on space robotics and highlights their pivotal role in expanding human presence and scientific understanding in space, offering strategic insights and recommendations to guide future research and development in this critical field.

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1. Introduction

Human senses—vision, touch, smell, taste, and hearing—are vital for interacting with and understanding our environment. They enable delicate tasks, like handling fragile objects, through tactile feedback that guides applied force. Replicating this sensory capability in robotics is challenging, especially in unstructured environments like space where sensory input is limited. Tactile sensors provide essential feedback for precise manipulation without prior detailed object knowledge, converting physical interactions into measurable data such as

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texture, shape, temperature, pressure, and torque. In space robotics, they enable complex tasks like assembly, repair, and scientific experiments by offering critical feedback about the environment and objects handled.

Over the decades, tactile sensing in robotics has evolved significantly. Starting with basic tactile sensors in the 1970s, advancements led to tactile arrays for object recognition and multifingered robotic hands in the 1980s. The 1990s introduced “robotic skin” with sensor meshes for enhanced environmental sensing. Recent developments integrate tactile sensors with artificial intelligence, refining sensory processing and interaction capabilities. Fig. 1 illustrates this progression.

Tactile sensors are categorized based on their working principles, each with unique advantages and challenges:

- (1) Resistive sensors: Simple and robust; commonly used but limited in sensitivity and resolution.¹
- (2) Capacitive sensors: High sensitivity and proximity detection; ideal for touchscreens but sensitive to environmental changes.²
- (3) Piezoelectric sensors: High sensitivity and fast response; suitable for dynamic applications but can be expensive with signal degradation over time.³
- (4) Optical sensors: High resolution and immunity to Electromagnetic Interference (EMI); valuable for precision measurements despite complexity and cost.⁴
- (5) Magnetic sensors: Robust and EMI-immune; suitable for industrial controls but affected by magnetic interference.⁵
- (6) Thermal sensors: Detect temperature changes and force; useful in medical diagnostics but have slow response and are affected by ambient temperatures.⁶

- (7) Ultrasonic sensors: Contactless operation for distance sensing; costly and environmentally sensitive.⁷
- (8) Electrochemical sensors: Highly sensitive to chemical changes; used in biomedical applications but can degrade over time.⁸
- (9) Quantum Tunnelling Composite (QTC) sensors: Highly sensitive and durable; ideal for robotics but require further development.⁹
- (10) Barometric sensors: Stable and compact; used for environmental monitoring but indirectly measure force and are influenced by weather conditions.¹⁰

Research trends reflect growing interest and technological evolution in tactile sensors. Since 2015, publications have increased notably, highlighting advancements and expanding applications. Resistive sensors maintain steady interest due to simplicity and cost-effectiveness. Capacitive and piezoelectric sensors have grown significantly, driven by high sensitivity and precision. Optical sensors dominate publications, underscoring their critical role in high-resolution applications. Fig. 2 illustrates these trends from 2015 to 2024.

A review of recent literature reveals significant advancements in tactile sensing technologies. Table 1.^{11–23} presents selected survey and review articles illustrating the field’s breadth and depth. These studies cover topics from fundamental sensor design to specific applications in robotics and healthcare, highlighting rapid progress in materials science, sensor engineering, and integration methodologies. Such advancements expand the capabilities and applications of tactile sensing in robotics.

This review focuses on four tactile sensor types particularly relevant to space robotics: resistive, capacitive, piezoelectric,

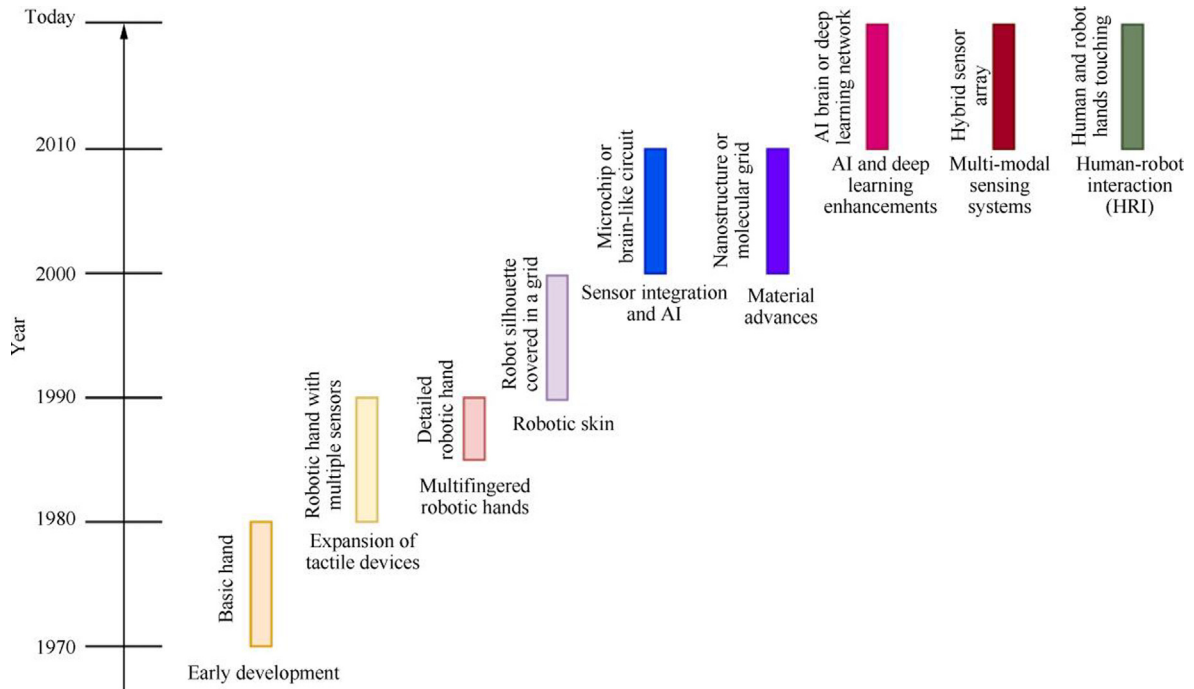


Fig. 1 Evolution of robotic tactile sensing.

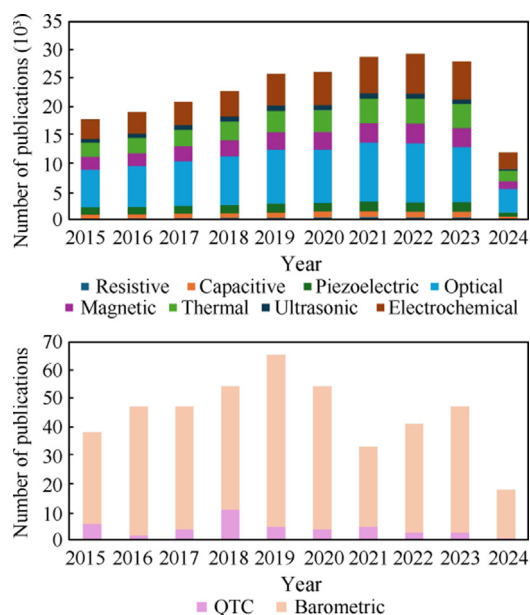


Fig. 2 Publication trends in tactile sensor research (2015–2024).

and optical. Valued for robustness and adaptability to extreme environments:

- (1) Resistive sensors offer reliability under harsh conditions, suitable for direct contact tasks like docking.¹
- (2) Capacitive sensors excel in proximity detection without contact, crucial for maneuvering near delicate objects.²
- (3) Piezoelectric sensors, known for rapid response and high sensitivity, are ideal for monitoring vibrations and dynamic forces in spacecraft.³
- (4) Optical sensors provide high-resolution feedback and EMI immunity, essential for precision tasks in space.⁴

This article provides a comprehensive overview of these technologies, detailing mechanisms, advantages, disadvantages, and applications, showcasing innovation in tactile sensing for space robotic systems.

The article is structured as follows (see Fig. 3 for an overview):

Section 1. Introduction: Highlights the importance of tactile sensing in enhancing robotic capabilities in space, discussing evolution and categorization based on working principles.

Section 2. Space Environment and its Impact on Tactile Sensing: Examines how space environments affect tactile sensing technologies, highlighting challenges like zero gravity, extreme temperatures, radiation, vacuum, magnetic fields, Electrostatic Discharge (ESD), and micrometeoroids.

Section 3. Comparative Analysis of Tactile Sensors: Analyzes resistive, capacitive, piezoelectric, and optical sensors, focusing on principles, variants, applications, and recent advancements in space exploration.

Section 4. Application of Tactile Sensors in Robotics: Discusses applications in space robotics, showcasing examples and projects effectively utilizing these sensors.

Section 5. Conclusion and Prospective: Summarizes insights and emphasizes the critical role and future potential of tactile sensing technologies in advancing robotic capabilities in space and demanding environments.

2. Space environment and its impact on tactile sensing

Space exploration presents unique challenges for tactile sensors due to the harsh and variable conditions of the extraterrestrial environment. As illustrated in Fig. 4, key factors affecting sensor functionality and durability include zero gravity, extreme temperature variations, radiation exposure, vacuum conditions, magnetic fields, ESD, and impacts from micrometeoroids and space debris.

These environmental factors necessitate specialized design considerations to ensure tactile sensors maintain high sensitiv-

Table 1 Comprehensive overview of survey and review articles on tactile sensing in robotics (2015–2024).

Study	Year	Key contributions
Shu et al. ¹¹	2024	Recent advancements in materials, designs, and applications of tactile sensors
Cheng et al. ¹²	2023	Discussed new materials and microstructures for capacitive sensors; reviewed applications in wearable devices and robotics
Qi et al. ¹³	2023	Discussed the use of PVDF materials in the development of flexible piezoelectric sensors
Qu et al. ¹⁴	2023	Overview of tactile sensing principles for soft grippers, applications, and sensing methodologies
Bayer ¹⁵	2022	Analyzed various MEMS sensors and their applications in robotics
Zhou et al. ¹⁶	2022	Investigated slip detection, grasp stability, and regrasp techniques
Nguyen and Lee ¹⁷	2021	Discussed the development of small-sized flexible tactile sensors for healthcare and AI applications
Won et al. ¹⁸	2021	Reviewed tactile sensing systems for tumor characterization using various sensing technologies
Yamaguchi and Atkeson ¹⁹	2019	Reviewed existing tactile sensors, modalities, and applications in robotics; emphasized vision-based tactile sensing
Chi et al. ²⁰	2018	Discussed diverse sensing mechanisms, material selection, and design considerations; analyzed sensor performance
Zou et al. ²¹	2017	Provided an overview of smart tactile systems, discussed signal processing technologies and transduction principles
Salim and Lim ²	2017	Evaluated recent trends in inkjet-printed tactile sensors, discussed materials and printing techniques
Cutkosky and Provancher ²²	2016	Reviewed various tactile sensors and transduction methods; discussed tactile information interpretation
Kappasov et al. ²³	2015	Reviewed computational techniques for tactile data exploitation; discussed tactile feedback-based control systems

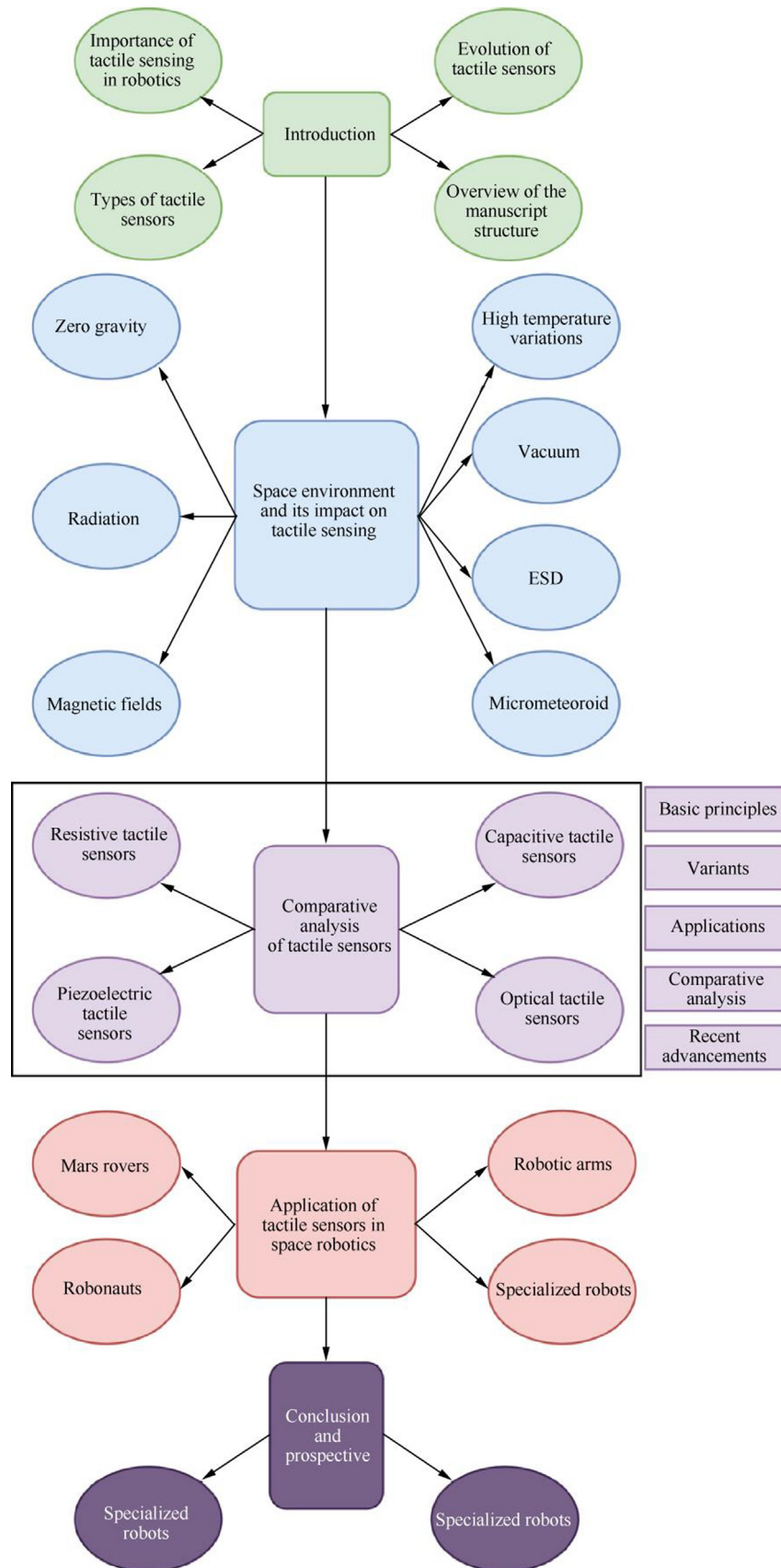


Fig. 3 Overview of manuscript structure, illustrating key sections and their interrelationships.

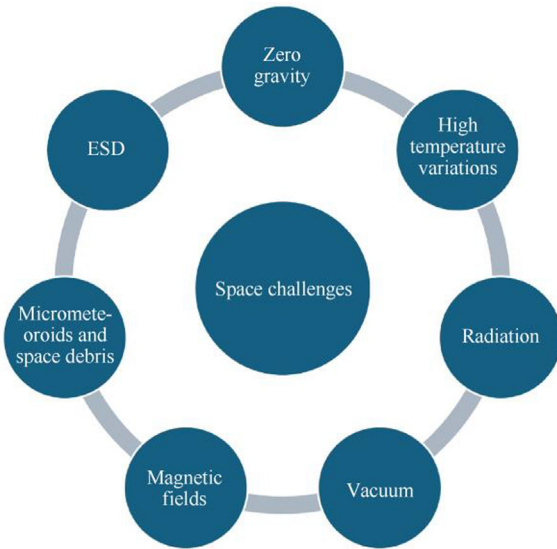


Fig. 4 Space environment challenges.

ity and reliability during space missions. Each of these challenges imposes specific constraints on sensor design and operation.

In the following subsections, we will explore how these space environment factors specifically impact tactile sensing technologies and discuss the unique design requirements they necessitate for space robotics applications.

2.1. Zero gravity

In microgravity, the absence of gravity alters object interactions, posing challenges for tactile sensors in robotics. Without gravitational pull, objects float, affecting consistent contact with sensor surfaces—crucial for accurate measurements. On Earth, a robotic gripper relies on an object's weight for consistent sensor contact; in space, this is not guaranteed, leading to potential inaccuracies.

Key challenges include:

- (1) Inconsistent contact pressure: Affects resistive and capacitive sensors reliant on consistent force, causing fluctuating readings.
- (2) Altered force distribution: Impacts piezoelectric sensors as mechanical stresses change without gravity, potentially reducing signal generation.
- (3) Modified light patterns: Affects optical sensors; deformation under touch alters light reflection/refraction, requiring advanced calibration.

To address these challenges, researchers have developed several adaptation strategies:

- (1) Advanced materials and structures: Monajemi and Ayazi et al.²⁴ used HARPSS technology to fabricate microgravity capacitive accelerometers with vertically corrugated electrodes (Fig. 5), reducing mechanical noise. The design achieved high sensitivity (4.5 pF/g) and low noise (0.95 $\mu\text{g}/\sqrt{\text{Hz}}$), suitable for precise space measurements.

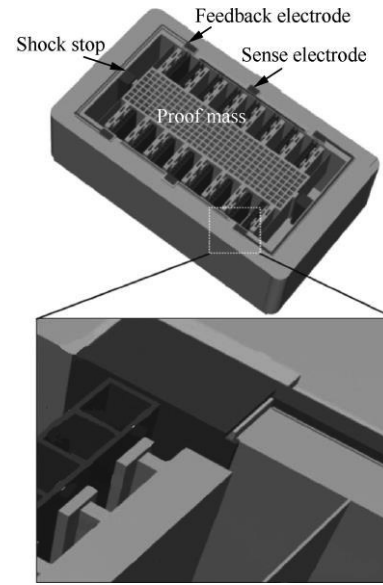


Fig. 5 HARPSS accelerometer design.²⁴

- (2) 3D printing techniques: Hendrich et al.²⁵ embedded low-cost force sensors into 3D-printed robotic components, creating customizable sensors ideal for microgravity. These detect forces as low as 0.02 N and can be tailored for specific applications.
- (3) Active force application: Wang et al.²⁶ developed a six-dimensional force sensor using a shunt three-legged parallel configuration (Fig. 6). Incorporating neural network-based data decoupling and gravity compensation algorithms, the sensor achieved high accuracy with minimal errors (<1%).
- (4) Material selection: Jiang et al.²⁷ utilized silver nanoparticle ink and La-doped BaTiO₃ to create high-sensitivity, flexible capacitive sensors suitable for space. The sensors showed high sensitivity (0.12 nF/%RH), fast response times, and stable performance under varying conditions.
- (5) Gravity compensation algorithms: Fukushima et al.²⁸ proposed a least squares method for online gravity and friction compensation in haptic systems, reducing torque estimation errors by over 50%, enhancing tactile sensitivity in microgravity.

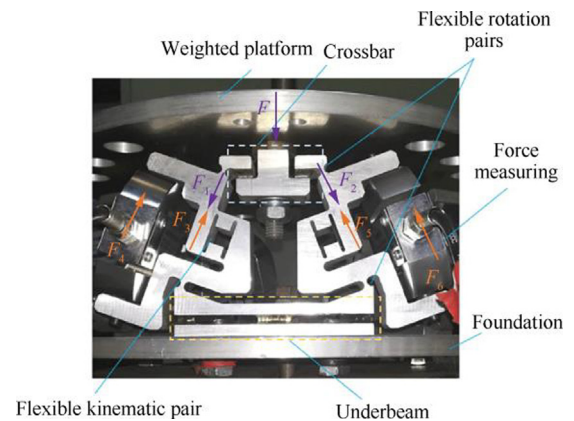


Fig. 6 Structure of six-dimensional sensor.²⁶

For optical tactile sensors, several strategies have been developed that can be categorized into the following:

- (1) Total Internal Reflection (TIR) structures: Sakamoto and Kawano²⁹ enhanced sensor robustness by ensuring internal light reflection using TIR, eliminating the need for external coatings.
- (2) Miniaturized optical components: Gindele and Novotny³⁰ developed miniaturized spectrometer modules with high diffraction efficiency, achieving spectral resolutions below 7 nm. Passive temperature compensation mitigated wavelength shifts due to thermal expansion.
- (3) Adaptive calibration techniques: Chen et al.³¹ employed deep domain adaptation for force calibration in optical sensors, reducing prediction errors by over 10%, allowing sensors to maintain accuracy without extensive labeled datasets.

These advancements improve tactile sensor performance in microgravity, but further research is needed to enhance reliability, energy efficiency, and integration of multiple sensing modalities.

2.2. High temperature variations

Space environments exhibit extreme temperature fluctuations affecting tactile sensing systems. In Low Earth Orbit, temperatures range from -170°C to $+123^{\circ}\text{C}$,³² and lunar surfaces vary from -248°C to $+119^{\circ}\text{C}$.³³ These extremes impact sensors:

- (1) Resistive Sensors: Temperature alters material resistance, causing inaccurate force measurements; high temperatures increase thermal noise, low temperatures induce brittleness.
- (2) Capacitive Sensors: Dielectric properties change with temperature, affecting sensitivity and accuracy.
- (3) Piezoelectric Sensors: Temperature impacts piezoelectric coefficients, altering signal generation in response to stress.
- (4) Optical Sensors: Thermal expansion or contraction misaligns optical components, affecting measurement accuracy.

Key strategies to mitigate these challenges:

- (1) Thermal Control Techniques:
 - (A) Multi-Layer Insulation (MLI): Mesforoush et al.³⁴ showed MLI sheets with aluminized Kapton layers effectively provide thermal shielding by minimizing heat transfer. Kapton blankets have lower effective emittance than PET, reducing thermal gradients and enhancing sensor reliability.
 - (B) Radiative Heat Exchange Surfaces: Lv et al.³³ emphasized surfaces that maximize heat dissipation through thermal radiation. Variable emissivity radiators adjust heat rejection capacity, crucial for managing thermal loads varying up to 200°C during missions.

- (C) Active Thermal Management System (TMS): Wang et al.³⁵ discussed TMS using mechanical components like pumps and fans for dynamic heat dissipation. Active TMS can handle peak loads (e.g., up to 100 kW in aircraft), providing precise thermal control essential for electronic reliability.

- (2) Advanced Materials and Technologies:

- (A) Encapsulated Annealed Pyrolytic Graphite (APG): Kugler³⁶ demonstrated that APG within an aluminum shell enhances thermal conductivity, reducing operating temperatures by $2\text{--}5^{\circ}\text{C}$ and offering weight reductions compared to traditional materials.
- (B) Thermal Interface Materials (TIMs): Sayer et al.³⁷ explored TIMs incorporating micro and nano-scale technologies to improve thermal conductivity and reliability, even under radiation exposure. Despite increased thermal contact resistance due to radiation, advanced TIMs ensure effective heat dissipation.
- (C) Near-Junction Thermal Transport (NJTT): Bar-Cohen et al.³⁸ highlighted NJTT techniques focusing on reducing thermal resistance near electronic junctions with high heat fluxes ($> 10\text{ kW/cm}^2$), crucial in the vacuum of space.

- (3) Advanced Sensing Solutions: Ravelo Arias et al.³⁹ showed that Ru-based sensors (Fig. 7) exhibit exceptional stability under total ionizing dose irradiation, with less than 0.5% resistance variation, ensuring accurate temperature measurements in harsh space conditions.

These strategies aim to maintain tactile sensor accuracy and reliability across extreme temperatures in space. Further research is needed to develop sensors that perform consistently throughout the entire temperature spectrum experienced in space missions.

2.3. Radiation

Space radiation poses significant challenges for tactile sensing systems. Radiation sources include solar proton events, cosmic rays, and particles trapped in the Van Allen belts.⁴⁰ These can cause lattice displacement, ionization effects, cumulative damage, and single-event effects in electronic components.⁴¹ The specific effects on tactile sensors include:

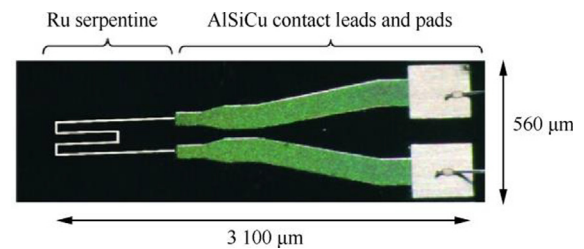


Fig. 7 Layout of Ru-based thin film temperature sensor.³⁹

- (1) Resistive Sensors: Radiation alters electrical properties of resistive materials, changing resistance-force relationships and leading to inaccurate measurements.
- (2) Capacitive Sensors: Ionizing radiation causes charge buildup in dielectric materials, affecting capacitance and leading to sensor drift or failure.
- (3) Piezoelectric Sensors: Radiation degrades the crystal structure of piezoelectric materials, reducing sensitivity or altering properties.
- (4) Optical Sensors: Radiation causes darkening of optical materials, reducing light transmission and affecting accuracy.

Key strategies to address radiation challenges:

- (1) Shielding Techniques:
 - (A) Passive Radiation Shielding: Steffens et al.⁴² highlighted materials like aluminum and Carbon Fiber Reinforced Plastics (CFRP) with metallic coatings for effective radiation blocking. A 3 mm aluminum slab can stop protons up to 12.5 MeV. For higher-energy protons and secondary radiation, layering high- and low-Z materials (e.g., CFRP with tungsten or tantalum coatings) enhances protection. W-enhanced polyethylene provides up to a 30% total dose reduction compared to aluminum, with up to 45% weight savings.
 - (B) Optimized Sensor Placement: Kogan et al.⁴³ emphasized embedding sensors beneath radiation shielding to reduce stress concentrations and maintain performance. Proper placement ensures sensors operate within elastic ranges under varying conditions (−80 °C to 120 °C).
- (2) Advanced Materials:
 - (A) Silicon-On-Insulator (SOI) and Silicon-On-Sapphire (SOS) Technologies: Simoen et al.⁴⁴ demonstrated superior radiation tolerance of SOI and SOS compared to bulk silicon, due to the buried oxide layer isolating active silicon. SOI devices showed less than a 5% threshold voltage shift after exposure to 1 Mrad (Si). SOI FinFETs exhibited minimal voltage shifts even after 500 krad exposure. SOS technologies offer greater immunity due to sapphire's electrical isolation, protecting against single-event upsets.
 - (B) Radiation-Resistant Capacitive Sensors: Jiang et al.⁴⁵ developed capacitive edge sensors (Fig. 8) for space telescopes operating under high radiation (up to 1.6×10^9 rad over ten years). Despite exposure, sensors maintained relative error between 0.85% and 7.65% in displacement detection (6 nm to 20 μ m range). The design uses alumina ceramic substrates and multilayered metallic coatings (gold and copper) to protect against degradation.

These advancements demonstrate progress in developing radiation-resistant tactile sensing technologies for space robotics. However, challenges remain in developing sensors

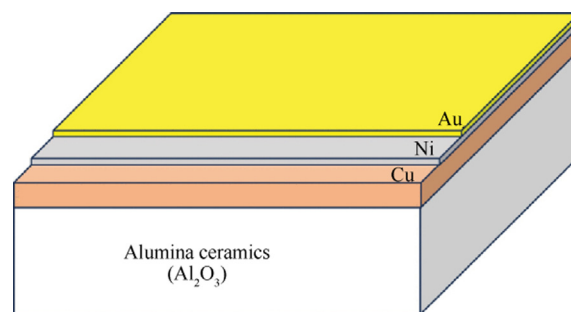


Fig. 8 Structural composition of capacitive edge sensor's plates.⁴⁵

that can maintain long-term stability and accuracy under prolonged radiation exposure. Future research should focus on:

- (1) Developing new materials with inherent radiation resistance for use in tactile sensors.
- (2) Improving radiation-hardened electronic components specifically for tactile sensing applications.
- (3) Designing sensor systems with built-in redundancy and self-calibration capabilities to compensate for radiation-induced degradation over time.

2.4. Vacuum

In the vacuum of space, the absence of atmospheric pressure alters material behavior, presenting challenges for tactile sensors. Without atmospheric pressure, materials can outgas and deform unpredictably, affecting sensors that rely on stable properties and clean conditions.

Key challenges include:

- (1) Outgassing: Materials release trapped volatile compounds in a vacuum, which can condense on optical surfaces or mechanical components. This contamination affects optical and mechanical tactile sensors by reducing signal clarity and increasing noise.
- (2) Material deformation: Lack of pressure can cause materials to expand or contract unpredictably, altering mechanical properties. This impacts resistive and piezoelectric sensors, leading to calibration shifts and reduced accuracy or failure.
- (3) Heat dissipation: In a vacuum, heat cannot dissipate through convection, placing thermal stress on all sensor types. This can cause overheating, material degradation, or misalignment, especially in optical sensors requiring precise alignment.

Key strategies to address these challenges:

- (1) Vacuum Bake-Out: Szmolka et al.⁴⁶ demonstrated that traditional vacuum bake-out effectively reduces outgassing in space hardware, particularly silicone-based materials (Fig. 9). Under vacuum conditions ($< 1 \times 10^{-5}$ mbar) at 85 °C, mass loss due to outgassing (Total Mass Loss (TML)) for silicone adhesives like Si-I was about 2.2% after 72 h, compared to 1.9% in nitrogen purged bake-out. Vacuum bake-out efficiently removes volatile compounds, reducing contamination risks.

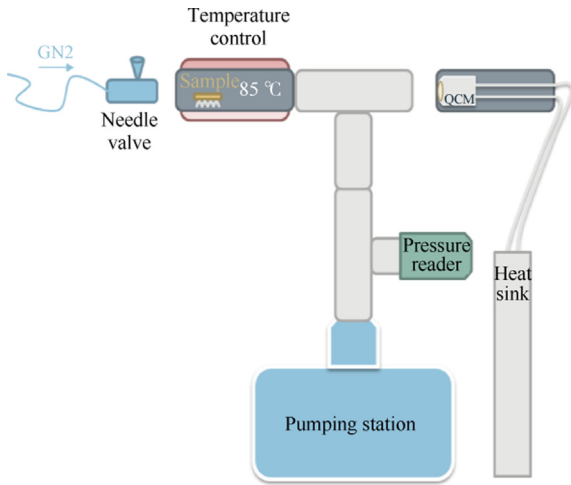


Fig. 9 Schematic diagram of traditional vacuum bake-out method.⁴⁶

Additionally, for more space-sensitive materials such as Si—II, the vacuum bake-out method resulted in a Residual Mass Loss (RML) of 0.14%, while purged bake-outs (Fig. 10⁴⁶) showed a higher RML of around 0.06%. Vacuum bake-outs demonstrated superior efficiency in removing volatile outgassing species, especially when compared to ambient conditions, which were less effective at mitigating offgassing.

- (2) **Material Analysis and Selection:** Roussel et al.⁴⁷ studied outgassing behavior of aerospace materials like Black Kapton® and NuSil CV4-2946. For Black Kapton®, TML was 1.2%, with contaminants like water and N, N-dimethylhydroxylamine released at various temperatures. NuSil CV4-2946 had TML around 0.8%, with contaminants identified as octane and trimethylsilyl. Understanding outgassing rates is essential for selecting low-outgassing materials to prevent contamination of sensitive equipment.

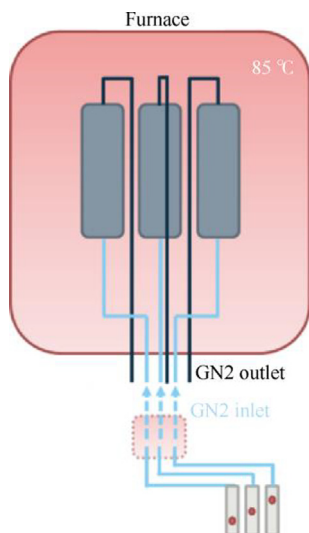


Fig. 10 Schematic diagram of purged bake-out method.⁴⁶

- (3) **Treatment Optimization:** Mao et al.⁴⁸ explored methods to reduce volatility of silicone rubber composites. Post-heating at 200 °C for 4 h effectively reduced volatile components, resulting in TML of 0.2% and Collected Volatile Condensable Material (CVCM) of 0.02%, well below ASTM E595 limits (TML ≤ 1%, CVCM ≤ 0.1%). This method preserves mechanical properties while removing volatiles, optimizing materials for space environments.

Understanding and mitigating outgassing effects are crucial for ensuring the reliability and longevity of tactile sensors and spacecraft systems in the vacuum of space.

2.5. Magnetic fields

In space, magnetic fields—especially in regions like Earth’s magnetosphere—can induce unwanted currents in electronic systems through EMI, posing significant challenges for tactile sensing in robotics. Magnetic fields interfere with electronic signals, reducing sensor accuracy and reliability.

Key challenges include:

- (1) **Induced currents:** Affect resistive and capacitive sensors by generating unwanted currents within circuits, causing signal distortion or noise and leading to inaccuracies in force and pressure measurements.
- (2) **EMI:** Impacts piezoelectric and optical sensors by distorting or degrading signals, causing incorrect readings or sensor failures in critical applications.
- (3) **Magnetic susceptibility:** Influences overall sensor operation; sensors containing ferromagnetic materials may malfunction in strong magnetic fields, leading to misalignment or malfunction, particularly in precision applications.

Key strategies to address these challenges:

- (1) **Advanced Materials:**
 - (A) **Magnetic shielding materials:** Sani et al.⁴⁹ indicated that ferrites effectively mitigate EMI due to their low eddy current loss and strong magnetic permeability, achieving reflection losses as low as −56.9 dB at 8.32 GHz with a 3.6 mm thickness.
 - (B) **High-performance Microwave Absorption Materials (MAMs):**⁴⁹ Carbon-based composites like graphene and Carbon Nanotubes (CNTs) provide superior EMI shielding by converting electromagnetic waves into heat. Ferrite and CNT composites achieve reflection losses up to −55.5 dB at 13.4 GHz with a 1.5 mm thickness, suitable for spacecraft applications where weight and efficiency are critical.
 - (C) **Radar Absorbing Materials (RAMs):**⁴⁹ Carbon fibers and nanotubes are used in RAMs for stealth technology, offering excellent EMI shielding across a broad frequency range while maintaining low density.
 - (D) **Nano-silver decorated textiles:** Stupar et al.⁵⁰ developed textiles coated with silver nanoparti-

cles, achieving significant EMI shielding effectiveness (up to 57.25 dB in the 5–12 GHz range) and increased conductivity, ideal for lightweight space applications.

(2) System Design:

- (A) FPGA-based systems: Zhang et al.⁵¹ proposed using Field-Programmable Gate Arrays (FPGAs) for internal processing to reduce reliance on EMI-susceptible external controllers (Fig. 11). Their system operated at 150 MHz, achieving improved stability with less than 5 W power consumption.
- (B) Aluminum alloy housings:⁵¹ Integrating aluminum housings shields sensitive electronics from EMI, protecting internal circuitry from electromagnetic fields.
- (C) Enhanced communication buses:⁵¹ Modifying communication buses (e.g., Controller Area Network (CAN) bus) with driver circuits and filtering mechanisms (common-mode inductors, transient suppression diodes) mitigates noise and improves data transmission in EMI-prone environments.

These advancements demonstrate progress in developing EMI-resistant technologies for space robotics. Continued research is crucial for enhancing the reliability of tactile sensing systems in the complex magnetic environment of space.

2.6. Micrometeoroids and space debris

Micrometeoroids and space debris pose significant risks to spacecraft due to their extremely high velocities (3 to 18 km/s). Even tiny particles can cause severe damage upon impact, affecting sensitive components like tactile sensors, which rely on precise and delicate parts. Unlike Earth, where atmospheric resistance mitigates such threats, space lacks this protection, increasing the risk and potentially contributing to the Kessler syndrome—a cascade of collisions amplifying further impacts.⁵²

2.6.1. Direct environmental challenges

- (1) High-velocity impacts: Can puncture or fracture sensor surfaces, causing immediate failures in resistive, capacitive, piezoelectric, and optical sensors.

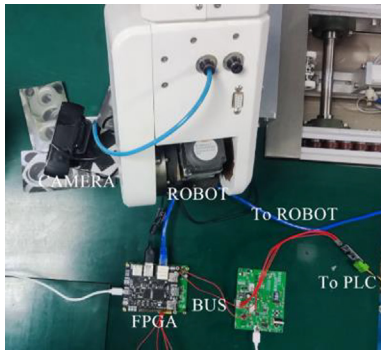


Fig. 11 Testbed setup of FPGA-based robotic system for EMI mitigation.⁵¹

- (2) Structural integrity and damage: Repeated impacts lead to cumulative structural damage (pitting, cracking, deformation), compromising sensor precision and functionality.
- (3) Shock and vibration effects: Impacts generate shock-waves and vibrations that misalign sensor components, disrupt calibration, and degrade tactile feedback accuracy, especially in piezoelectric and optical sensors.

2.6.2. Specific environmental factors for tactile sensors

- (1) Sensitivity to surface damage: Tactile sensors require pristine surfaces for accurate measurements; debris impacts damage these surfaces, leading to erroneous readings.
- (2) Impact on sensor calibration and accuracy: Vibrations and shocks cause misalignments and calibration drift; recalibration may not be feasible in space, compromising data accuracy.
- (3) Material degradation and fatigue: Repeated impacts cause material fatigue, leading to cracks and fractures, reducing sensor lifespan and reliability.

Key strategies to address these challenges:

- (1) Advanced Shielding Technologies:

Stuffed Whipple Shield: Pai et al.⁵³ described an advanced multi-layer shield consisting of a thin outer bumper, a porous filler (foams or fabrics), and a rear wall to absorb impact energy. Effective against impacts from 3 to 18 km/s, it breaks up and disperses debris, preventing severe damage. Metallic foams reduce debris kinetic energy by up to 40%. In tests at 7 km/s, the shield achieved 25% better debris fragmentation and 50% reduction in rear wall damage compared to traditional shields.

- (2) Material Enhancements:

Multi-layer configurations: Christiansen et al.⁵⁴ highlighted combining aluminum, Nextel ceramic fabric, and Kevlar layers for superior protection. Nextel disrupts incoming projectiles, improving energy absorption by 30% compared to aluminum. Kevlar slows and disperses debris fragments, reducing their velocity by up to 50% after passing through Nextel.

- (3) Self-Calibrating Mechanisms:

Real-time recalibration algorithms: Maye et al.⁵⁵ proposed self-calibrating algorithms enabling sensors to recalibrate after shocks and vibrations from impacts, ensuring continued accuracy without manual intervention. The algorithm reduces recalibration errors by 30%–50%, maintaining high precision even after multiple debris impacts.

- (4) Sensor Redundancy:

Redundant sensor arrays: Rovetta et al.⁵⁶ emphasized implementing redundancy to ensure reliability. If one sensor is damaged, others maintain operational integrity. In their setup with the 6 DOF manipulator “Gilberto,” redundancy

in sensors and control systems allowed accurate task performance despite partial failures.

These strategies enhance the resilience of tactile sensors against micrometeoroids and space debris. Ongoing research is essential to improve protection methods, sensor robustness, and maintain mission-critical operations in harsh space environments.

2.7. ESD

ESD poses a significant threat to spacecraft components, including tactile sensors, due to the accumulation and sudden release of static electricity in the low-humidity and high-radiation environment of space.⁵⁷ ESD occurs when charged particles build up on surfaces and then discharge, potentially damaging sensitive electronics. On Earth, grounding and controlled environments mitigate ESD risks, but in space, these safeguards are less effective.

Key challenges posed by ESD include:

- (1) Hard failures: ESD events can cause permanent damage to the circuitry of resistive and capacitive sensors, leading to complete sensor failure, especially without adequate protection.
- (2) Soft failures: ESD can induce temporary malfunctions or reduce the accuracy of piezoelectric sensors, causing incorrect readings or performance degradation. While not immediately fatal, these issues can compromise mission-critical operations.
- (3) Latent failures: Repeated ESD exposure can gradually degrade electronic components in optical sensors, leading to failures over time and shortening the lifespan of tactile sensors.

Key strategies to address ESD-related challenges include:

- (1) Environmental Controls:
 - (A) Humidity control: Maintaining optimal humidity levels (30%–70%) during sensor manufacturing, assembly, and testing reduces static charge buildup. Low humidity (< 30%) increases ESD risk significantly, while higher humidity can lower ESD risk by up to 50%.⁵⁸
 - (B) Ionizers:⁵⁸ Utilizing ionizers in assembly areas neutralizes static charges on non-conductive surfaces, reducing surface charge by up to 90% when strategically placed.
 - (C) Proper grounding⁵⁸: Grounding workstations and personnel prevents static electricity buildup during handling of sensitive electronics.
- (2) Circuit-Level Protection:
 - (A) Clamping circuits and TVS diodes: These components protect circuits by diverting excess energy during an ESD event. TVS diodes respond in nanoseconds, clamping voltage to safe levels (< 30 V), and can handle ESD events up to 15 kV.⁵⁸
 - (B) Fuse elements: Fuses physically break the circuit when excessive current flows, isolating sensitive components from ESD-induced surges. They have been tested to withstand currents up to 30 A.⁵⁸

- (C) Layout optimization: Minimizing parasitic inductances and ensuring optimal grounding paths reduce ESD vulnerability. Improved layouts can reduce ESD failure rates from 5% to 3%.⁵⁸
- (D) Capacitive filtering: Placing decoupling capacitors near critical integrated circuits filters high-frequency noise and mitigates voltage spikes, reducing ESD impact by 30%–50%.⁵⁸

(3) Advanced Materials:

ESD-protective composites: Nisticò et al.⁵⁹ highlighted the use of inorganic fillers like metallic particles (silver, copper, aluminum) and carbon-based materials (CNTs, graphite) to create composites that dissipate static electricity effectively.

- (A) Silver (Ag): High electrical conductivity allows maintaining low resistivity levels with minimal filler content (percolation threshold as low as 0.1 vol%). Silver nanowires provide sheet resistance as low as 10 Ω /sq, ideal for robust ESD protection in weight-sensitive applications.
- (B) CNTs and graphite: High aspect ratios offer low percolation thresholds, enhancing conductivity while maintaining structural integrity. CNTs provide volumetric resistivity below 10^{-3} Ω -cm.
- (C) Ceramic fillers: Materials like boron nitride and silicon carbide improve electrical conductivity, thermal stability, and mechanical properties, offering dual benefits of thermal management and ESD protection.

By incorporating these strategies, ESD risks can be mitigated, enhancing the reliability and longevity of tactile sensing systems in the challenging electrostatic environment of space. Continued research is essential to develop advanced protection methods suitable for space robotics.

3. Comparative analysis of tactile sensors

This section explores four primary types of tactile sensors used in space exploration: resistive, capacitive, piezoelectric, and optical. Each sensor type employs distinct principles to detect and measure forces, enabling robots to interact accurately with their environment. The section delves into the applications and potential of these sensors in space technology, highlighting their roles in enhancing robotic systems for space missions.

3.1. Resistive tactile sensors

Resistive tactile sensors play a crucial role in space exploration and satellite operations. These sensors, which operate on the principle of pressure-induced changes in electrical resistance, have evolved significantly since their conceptual origins in the work of Du Moncel.⁶⁰ Modern space-grade resistive sensors often incorporate advanced conductive polymers and sophisticated electrode matrices, reflecting substantial progress in materials science and sensor technology tailored for extraterrestrial environments.

3.1.1. Basic principles

Resistive tactile sensors operate on the principle that the electrical resistance of a material changes in response to applied

pressure. Typically, a conductive polymer is sandwiched between two electrodes (Fig. 12). When force is applied, the contact area between the polymer and electrodes changes, altering the resistance. The sensor's resistance R is given by

$$R = R_V + R_S \quad (1)$$

where R_V is the volume resistance, and R_S is the surface resistance varying with the applied load. The surface resistance R_S can be modeled as

$$R_S = R_{S0} \left(\frac{A_0}{A(F)} \right) \quad (2)$$

where R_{S0} is the initial surface resistance, A_0 is the initial contact area, and $A(F)$ is the contact area under force F .

3.1.2. Variants of resistive tactile sensors

Fig. 13 illustrates the taxonomy of space-adapted resistive tactile sensors:

- (1) Single-Layer Sensors: Utilize a single conductive layer; simple and energy-efficient but have limited spatial resolution.

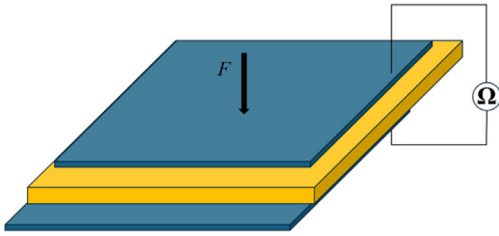


Fig. 12 Resistive tactile sensor.

- (2) Two-Layer Sensors: Consist of two conductive layers separated by a spacer; offer high-resolution sensing suitable for control panels and robotic manipulation.
- (3) Conductive Polymer Sensors: Use polymers whose resistance changes under compression; provide detailed feedback for advanced robotics but require protection against radiation and temperature extremes.
- (4) Textile-Based Sensors: Incorporate conductive fibers into textiles; flexible and adaptable for integration into astronaut suits and health monitoring systems.

3.1.3. Applications in space exploration

Resistive tactile sensors enhance various aspects of space missions (Fig. 14):

- (1) Robotic Grippers for Satellite Servicing: Provide precise force feedback for handling delicate components.
- (2) Planetary Exploration Rovers: Assist in terrain interaction and sample collection.
- (3) Astronaut Gloves: Improve dexterity and tactile feedback during Extravehicular Activities (EVAs).
- (4) Docking Systems: Aid in precise alignment and connection of spacecraft modules.
- (5) Health Monitoring Systems: Monitor astronauts' physiological parameters through suit-integrated sensors.

3.1.4. Comparative analysis of resistive tactile sensors for space applications

Table 2 provides a comprehensive comparison of resistive tactile sensors for space applications, highlighting key attributes that influence their performance and suitability for various space-based tasks.

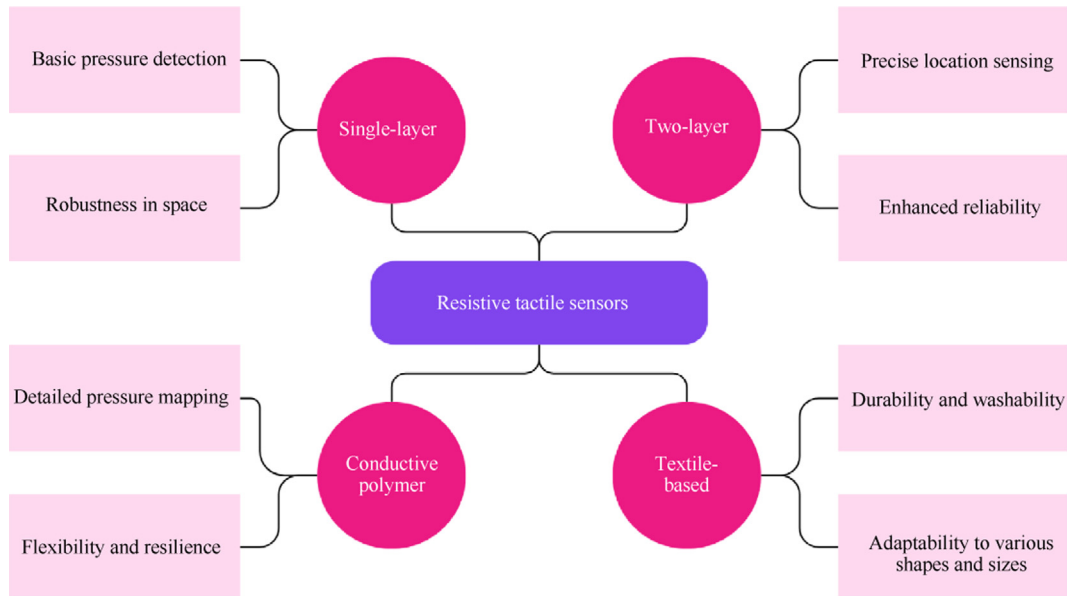


Fig. 13 Taxonomy of space-adapted resistive tactile sensors.

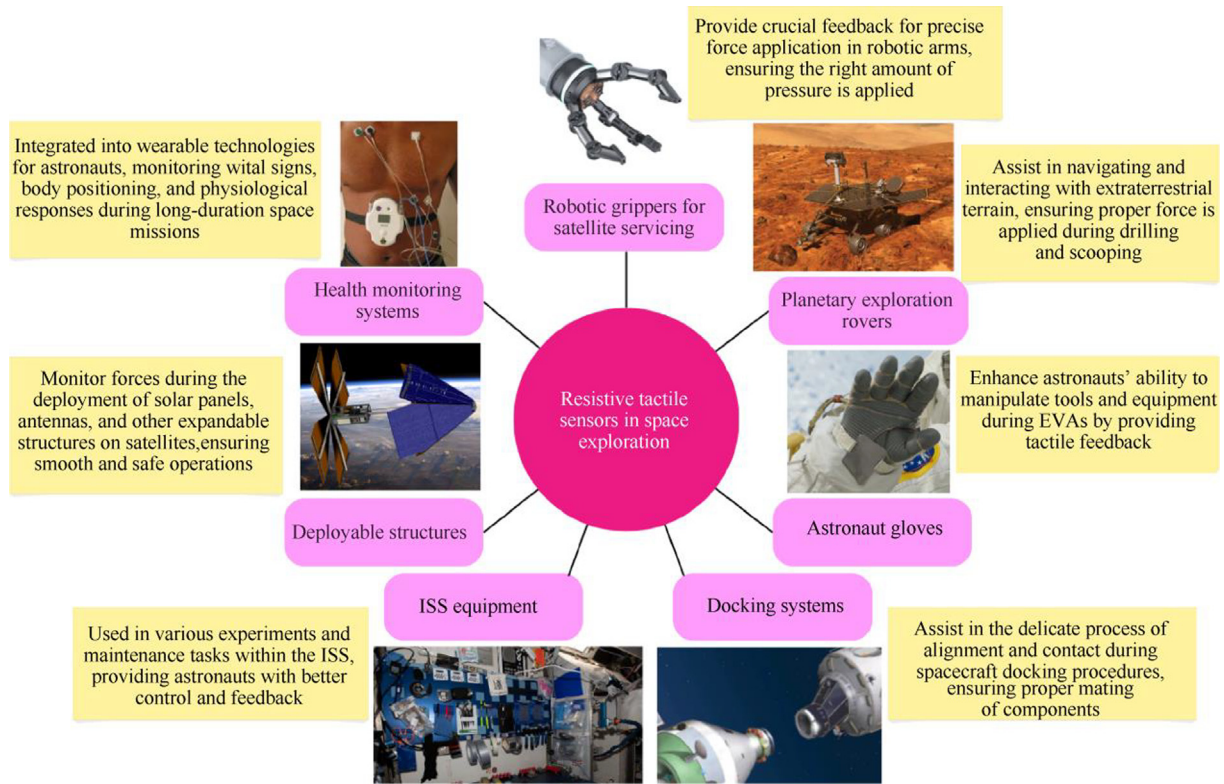


Fig. 14 Applications of resistive tactile sensors in space exploration.

3.1.5. Recent advancements

(1) Material Innovation:

- (A) **Durable Composites**: Development of silver nanowire-PDMS composites improves mechanical and electrical properties for harsh space environments.⁶¹
- (B) **Flexible Designs**: Crossed-wire approaches enhance adaptability for robotic hands in unstructured space environments.⁶²
- (C) **Self-Healing Materials**: Biomimetic sensors increase durability for long-term space missions.⁶³
- (D) **Large-Scale Integration**: Shape-conforming arrays improve safe interaction capabilities for space robots.⁶⁴
- (E) **Adaptive Sensing**: Tunable sensing arrays adjust force detection for varying gravitational conditions.⁶¹

(2) Flexible and Stretchable Sensors:

- (A) **Adaptable Sensing Surfaces**: Microwave transmission-line sensors are highly flexible and suitable for wide-area applications in space suits or habitat monitoring.⁶⁵
- (B) **Durability and Sensitivity**: Interlinked microcone resistive sensors offer enhanced sensitivity and stability, potentially useful for robotic manipulators in space.⁶⁶
- (C) **Integration with Space Equipment**: Core-shell fiber tactile sensors are stretchable and applicable to complex geometries of space vehicles or equipment.⁶⁷

- (D) **Environmental Resilience**: Metal nanowire network sensors maintain conductivity under strain, suitable for varying gravitational conditions.⁶⁸

(3) Integration with Other Sensing Technologies:

- (A) **Multimodal Sensing**: Dual-stream integrated sensors combine pressure and temperature sensing with deep learning for accurate detection of complex stimuli.⁶⁹
- (B) **Intelligent Systems**: MXene-ZnO memristor multimodal sensors enable in-sensor computing, potentially reducing processing load on space-based systems.⁷⁰
- (C) **3D Configurable Arrays**: Electronic whiskers provide multimodal sensing of temperature, stiffness, and texture, applicable for intricate space robotic manipulations.⁷¹
- (D) **Customizable Platforms**: Modular tactile sensor arrays offer flexible, customizable designs adaptable to various space robotic applications.⁷²

These advancements address key challenges in space robotics, focusing on durability, flexibility, adaptability, and integration of tactile sensors in extreme space conditions. The innovations enhance the reliability and performance of tactile sensing systems during extended space missions.

3.2. Capacitive tactile sensors

Capacitive tactile sensors are sophisticated devices that utilize the principles of electrical capacitance—the inherent capability

Table 2 Comparative analysis of resistive tactile sensors for space applications.

Attribute	Single-Layer	Two-Layer	Conductive polymer	Textile-Based
Sensing Principle	Resistance change in single layer	Contact between two conductive layers	Polymer resistance change when compressed	Resistance change in conductive threads
Material Used	Space-grade conductive ink/polymer	Radiation-resistant conductors, vacuum-compatible spacer	Radiation-hardened conductive polymers	Space-grade textiles with conductive fibers
Sensitivity	Moderate	High	Very High	Variable
Response Time	Fast	Quick	Slower than metal-based	Varies with textile properties
Operating Conditions	Extreme space environments	Wide range, including temperature extremes	Requires special formulation for space	Adaptable to EVA conditions
Key Advantage	Simple, energy-efficient	High-resolution sensing	Detailed feedback for robotics	Flexible, suit-integrable
Key Challenge	Limited spatial resolution	Complex manufacturing	Radiation and temperature protection	Long-term space durability
Space Application	Basic pressure sensing	Control panels, robotic manipulations	Advanced robotics, sample collection	Health monitoring, EVA enhancement

of a system to hold an electric charge. These sensors have found significant applications in space exploration and spacecraft systems due to their reliability, sensitivity, and adaptability to extreme environments.⁷³

3.2.1. Basic principles

Capacitive tactile sensors operate on the principle of electrical capacitance—the ability of a system to store electric charge. The most common form is the parallel-plate capacitor, consisting of two conductive plates separated by a dielectric material (Fig. 15). The capacitance C is given by

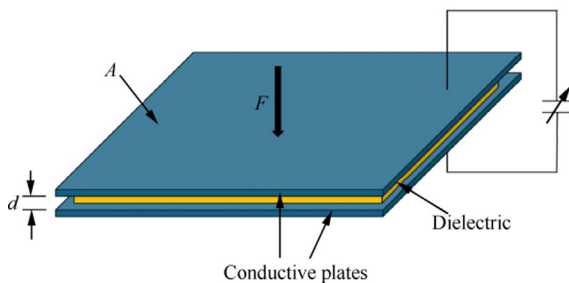
$$C = \epsilon_r \epsilon_0 \frac{A}{d} \quad (3)$$

where ϵ_0 is the permittivity of free space, ϵ_r is the relative permittivity of the dielectric material A is the area of the plates, d is the distance between the plates.

Changes in touch, pressure, or proximity alter the capacitance by changing A , d , or ϵ_r . Advanced capacitive sensors for space applications incorporate complex geometries and materials to enhance functionality and durability in harsh environments.

3.2.2. Variants of capacitive sensors

Capacitive tactile sensors have evolved into various types tailored for space exploration. Fig. 16 illustrates six key types that have emerged as pivotal in advancing space robotics:

**Fig. 15** Operational diagram of a capacitive tactile sensor.

- (1) Surface Capacitive Sensors (SCS): Use a single conductive layer; suitable for basic touch detection.
- (2) Projected Capacitive Sensors (PCAP): Feature a dual-layer design enabling multi-touch capabilities, essential for complex manipulations.
- (3) Self-Capacitance Sensors: Utilize a single electrode; provide high sensitivity for detecting subtle environmental changes.
- (4) Mutual Capacitance Sensors: Use an electrode grid for precise multi-touch detection, facilitating intricate human-robot interactions.
- (5) Transcapacitive Sensors: Detect interactions through non-conductive materials, valuable for unknown substances on alien terrains.
- (6) Load Capacitive Sensors: Measure force through surface deformation, critical for manipulating objects in varying gravitational fields.

3.2.3. Applications of capacitive tactile sensors in space exploration

Capacitive tactile sensors are crucial in various space applications (Fig. 17):

- (1) Robotic Manipulation: Enable fine force control and object recognition in robotic arms and grippers, enhancing dexterity in microgravity.
- (2) Rovers: Assist in terrain analysis and sample collection by detecting changes in ground composition and providing feedback on sample characteristics.
- (3) Space Suits: Improve glove sensors and health monitoring, offering better tactile feedback and vital signs monitoring during EVAs.
- (4) Docking and Assembly: Provide proximity detection and assembly feedback for automated docking procedures and in-space assembly tasks.
- (5) Debris Detection and Avoidance: Used in systems to detect and track space debris, enabling debris mapping and surface inspection.
- (6) Adaptive Gripping Systems: Create adaptive grippers that adjust based on the object's properties, preventing slips.

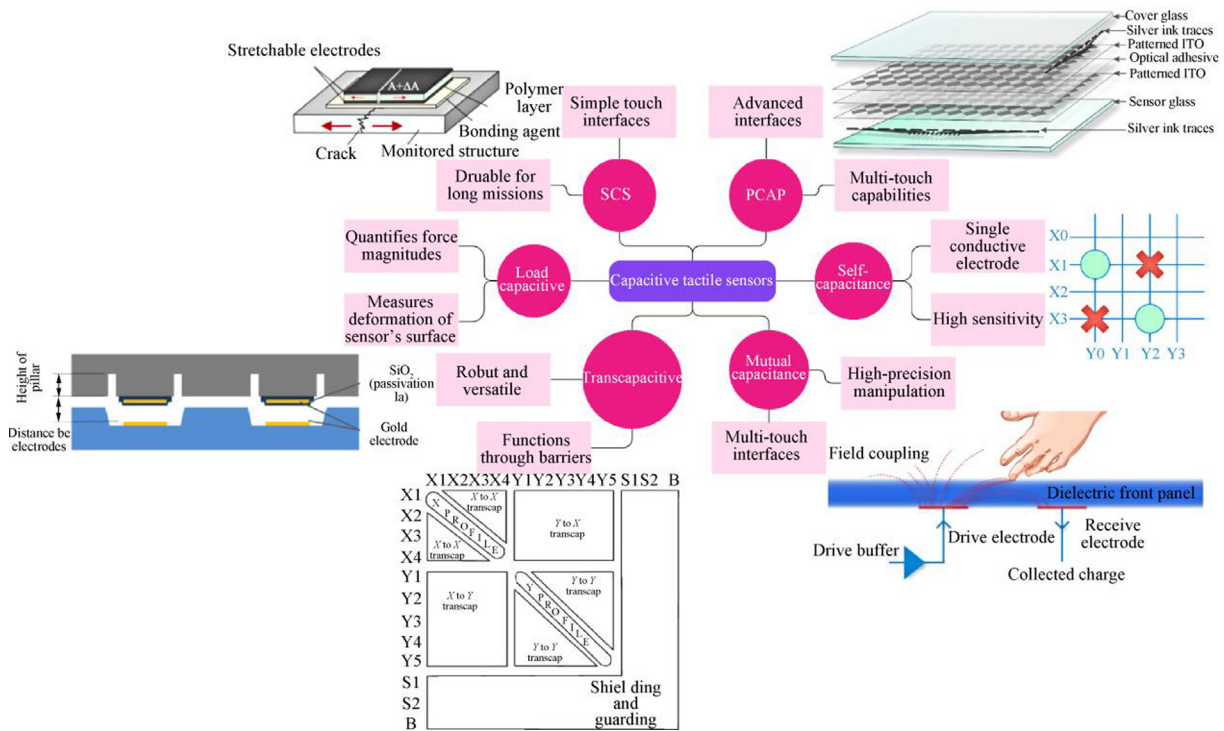


Fig. 16 Taxonomy of capacitive tactile sensors.

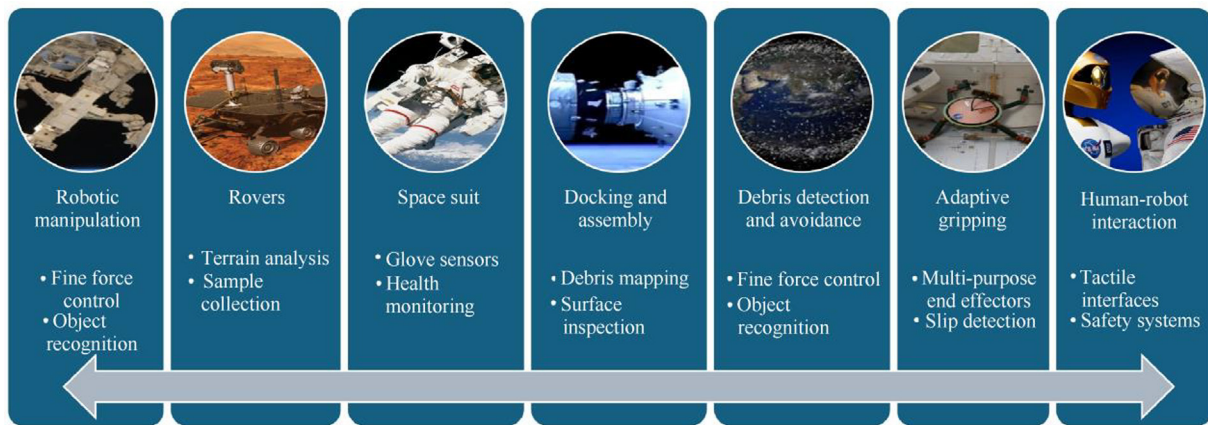


Fig. 17 Applications of capacitive tactile sensors in space exploration.

- (7) Human-Robot Interaction: Facilitate intuitive interfaces and ensure safe operation of robots around human crew members.

3.2.4. Comparative analysis

Table 3 provides a detailed comparison of capacitive tactile sensors, emphasizing attributes like sensing mechanisms, materials, sensitivity, response time, and operating conditions.

3.2.5. Recent advancements

- (1) Material Innovation:

(A) Durable Composites: Zinc-aluminum layered double hydroxides, MXene, and silver nanowire composites enhance sensitivity through electrostatic interactions, useful for precise manipulations in space.⁷⁴

Table 3 Comparative analysis of capacitive tactile sensors.

Attribute	Surface capacitive	Projected capacitive	Self-capacitance	Mutual capacitance	Transcapacitive	Load capacitive
Sensing principle	Change in electric field near single layer	Capacitance changes across conductive grid	Capacitance changes between electrode and ground	Capacitance changes between two electrodes in grid	Capacitance changes through dielectric medium	Capacitance changes due to deformation under weight
Material used	Single conductive layer on glass/plastic	ITO layers separated by dielectric	Single electrode with dielectric coating	Conductive grid layers with dielectrics	Electrodes with dielectric overlay	Flexible dielectric between conductive plates
Sensitivity	High for single touch	Very high, multi-touch capable	High for single-touch at distance	High, detailed multi-touch	Moderate to high through overlays	Sensitive to pressure changes
Response time	Fast	Fast	Fast	Quick	Varies, generally fast	Moderate, depends on dielectric elasticity
Operating conditions	Indoor, less effective with gloves	Adaptable, works through overlays	Limited outdoor use	Effective across various environments	Effective in harsh conditions	Best in controlled environments
Key advantage	Cost-effective, durable	High resolution, complex gestures	Simple design, hover detection	Accurate multi-touch tracking	Durable, operates through thick overlays	Accurate force measurement
Key disadvantage	Single-touch only	Complex manufacturing	Prone to ghost touches	Requires sophisticated processing	May need environmental calibration	Sensitivity can vary with long-term use
Potential space application	Basic interfaces in spacecraft	Advanced control panels	Proximity detection in airlocks	Multi-touch interfaces in space stations	Robust sensors for EVA equipment	Force-sensitive controls, tactile feedback in robotics

(B) Flexible and Adaptive Designs: Microstructured porous materials and hemispheric structures offer multiaxial, multimodal sensing adaptable to complex surfaces, suitable for space suit gloves or robotic end-effectors.⁷⁵

(C) Advanced Manufacturing: 3D-printed elastomeric foam-based dielectrics allow rapid production of flexible e-skins, customizable for specific space missions.⁷⁶

(D) High-Performance Materials: Microconformal graphene electrodes provide ultrahigh sensitivity and tunability, enhancing tactile feedback in space operations.⁷⁷

(2) 3D Touch and Force Sensing:

(A) Multidimensional Interaction: Combining dynamic force sensing with capacitive touch enables nuanced human-machine interfaces, useful for controlling space equipment.⁷⁸

(B) Capacitive Servoing: Real-time pose estimation improves physical interactions, applicable for robotic arms in space operations.⁷⁹

(C) Spatial Force Decoupling: Decoupling forces in 3D allows precise force measurements from multiple directions, crucial for manipulating objects in microgravity.⁸⁰

(D) Advanced Sensor Design: Highly ordered porous dielectric structures improve sensitivity and response times across broad pressure ranges, suitable for varying gravitational conditions.⁸¹

(E) Embedded Sensing in Robotic Systems: 3D-printed tactile sensors integrated into robotic hands enhance sensory feedback and simplify manufacturing for space-specific robotic end-effectors.⁸²

(3) Integration with Other Sensing Technologies:

(A) Hybrid Sensing Systems: Capacitive-triboelectric hybrid sensors maintain high sensitivity and broad linearity range, useful for diverse tactile sensing needs in space environments.⁸³

(B) Advanced Robotic Integration: Capacitive sensors with SVM algorithms enable precise object recognition, crucial for autonomous space robotics.⁸⁴

(C) CMUTs in Robotic Grippers: Capacitive Micro-machined Ultrasonic Transducers combine proximity and tactile sensing, enhancing manipulation capabilities in space.⁸⁵

(D) Intelligent Sensory Systems: Dual-stream deep learning frameworks accurately detect and differentiate complex stimuli like pressure and temperature changes, applicable for space environmental monitoring.⁶⁹

(E) Multifunctional Platforms: Ionic hydrogel-based sensors in soft robotic grippers provide nuanced force control and high-accuracy object recognition, suitable for delicate operations in microgravity.⁸⁶ Kirigami-inspired multimodal sensors offer strain-insensitive and versatile sensing capabilities, adaptable to various space applications.⁸⁷

These advancements address the need for versatile, reliable, and intelligent sensing systems in space. The integration of multiple sensing modalities and advanced data processing techniques enhances the potential for more sophisticated and autonomous robotic operations, improving capabilities in tasks ranging from satellite servicing to planetary exploration.

3.3. Piezoelectric tactile sensors

Piezoelectric tactile sensors represent a unique class of sensing devices that exploit the piezoelectric effect to convert mechanical stress into electrical signals. This inherent property makes them particularly valuable for detecting and measuring dynamic forces, pressures, and vibrations in space robotics applications.

3.3.1. Basic principles

Piezoelectric tactile sensors convert mechanical stress into electrical signals based on the piezoelectric effect. When a piezoelectric material (e.g., lead zirconium titanate (PZT)) is deformed by an applied force F , it generates an electrical charge due to the alignment of internal dipoles (Fig. 18.⁸⁸). This charge accumulation results in a measurable voltage proportional to the force.

Additionally, deformation can alter the material's thickness, causing a shift in its resonance frequency f ⁸⁹:

$$f = f_0 + \Delta f \quad (4)$$

$$\Delta f = -\frac{f_0 \Delta d}{d_0} \quad (5)$$

where f_0 is the initial resonance frequency, Δf is the change due to the applied force, Δd is the thickness deformation, d_0 is the original thickness.

3.3.2. Variants of piezoelectric sensors

Fig. 19 illustrates five key types adapted for space applications:

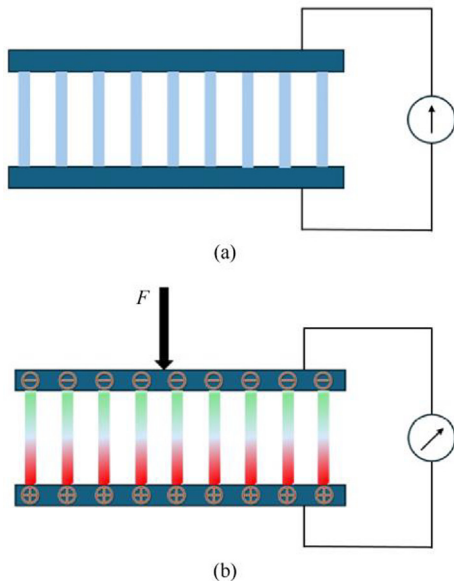


Fig. 18 Operating principle of a piezoelectric tactile sensor:⁸⁸ (a) Resting state; (b) Upon the application of force F .

- (1) Direct Piezoelectric Sensors: Generate electrical charge from mechanical stress; ideal for simple, power-limited applications.
- (2) Reverse Piezoelectric Sensors: Induce mechanical stress via applied electrical fields; useful for precise actuation in robotics.
- (3) Shear Piezoelectric Sensors: Measure lateral forces; crucial for robotic grippers in microgravity.
- (4) Composite Piezoelectric Sensors: Combine piezoelectric materials with other substrates for enhanced flexibility and robustness; valuable for structural health monitoring.
- (5) Film-Based Piezoelectric Sensors: Offer flexibility and high response; suitable for integration into astronaut suits or flexible robotic components.

3.3.3. Applications in space exploration

Piezoelectric tactile sensors are essential in various space applications (Fig. 20):

- (1) High-Precision Force Sensing: Measure dynamic forces and vibrations for robotic operations and object manipulation.
- (2) Impact Detection and Monitoring: Detect micrometeoroid impacts and landing forces on spacecraft.
- (3) Acoustic Sensing and Communication: Used for seismic activity detection and obstacle detection.
- (4) Tactile Sensing in Extreme Temperatures: Operate in high-temperature missions (e.g., Venus) and extremely cold environments.
- (5) Precision Control in Space Manufacturing: Provide feedback in space-based 3D printing and microassembly.
- (6) Health Monitoring of Space Structures: Detect early signs of material fatigue in spacecraft.
- (7) Energy Harvesting: Convert vibrations into supplementary power for sensor networks.
- (8) Pressure Mapping for Planetary Exploration: Analyze soil properties and measure ice shell thickness.
- (9) Fluid Dynamics Studies in Microgravity: Monitor fluid movement in fuel tanks and life support systems.

3.3.4. Comparative analysis of piezoelectric tactile sensors

Table 4 presents a detailed comparison of piezoelectric tactile sensors. The analysis considers sensing mechanisms, materials, sensitivity, response time, and operating conditions, providing a comprehensive view of their applicability.

3.3.5. Recent advancements of piezoelectric tactile sensors

- (1) Material innovation for space-compatible piezoelectric tactile sensors

① Novel Piezoelectric Composites:

- (A) Pyroelectric Polyelectrolyte Brushes: Offer potential for energy harvesting and biosensing in space environments.⁹⁰

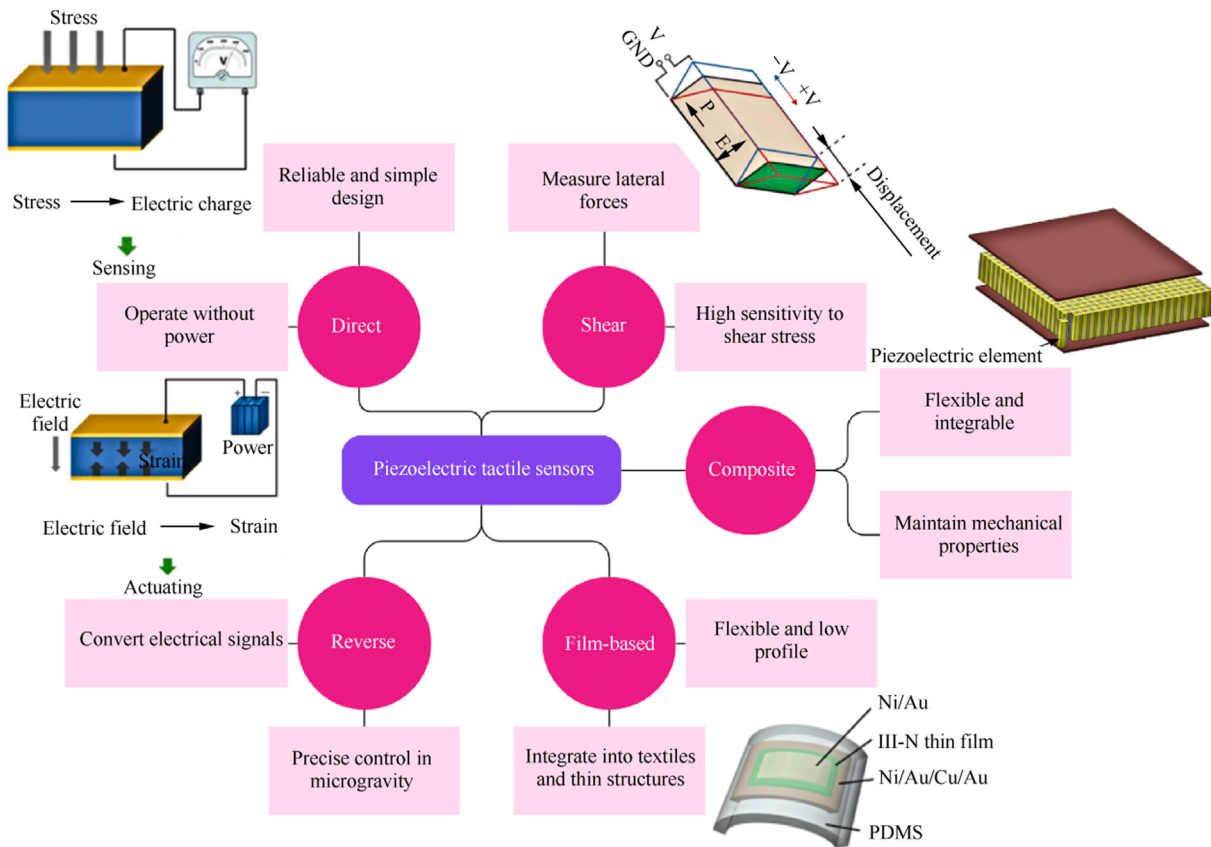


Fig. 19 Taxonomy of piezoelectric tactile sensors.

- (B) PVDF-Based Nanocomposite Films: Optimized nanoparticle size enhances piezoelectric properties, suitable for space-grade sensors.⁹¹

② Space-Compatible Robotic Skin Materials:

- (A) Self-Sensing Piezoelectric Robot Skin: Provides cost-effective tactile sensing for safe human-robot interaction in space.⁹²
- (B) BaTiO₃ Nanoparticle-Reinforced Polyurethane: Improves piezoelectric properties for robot skin in space applications.⁹³

③ Advanced Sensor Designs:

- (A) Water-Filled Acoustic Waveguides: Enable simultaneous force and location sensing with bending insensitivity, ideal for space suit gloves or flexible robotic appendages.⁹⁴
- (B) Double-Layer MWNT-PVDF Composite: Mimics human tactile receptors, potentially enhancing space robotic manipulation.⁹⁵

④ Multifunctional Materials:

Ferrocene-Based Organic Molecule Crystals: Provide ultra-sensitive strain sensing for flexible space suit sensors.⁹⁶

Edge Mode in Piezoelectric Ceramics: Offers high-sensitivity tactile sensing for precise robotic control in space.⁹⁷

(2) Flexibility and stretchability for space-compatible piezoelectric tactile sensors

① Durable Flexible Designs:

- (A) Crack-Free Metal-Polymer Interfaces: Enhance reliability of flexible piezoelectric devices in harsh space environments.⁹⁸
- (B) Core-Shell Structured Fibrous Piezoelectric Mat: Improves mechanical robustness while maintaining sensitivity, suitable for space suit integration.⁹⁹

② Bio-Inspired Structures:

Soft-Rigid Hybrid Design: Inspired by bivalve shells, enhances flexibility and damage tolerance, crucial for withstanding space debris impacts.¹⁰⁰

③ High-Performance Composites:

- (A) Stretchable Polymer Composites with Ferroelectric Ceramics: Balance flexibility with high piezoelectric performance, applicable for adaptive space robotics.¹⁰¹

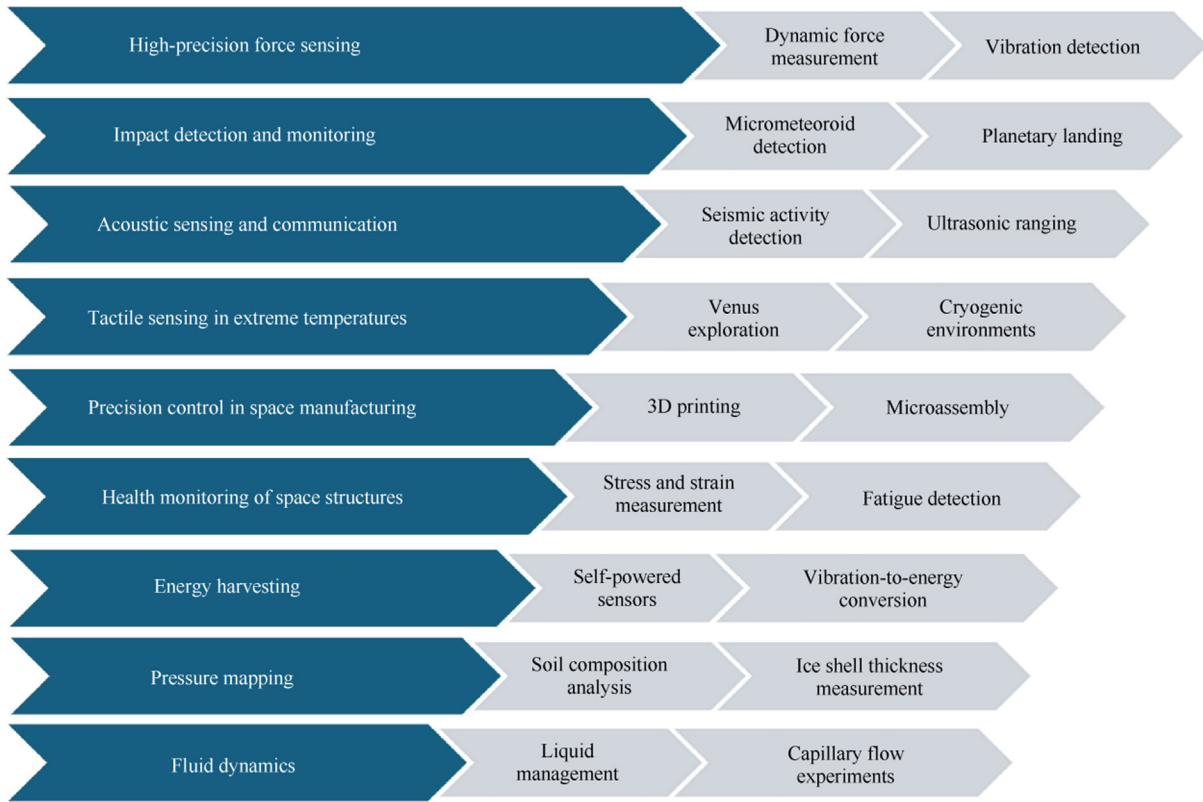


Fig. 20 Applications of piezoelectric tactile sensors in space exploration.

Table 4 Comparative analysis of piezoelectric tactile sensors.

Attribute	Direct piezoelectric	Reverse piezoelectric	Shear piezoelectric	Composite piezoelectric	Film-Based piezoelectric
Sensing Principle	Generates charge under mechanical stress	Applies electric fields to induce strain	Measures shear-induced polarization changes	Uses material combinations for enhanced properties	Utilizes thin films for flexibility
Material Used	Piezoelectric crystals (quartz, PZT)	Piezoelectric crystals with electrodes	Specialized shear-oriented materials	Hybrid materials with flexible substrates	Thin piezoelectric films on flexible substrates
Sensitivity	High for pressure and force changes	Sensitive to electrically induced strains	High for lateral forces	Tailored sensitivity by design	Moderate to high, optimized for conformity
Response Time	Fast for dynamic pressure changes	Rapid for electrically induced changes	Quick reaction to shear forces	Varies by structure and integration	Quick, suitable for real-time monitoring
Operating Conditions	Robust, high-force environments	Controlled environments for electrical manipulation	Ideal for lateral force measurement	Diverse environments, enhanced by design	Wearable and flexible applications
Key Advantage	Direct measurement, robust and reliable	Precision in actuation and control	Specialized for directional forces	Combines benefits of multiple materials	High flexibility, wearable integration
Key Disadvantage	Limited to pressure and force	Requires electrical input, complex circuitry	Specialized application focus	Potentially complex manufacturing	Potentially lower sensitivity than rigid sensors
Potential Space Application	Pressure monitoring in spacecraft	Precise control in space robotics	Vibration detection in space structures	Advanced sensors for space suits	Flexible sensors for astronaut health monitoring

- (B) Ce-Doped BaTiO₃ Nanofibers: Provide flexible sensors with enhanced piezoelectric properties for intelligent space robotic applications.¹⁰²

④ Multifunctional Capabilities:

- (A) Self-Chargeable Piezoelectric Supercapacitor: Enables energy harvesting and multi-phenomenon detection, ideal for self-powered space systems.¹⁰³
- (B) Binary Cooperative Magnetoelectric Materials: Create self-powered flexible sensors for space robotics and equipment.¹⁰⁴

These innovations meet the challenges of creating durable, flexible, and multifunctional tactile sensors that operate effectively in harsh space environments.

(3) Integration with other sensing technologies

① Multi-Modal Sensing:

- (A) Hybrid Silicon Carbonitride Piezoresistive Sensors: Offer enhanced sensitivity at high temperatures, suitable for extreme space environments.¹⁰⁵
- (B) Dual-Mode Piezoresistive/Piezoelectric Sensors: Potential for detecting fluid leaks in space habitats or vehicles.¹⁰⁶

② Advanced Actuation:

Hybrid Piezoelectric-Electrostatic MEMS Actuators: Provide precise positioning capabilities for delicate space operations.¹⁰⁷

③ Energy Harvesting and Sensing:

- (A) Hybrid Piezoelectric-Triboelectric Sensors: Combine energy harvesting and sensing capabilities, ideal for self-powered space systems.¹⁰⁸
- (B) Silicone-Based Hybrid Vibration Energy Harvesters: Potential for powering small devices in space using ambient vibrations.¹⁰⁹

④ Multifunctional Capabilities:

- (A) Photon-Assisted Piezoelectric Color-Tactile Sensors: Potential for enhancing visual feedback in space suits or robotic vision systems.¹¹⁰
- (B) POSFET Tactile Sensing Chips: Improve tactile sensing accuracy for space robotic manipulators.¹¹¹

⑤ Material Analysis:

Multifunctional Tactile Sensors for Hardness Detection: Useful for in-situ material analysis on planetary surfaces.¹¹²

These advancements address the need for multifunctional, energy-efficient, and highly accurate sensing systems that can thrive in the unique conditions of space. Integrating piezoelectric sensors with other technologies enhances autonomous

robotic operations, vital for long-duration missions where power efficiency and adaptability are essential.

3.4. Optical tactile sensors

Optical tactile sensors represent a sophisticated class of devices that translate physical contact and forces into optical signals. These sensors vary in complexity from simple reflective systems to advanced imaging and interferometric methodologies, each leveraging light's properties to detect and measure interaction with their environment.

3.4.1. Basic principles

Optical tactile sensors convert physical contact and forces into optical signals by modulating light. Typically, they use optical fibers or waveguides embedded in a deformable substrate. When pressure is applied, it causes deformation, changing the optical properties such as intensity, phase, or wavelength of the transmitted light.

The change in light intensity I can be expressed as ¹¹³

$$I = I_0 \cos^2 \left(\frac{\pi d \Delta n}{\lambda} \right) \quad (6)$$

where I_0 is the initial light intensity, d is the deformation, Δn is the change in refractive index due to deformation, λ is the wavelength of the light.

Fiber Bragg Grating (FBG) sensors measure the shift in Bragg wavelength $\Delta \lambda_B$ due to strain:

$$\Delta \lambda_B = 2 \lambda_B \left(\frac{\Delta n}{n} + \frac{\epsilon}{2} \right) \quad (7)$$

where λ_B is the Bragg wavelength, n is the refractive index of the fiber, ϵ is the strain induced by the applied force.

3.4.2. Variants of optical tactile sensors

Fig. 21 illustrates three main types tailored for space applications:

- (1) Fiber Optic Sensors: Utilize optical fibers to transmit light; highly sensitive and immune to EMI; ideal for spacecraft instrumentation, space suits, and robotic manipulators.
- (2) Imaging-Based Sensors: Employ camera systems to capture surface deformations under applied pressure; enhance robotic dexterity; useful in robotic grippers and touchless control panels within spacecraft.
- (3) Interferometric Sensors: Leverage light wave interference for extremely high precision measurements; crucial for tasks requiring nanometric resolution, such as surface analysis of extraterrestrial materials.

3.4.3. Applications in space exploration

Optical tactile sensors offer significant advantages due to their high resolution and EMI immunity (Fig. 22):

- (1) High-Resolution Surface Mapping: Create detailed maps of object surfaces and terrains for planetary analysis and sample characterization.

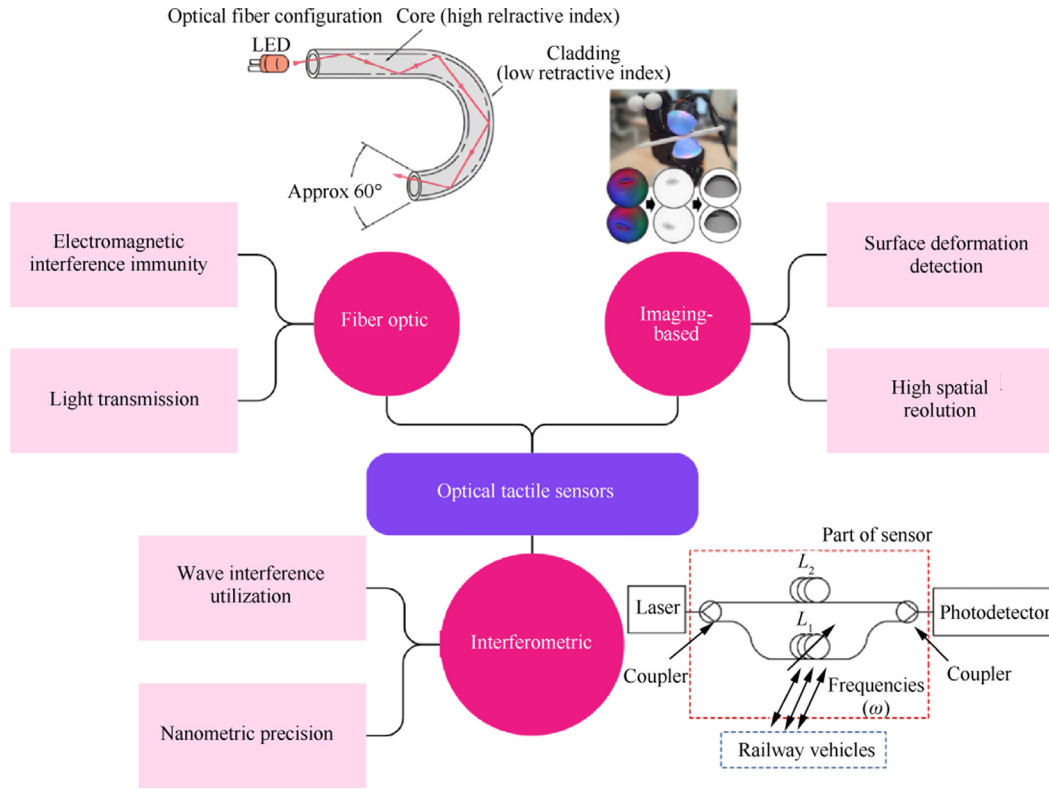


Fig. 21 Taxonomy of optical tactile sensors.

High resolution surface mapping	Precision manipulation in microgravity	Shape and texture recognition	Slip detection and prevention	Damage and wear inspection	Docking and berthing	ISRU	Human-Robot interaction	Biomedical application
Planetary surface analysis	Delicate object handling	Debris identification	Secure grasping	Micrometeoroid impact detection	Alignment verification	Material identification	Intuitive control interfaces	Health monitoring
Sample characterization	Assembly tasks	Geological classification	Dynamic force adjustment	Wear analysis	Soft capture	Excavation feedback	Safety monitoring	Telemedicine tools

Fig. 22 Applications of optical tactile sensors in space exploration.

- (2) Precision Manipulation in Microgravity: Enable precise object handling and assembly tasks, crucial for delicate scientific instruments.
- (3) Shape and Texture Recognition: Facilitate debris identification and geological classification during planetary missions.
- (4) Slip Detection and Prevention: Allow robotic grippers to adjust gripping force dynamically to secure objects.
- (5) Damage and Wear Inspection: Detect micrometeoroid impacts and monitor mechanical wear on spacecraft surfaces.
- (6) Docking and Berthing Operations: Enhance precision in spacecraft docking through alignment verification.
- (7) In-Situ Resource Utilization (ISRU): Aid in material identification and provide real-time excavation feedback for resource extraction missions.
- (8) Human-Robot Interaction in Space: Enhance interfaces between astronauts and robotic assistants, offering intuitive control and safety.
- (9) Biomedical Applications: Integrated into wearable devices for health monitoring and telemedicine, supporting astronaut health during long missions.

3.4.4. Comparative analysis of optical tactile sensors

Table 5 provides a detailed comparison of optical tactile sensors, focusing on key attributes that influence their performance.

3.4.5. Recent advancements

(1) Material and design innovation

① Radiation-Hardened Materials:

- (A) Nanoparticle-Based Organic-Polymer Hybrids: Offer superior space radiation hardness and low out-gassing properties.¹¹⁴
- (B) Radiation-Resistant Coatings: Hydrophobic and hydrophilic coatings enhance durability of optical components against cosmic rays.¹¹⁵
- (C) Nonlinear Carbon-Nanotube Polymers: Provide excellent radiation resistance for optical limiting and switching applications.¹¹⁶

② Temperature-Resistant Designs:

- (A) Sapphire Optical Fibers: Withstand extreme temperatures up to 1750 °C.¹¹⁷
- (B) Polyimide-Coated Fibers: Operate stably at temperatures up to 325 °C.¹¹⁸
- (C) Femtosecond Laser-Inscribed Gratings: Create thermally stable sensors in sapphire fibers.¹¹⁹

③ Miniaturization:

- (A) MEMS Integration: Enables ultracompact sensors with high precision.¹²⁰
- (B) Waveguide-Based Systems: Allow for miniaturized optical paths.¹²¹
- (C) Planar Photonic Crystals: Manipulate light at micro-scale for compact designs.¹²²

(2) Advanced sensing techniques

① High-Resolution Sensing:

- (A) GelSight Technology: Measures high-resolution geometry and infers local force and shear, suitable for detailed shape recognition.¹²³
- (B) OmniTact Sensor: Provides multi-directional high-resolution touch sensing using micro-cameras.¹²⁴
- (C) Reflective Optical Sensors: Achieve nanometric resolution over millimetric ranges, applicable for micro/nano-manipulation.¹²⁵
- (D) Minsight Sensor: Fingertip-sized, vision-based sensor for high-resolution 3D force vector detection.¹²⁶

② Multi-Modal Sensing:

- (A) Optum Sensor: Measures pressure, hardness, and texture; designed for on-orbit servicing.¹²⁷
- (B) Fiber-Optic Sensor Arrays: Integrate static and dynamic force sensing for enhanced manipulation.¹²⁸
- (C) Hybrid Visual-Tactile Sensing: Combines visual and tactile data for detecting surface anomalies.¹²⁹
- (D) VisTac Sensor: Integrates high-resolution tactile and visual perception for accurate object manipulation.¹³⁰

③ Real-Time Data Processing:

- (A) TouchRoller: Enables rapid assessment of large surface areas, suitable for efficient texture analysis.¹³¹
- (B) Evetac Sensor: Event-based optical tactile sensor with 1000 Hz processing for immediate feedback control.¹³²

These advancements address the need for high-precision manipulation, multi-modal environmental interaction, and

Table 5 Comparative analysis of optical tactile sensors.

Attribute	Fiber optic sensors	Imaging-Based sensors	Interferometric sensors
Sensing Principle	Light transmission changes in optical fibers	Surface deformation captured by cameras	Wave interference patterns of light
Material Used	Optical fibers, often with specialized coatings	Transparent elastomers, cameras, LEDs	High-precision optical components, mirrors
Sensitivity	High, especially to subtle pressures	Moderate to high, depends on imaging resolution	Extremely high, nanometric precision
Response Time	Fast, limited by light transmission speed	Moderate, depends on image processing speed	Very fast for precision measurements
Operating Conditions	Excellent in extreme environments, EMI-immune	Suitable for controlled environments, sensitive to lighting	Requires stable conditions for high precision
Key Advantage	EMI immunity, suitable for harsh environments	Visual feedback, complex surface analysis	Extremely high precision measurements
Key Disadvantage	Can be complex to integrate in large areas	Requires clear optical path, sensitive to contamination	Highly sensitive to environmental disturbances
Potential Space Application	Spacecraft instrumentation, space suits	Robotic grippers, touchless control panels	Fine adjustments in space instruments, material analysis

real-time data processing in space conditions. The development of these advanced optical tactile sensors boosts the potential for more autonomous and sophisticated robotic operations, enhancing capabilities in tasks ranging from satellite servicing to planetary exploration.

(3) Flexibility and adaptability

① Flexible and Stretchable Sensors:

- (A) Elastic Membranes: Used in TacTip and GelSight sensors, allowing conformity to various surface geometries.¹³³
- (B) Flexible Foam Structures: Integrate optical fibers for robust and deformable tactile sensing.¹³³
- (C) Polymer-Optic Fiber Integration: Enables compact and flexible sensor configurations for space-constrained systems.¹³⁴

② Adaptable Designs:

- (A) Modular Sensor Systems: Allow reconfiguration for different tasks, such as manipulating various object sizes.¹³³
- (B) Scalable Designs: Parametric CAD models for robotic fingers ensure adaptability to different sizes and shapes.¹³³

These advancements address challenges like radiation exposure, extreme temperatures, and size constraints in space robotics. The development of radiation-hardened, temperature-resistant, and flexible optical tactile sensors enhances the potential for sophisticated and reliable sensing systems, advancing robotic capabilities in space exploration and maintenance.

4. Application of tactile sensors in space robotics

This section explores the integration of tactile sensors within space robotics. The discussion highlights specific examples of

real-world applications and projects that have successfully utilized different types of tactile sensors.

4.1. Mars rovers

NASA's Mars rovers are equipped with various sensors and instruments that enable them to explore the Martian surface, avoid obstacles, and conduct scientific research. Here is an overview of the key tactile sensors and instruments on the Perseverance, Spirit, Opportunity, Curiosity, and Sojourner rovers.

4.1.1. Perseverance

The Perseverance rover (Fig. 23¹³⁵), part of NASA's Mars 2020 mission,¹³⁶ utilizes advanced tactile sensors and instruments to analyze the Martian surface.

Notable tactile instruments include:

- (1) Planetary Instrument for X-ray Lithochemistry (PIXL) (Fig. 24): Utilizes X-ray fluorescence to determine the elemental composition of rocks and soil through close contact.¹³⁷
- (2) Scanning Habitable Environments with Raman & Luminescence for Organics and Chemicals (SHERLOC) (Fig. 25¹³⁸): Employs Raman and fluorescence spectroscopies to detect organic compounds and minerals altered by water.¹³⁹

4.1.2. Spirit and opportunity

Spirit and Opportunity (Fig. 26¹⁴⁰), part of NASA's Mars Exploration Rover mission, relied on various sensors to perform their missions. Key tactile sensors included:

- (1) Contact Sensors (Bumper Sensors) (Fig. 27¹⁴⁰): Detected obstacles through direct physical contact to prevent collisions.
- (2) Rock Abrasion Tool (RAT) (Fig. 28¹⁴⁰): Removed the surface layer of rocks to expose fresh material for analysis by other instruments.

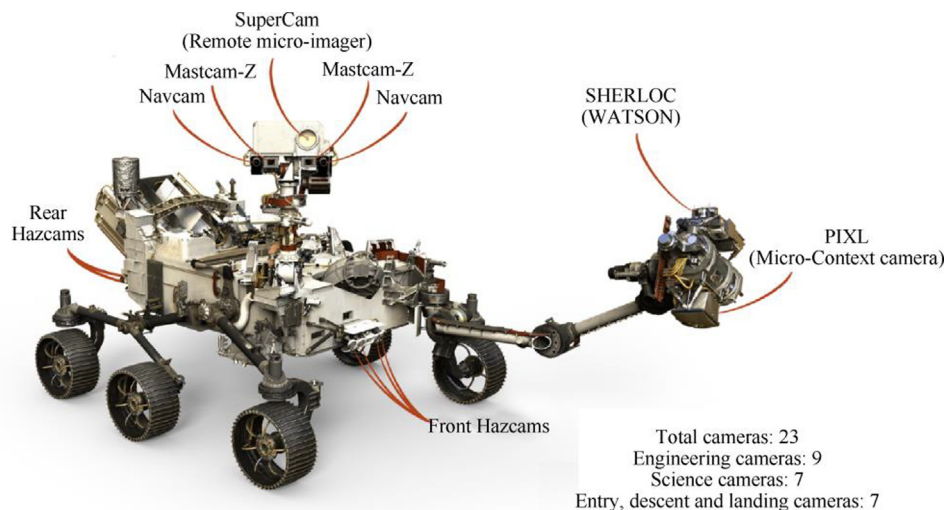


Fig. 23 Perseverance rover.¹³⁵



Fig. 24 PIXL.¹³⁷



Fig. 28 RAT.¹⁴⁰



Fig. 25 An engineering model of SHERLOC.¹³⁸

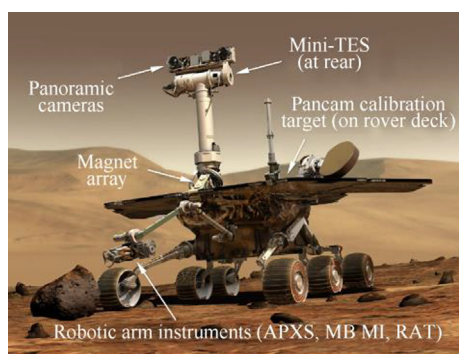


Fig. 26 Spirit and opportunity.¹⁴⁰



Fig. 27 Microscopic Imager and contact sensor.¹⁴⁰

In addition to tactile sensors, the Spirit and Opportunity rovers were equipped with various other sensors that supported their navigation and scientific objectives:

- (1) Wheel Encoders: Measure the rotation of the wheels to estimate the distance traveled (odometry).
- (2) Inclinometers: Monitor the rover's pitch and roll to ensure stability and prevent tipping.
- (3) Gyroscopes: Assist in maintaining the rover's heading by measuring its angular velocity.
- (4) Accelerometers: Measure the rover's acceleration in the X , Y , and Z axes.
- (5) Hazard Avoidance Cameras (Hazcams): Provide a view of the terrain directly in front and behind the rovers to detect obstacles and plan safe paths.
- (6) Navigation Cameras (Navcams): Used for general navigation and creating 3D maps of the surrounding terrain.
- (7) Panoramic Cameras (Pancams): Capture high-resolution, wide-angle images of the Martian surface.
- (8) Microscopic Imager: Provides extreme close-up views of rocks and soils.
- (9) Miniature Thermal Emission Spectrometer (Mini-TES): Determines the mineralogy of rocks and soils from a distance.
- (10) Mössbauer Spectrometer: Identifies iron-bearing minerals in geological samples.
- (11) Alpha Particle X-Ray Spectrometer (APXS): Determines the elements that make up rocks and soils.
- (12) Rock Abrasion Tool (RAT): Grinds away the surface of rocks to expose fresh material for analysis.
- (13) Magnet Array: Collects magnetic dust particles for analysis.

4.1.3. Curiosity

The Curiosity rover (Fig. 29¹⁴¹) from NASA's Mars Science Laboratory mission features advanced tactile instruments:¹⁴²

- (1) Alpha Particle X-Ray Spectrometer (APXS): Measures chemical elements in rocks and soil by making direct contact with samples.
- (2) Mars Hand Lens Imager (MAHLI): Provides high-resolution close-up images of rocks and soil textures.

Curiosity is equipped with a suite of other sensors including Cameras (Mastcam and Mars Descent Imager (MARDI)), Spectrometers (Chemistry & Camera (ChemCam), Chemistry & Mineralogy X-Ray Diffraction (CheMin), and Sample Analysis at Mars (SAM)), Radiation Detectors (Radiation Assessment Detector (RAD) and Dynamic Albedo of Neutrons

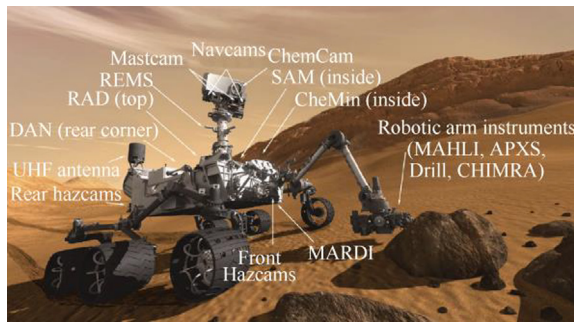


Fig. 29 Curiosity rover.¹⁴¹

(DAN)), and Environmental Sensors (Rover Environmental Monitoring Station (REMS) and Mars Science Laboratory Entry Descent and Landing Instrument (MEDLI)).

These tools enable Curiosity to analyze Martian geology extensively, contributing valuable data about Mars's past environmental conditions.

4.1.4. Sojourner

The Sojourner rover (Fig. 30), part of NASA's Mars Pathfinder mission,¹⁴³ was equipped with a variety of sensors designed to navigate and explore the Martian surface. Similar to the Spirit and Opportunity rovers, Sojourner had:

- (1) Contact Sensors (Bumper Sensors): Located on the front of the rover, these sensors were essential for preventing collisions and ensuring autonomous navigation.

In addition to tactile sensors, the Sojourner rover was equipped with various other sensors including Wheel Encoders, Tilt Sensors, Rate Gyro, Accelerometers, Proximity Sensors, and Potentiometers.

4.2. Canadarms

Canada has made significant contributions to space exploration with its series of robotic arms: Canadarm, Canadarm2, and the upcoming Canadarm3. These robotic systems, developed by the Canadian Space Agency, have evolved to incorporate tactile sensing capabilities, enhancing their ability to perform delicate and complex tasks in space.¹⁴⁴

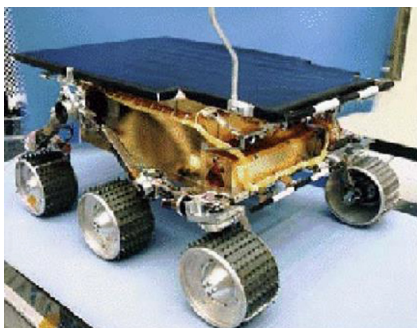


Fig. 30 Sojourner rover.¹⁴³

4.2.1. Canadarm

Canadarm (Fig. 31¹⁴⁵), also known as the Shuttle Remote Manipulator System (SRMS),¹⁴⁶ was the first Canadian robotic arm to be deployed in space. It was used on NASA's Space Shuttle missions for handling payloads and assisting with various assembly and maintenance tasks.

Canadarm did not have tactile sensors. It relied solely on visual feedback and manual control by astronauts.

4.2.2. Canadarm2

Canadarm2 (Fig. 32¹⁴⁷) introduced significant advancements over its predecessor, including the integration of tactile sensing capabilities.¹⁴⁸ This robotic arm has been servicing the International Space Station (ISS) since 2001.

Canadarm2 is equipped with force-moment sensors that provide a sense of "touch". These sensors allow the arm to detect forces and moments applied to it, enabling more precise handling of objects and improving its ability to perform delicate operations. The force-moment sensors also contribute to automatic collision avoidance, enhancing the safety of its operations.

4.2.3. Canadarm3

Canadarm3, the next-generation robotic system designed for the Lunar Gateway, will build on the capabilities of Canadarm2 with even more advanced tactile sensing.¹⁴⁸ Canadarm3 will feature force-moment sensors similar to those on Canadarm2, providing a sense of "touch" for precise manipulation of objects. Additionally, it will include a 3D Vision Sensor Tool that maps objects around it, further enhancing its operational precision and safety. Enhanced automatic collision avoidance capabilities will be integrated, leveraging tactile and visual sensing to prevent accidents during operations.

4.3. Robonauts

Robonauts are dexterous humanoid robots developed to assist astronauts with tasks requiring manual dexterity in space. They incorporate advanced tactile sensing technologies to perform autonomous grasping and manipulation tasks, enhancing their ability to interact with tools and equipment.

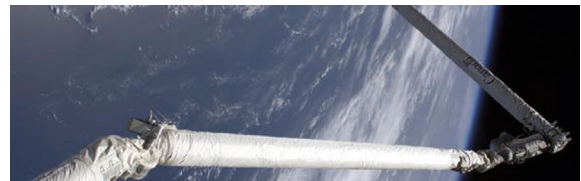


Fig. 31 Canadarm.¹⁴⁵



Fig. 32 Canadarm2.¹⁴⁷

4.3.1. Robonaut 1

Robonaut 1 (Fig. 33¹⁴⁹), developed by NASA and DARPA, is designed to perform tasks requiring a high degree of manual dexterity.

Significant tactile instruments include:

- (1) Force Sensing Resistors (FSRs): Initially used in Robonaut 1's glove, FSRs are low-cost, sensitive, and have simple electronics. However, their stiff backing limited their ability to conform to the curved shapes of the fingers and palm, reducing the sensed area.
- (2) QTC Sensors: The latest generation incorporates QTC sensors developed by Peratech, Ltd.¹⁵⁰ QTC sensors change resistance significantly in response to applied pressure, offering a wide dynamic range from approximately $10\text{ M}\Omega$ to $1\text{ }\Omega$. They can be manufactured in various shapes and thicknesses to fit the glove. QTC sensors are layered with a flex-circuit, a "force concentrator" layer, and a protective "grip surface" material to enhance sensitivity and coverage (Fig. 34¹⁵¹).
- (3) Sensor Distribution: The First Generation Glove used exclusively FSRs with 19 discrete contact points. The Second Generation Glove combined QTC and FSR sensors with 33 sensor locations, varying from discrete to continuous contact areas. Enhanced dexterous grasps are achieved with multiple sensors around the tips of the index and middle fingers, as well as the thumb, while large areas of the palm are covered for tool and power grasps (Fig. 35¹⁵¹).



Fig. 33 NASA/DARPA Robonaut 1.¹⁴⁹



Fig. 34 Assembly of QTC sensors with flex-circuit, force concentrator layer, and protective grip surface.¹⁵¹

4.3.2. Robonaut 2

Robonaut 2 (R2) (Fig. 36¹⁵²), developed by NASA and General Motors, represents a significant advancement over its predecessor. The R2 hand is designed to closely approximate human hand capabilities, enabling it to work with a wide range of tools and human interfaces.

Prominent tactile instruments include:

- (1) Phalange Tactile Load Cells: The fingers and thumb are equipped with novel six-degree-of-freedom force-torque sensors known as phalange tactile load cells. These sensors evolved from a low-profile design to an arch compatible with all phalange locations. They use semiconductor strain gauges mounted on an aluminum elastic element to maximize measurable bending strain within the limited space of the phalanges (Fig. 37¹⁵³).
- (2) Tendon Tension Sensors: The R2 hand includes sensors that measure the tension in the tendons by assessing compressive forces within the conduits where the tendons are routed. These sensors provide accurate measurements of tendon tension with an error margin of 5%–10%, accounting for interactions and friction within the conduits. The tendon tension sensors are integrated into the structure of the palm to protect them from incidental contact with other conduits and objects (Fig. 38¹⁵³).

4.4. Astrobee

Astrobee (Fig. 39¹⁵⁴) is a free-flying robotic system developed by NASA to assist with Intra-Vehicular Activities (IVA) on the ISS.¹⁵⁵ Comprising three robots, a docking station, and a

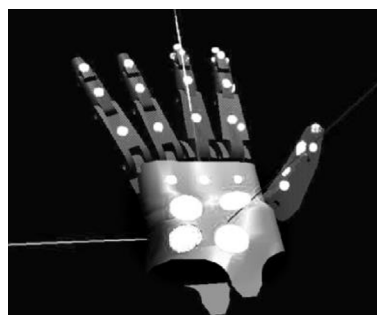


Fig. 35 Sensor distribution in first- and second-generation gloves.¹⁵¹



Fig. 36 Robonaut 2 in ISS's destiny laboratory.¹⁵²

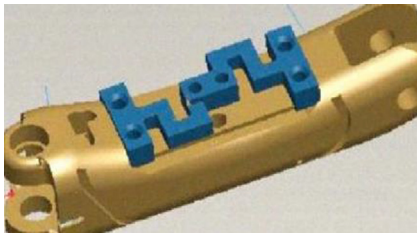


Fig. 37 Development of phalange tactile load cells for R2's fingers and thumb.¹⁵³

ground data system, Astrobeer enhances the efficiency of ISS operations and supports zero-gravity robotics research.

Key tactile sensors and features include:

- (1) **Force-Moment Sensors:** Astrobeer employs force-moment sensors to provide a sense of “touch”, crucial for interaction tasks (Fig. 40¹⁵⁵). These sensors detect forces and torques applied to the robot's surfaces, facilitating precise control during navigation and manipulation activities. They help Astrobeer detect obstacles, avoid collisions, and are vital during tasks such as grasping and using tools.
- (2) **Contact Sensors:** Integrated into Astrobeer's perching arm and other interaction points, these sensors detect physical contact with surfaces or objects (Fig. 41¹⁵⁵). This capability is essential for secure perching maneuvers and interactions with various payloads. The perching arm, equipped with tactile sensors, allows Astrobeer to grasp ISS handrails and stabilize itself, reducing power consumption and interference with ISS operations.

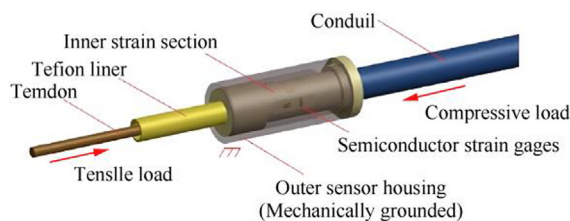


Fig. 38 Design and integration of tendon tension sensors in R2's palm.¹⁵³



Fig. 39 Astrobeer robot.¹⁵⁴

- (3) **Touch-Sensitive Interface:** Astrobeer features a touch-sensitive screen that facilitates human-robot interaction (Fig. 40¹⁵⁵). This interface allows astronauts to input commands directly and receive immediate feedback, enhancing control during complex operations.

4.5. European robotic arm (ERA)

The ERA (Fig. 42¹⁵⁶) is a versatile robotic system designed by the European Space Agency (ESA) to support operations on

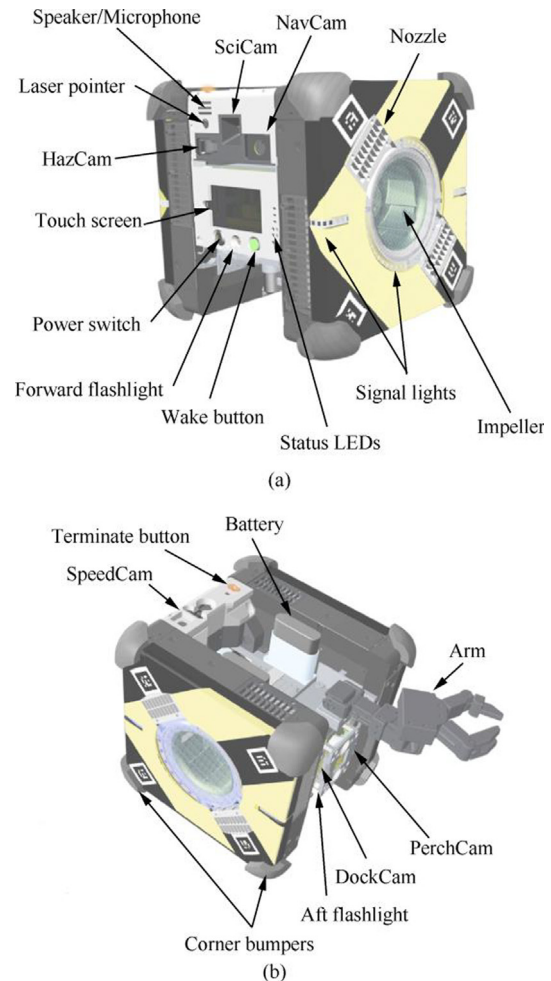


Fig. 40 Astrobeer robot. (a) Forward and left faces. (b) Top and left faces, with Perching Arm deployed.¹⁵⁵

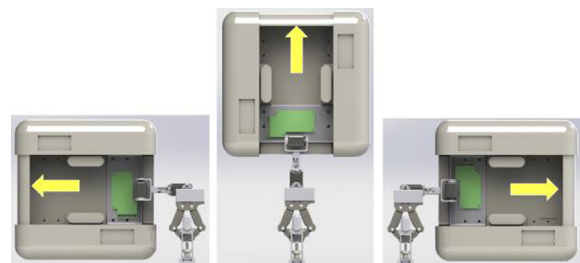


Fig. 41 Astrobeer perching arm pan range; yellow arrow indicates SciCam pointing direction.¹⁵⁵

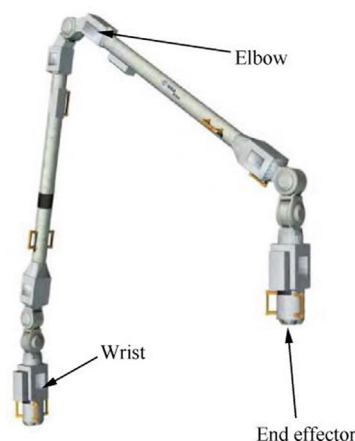


Fig. 42 Structure of ERA Arm.¹⁵⁶

the ISS. ERA enhances the ISS's capabilities by performing tasks such as payload handling, inspection, and maintenance of the station's exterior. By automating routine tasks and enabling precise handling of large objects in space, ERA significantly reduces the workload of astronauts.

ERA employs a Force/Torque Sensor (FTS) to enhance its manipulation capabilities.¹⁵⁶ The FTS is an electro-mechanical unit equipped with strain gauges that measure torque and force in six degrees of freedom. These sensors provide critical feedback, enabling precise control of the arm during operations such as grapple and guiding objects.

Key Features of the FTS:

- (1) Six Degrees of Freedom: Measures torque and force along all three translational and three rotational axes, providing comprehensive tactile feedback necessary for complex tasks.
- (2) Temperature Compensation: Designed to maintain accuracy across a range of temperatures, ensuring reliable performance in varying thermal environments.
- (3) Overload Protection: Rigid end stops protect the sensor from mechanical overload, enhancing durability and reliability during intense operations.

A notable mechanism integrated with the FTS is the Torque Force Sensor Rigidization Mechanism (TRM). This mechanism allows the FTS to lock when its measurement function is not needed, enhancing the structural stiffness of the arm. This capability is crucial for operations requiring high rigidity, such as when the arm acts as a shoulder joint or during the transportation of heavy objects.

4.6. Dextre (Special purpose dexterous manipulator)

Dextre (Fig. 43), part of Canada's contribution to the ISS, is a highly sophisticated dual-arm robot designed to perform delicate maintenance tasks on the ISS's exterior.¹⁵⁷ By reducing the need for astronauts to conduct risky and time-consuming spacewalks, Dextre allows them to focus more on scientific experiments. It can install and replace small equipment, such as exterior cameras and the 100 kg batteries used on the station, and can also replace defective components in the station's electrical system.



Fig. 43 Dextre robotic arm in operation on ISS.¹⁵⁷

Dextre's design incorporates advanced tactile sensing technology, essential for performing precise and delicate tasks in the challenging environment of space. The key tactile sensor utilized in Dextre is the Force-Moment Sensor (FMS).

Key features of FMSs are:

- (1) Six Degrees of Freedom: The FMS measures forces and torques in all directions, providing comprehensive tactile feedback necessary for complex tasks.
- (2) High Sensitivity: These sensors are highly sensitive, allowing Dextre to detect minute changes in force and torque, which is critical for delicate operations such as the insertion and removal of ORUs.
- (3) Feedback Control: The FMS provides real-time data to Dextre's control system, enabling precise manipulation of objects and automatic compensation for misalignments during task execution.

A notable mechanism integrated with the FMS is the Force-Moment Accommodation (FMA) control algorithm. This system enhances Dextre's operational capability by:

- (1) Compensating for Misalignments: The FMA uses real-time FMS data to adjust Dextre's movements, ensuring smooth insertion of ORUs without jamming or damaging components.
- (2) Stabilization During Operations: One of Dextre's arms stabilizes itself by grasping a pre-installed fixture on the ISS, providing a stable base for the other arm to perform tasks, thereby counteracting any compliance from the SSRMS.

Dextre's tactile sensing and force-moment accommodation capabilities make it a crucial asset for ISS maintenance, enabling precise and safe manipulation of various components, thus minimizing the need for astronaut EVA and enhancing overall mission efficiency.

4.7. Kibo robot arm

The Kibo Robot Arm, also known as the Japanese Experiment Module Remote Manipulator System (JEMRMS), is a vital component of the Kibo module on the ISS. Designed to support scientific experiments and maintenance tasks on Kibo's Exposed Facility, the JEMRMS consists of the Main Arm (MA) and the Small Fine Arm (SFA), both equipped with advanced sensors for precise and delicate operations in space.

The main tactile sensors in the JEMRMS are the FTSs located on the SFA. These sensors provide crucial tactile

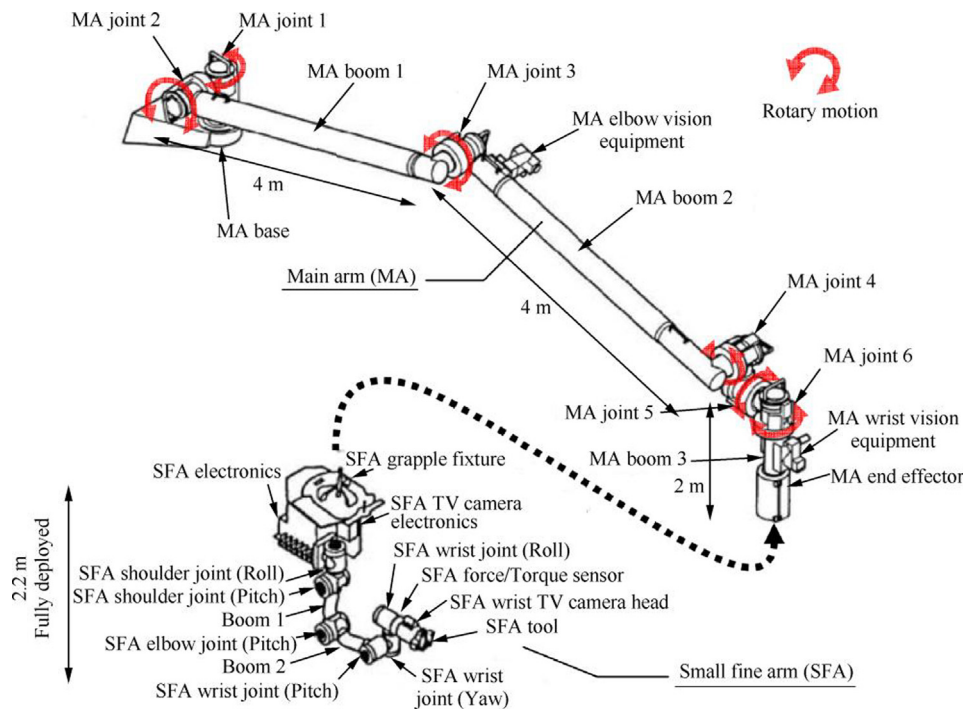


Fig. 44 Components and layout of JEMRMS, featuring FTS, MA, and SFA.¹⁵⁸

feedback during delicate operations, enabling the arm to detect and measure the force and torque applied to its end effector (Fig. 44¹⁵⁸).

Key Features of the FTS:

- (1) Six Degrees of Freedom: Measures forces and torques along all three translational and three rotational axes, offering comprehensive feedback necessary for complex manipulations.
- (2) High Sensitivity and Precision: Capable of detecting minute forces and torques, allowing the SFA to perform delicate tasks without damaging sensitive equipment.
- (3) Real-Time Feedback: Provides continuous data to the control system, enabling real-time adjustments during operations.

The integration of the FTS in the SFA enhances the JEMRMS's ability to perform tasks such as exchanging Orbital Replacement Units (ORUs) and handling scientific payloads with great care. This tactile feedback ensures that the robotic arm can mimic human-like precision and delicacy, essential for successful operations on the ISS.

4.8. LEMUR 3

Limbed Excursion Mechanical Utility Robot 3 (LEMUR 3) is a four-limbed robot developed by NASA's Jet Propulsion Laboratory (JPL) designed for climbing extreme terrains, including cliff faces and smooth surfaces like glass (Fig. 45¹⁵⁹). Each limb consists of seven identical actuators, providing a high degree of mobility and flexibility. The robot has demonstrated its capabilities in field tests on both natural and artificial surfaces.

Prominent tactile instruments include:

FTS: Each limb of LEMUR 3 terminates in a single-axis force/torque sensor, crucial for measuring contact forces during gripping. These sensors provide necessary feedback to ensure firm contact and engagement of the grippers. They help in applying a preload to the grippers, ensuring a secure grip before fully engaging them.

Other notable features:

- (1) Microspine Grippers: Used for climbing rocky surfaces, these grippers consist of hundreds of small hooks that conform to rough surfaces at multiple scales, providing a secure grip on vesicular basalt and other rock types.
- (2) Gecko Adhesive Grippers: Designed for smooth surfaces like glass, these grippers use synthetic adhesive materials that mimic the properties of gecko feet, allowing the robot to attach and detach from surfaces with precision.



Fig. 45 LEMUR 3 robot.¹⁵⁹

The combination of force-torque sensors and advanced grippers enables LEMUR 3 to traverse a variety of challenging environments, making it a versatile tool for space exploration and planetary missions.

5. Conclusions and prospective

The integration of tactile sensors in space robotics faces significant challenges due to technical complexities and harsh space environments. Each sensor type—resistive, capacitive, piezoelectric, and optical—has specific limitations such as sensitivity constraints, environmental susceptibility, and high costs. Overcoming these hurdles requires ongoing innovation in materials science, sensor design, and signal processing to enhance performance and reliability.

Despite these challenges, advanced tactile sensors hold transformative potential in space robotics:

- (1) **Complex Tasks:** Enable robots to perform assembly and repair tasks with human-like precision.
- (2) **Scientific Experiments:** Allow handling of delicate samples for detailed analysis.
- (3) **Data Collection:** Gather detailed environmental data for celestial exploration.
- (4) **Medical Assistance:** Aid in medical procedures during long-duration missions.
- (5) **Emergency Interventions:** Enhance robotic capabilities for critical tasks when human response is not feasible.

This review has highlighted the challenges, advancements, and applications of tactile sensing technologies in space robotics. The following sections provide strategic recommendations, practical guidelines, and future research directions.

5.1. Recommendations for selecting tactile sensors in space robotics

Selecting appropriate tactile sensors involves evaluating sensor capabilities against mission-specific requirements and environmental challenges. Recommendations include:

- (1) **Environmental Compatibility:**
 - (A) **Radiation-Hardness:** Use SOI and SOS capacitive sensors for high-radiation environments.
 - (B) **Temperature Extremes:** Opt for piezoelectric sensors with materials like BaTiO₃-reinforced polyurethane for thermal stability.
 - (C) **Vacuum Conditions:** Choose optical sensors with TIR structures and resistive sensors using vacuum-compatible materials.
- (2) **Sensitivity and Resolution:**
 - (A) **High-Precision Tasks:** Employ optical interferometric sensors for nanometric precision.
 - (B) **Dynamic Force Measurement:** Use piezoelectric sensors for detecting rapid force changes.
 - (C) **Basic Pressure Sensing:** Apply resistive sensors for general pressure monitoring.

(3) Flexibility and Adaptability:

- (A) **Conforming Surfaces:** Utilize flexible resistive and capacitive sensors for interacting with irregular surfaces.
- (B) **Wearable Applications:** Integrate textile-based resistive and capacitive sensors into astronaut suits.

(4) Energy Efficiency and Integration:

- (A) **Power-Constrained Missions:** Prefer resistive sensors for low power consumption.
- (B) **Multimodal Sensing:** Combine capacitive, piezoelectric, and optical sensors for comprehensive sensing.

(5) Cost and Manufacturing Considerations:

- (A) **Budget Constraints:** Select resistive and capacitive sensors for cost-effective solutions.
- (B) **Advanced Manufacturing:** Use 3D-printed sensor arrays and MEMS technologies to enhance capabilities.

(6) Durability and Longevity:

- (A) **Long-Term Missions:** Opt for robust optical sensors and QTC sensors.
- (B) **Maintenance and Redundancy:** Implement redundant sensor arrays and self-calibration algorithms.

5.2. Practical guidelines for sensor selection

A Sensor Selection Guideline flowchart (Fig. 46) outlines key steps for choosing tactile sensors based on mission requirements and environmental factors:

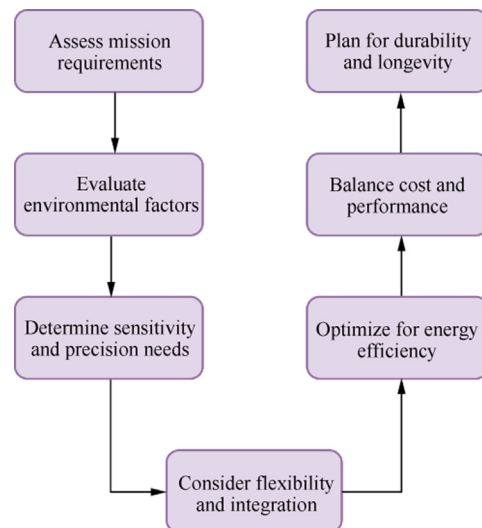


Fig. 46 Sensor selection guideline.

- (1) Evaluate Mission Objectives: Determine the tasks and precision required.
- (2) Assess Environmental Challenges: Consider radiation, temperature, and vacuum conditions.
- (3) Determine Sensitivity Needs: Match sensor sensitivity to task demands.
- (4) Consider Flexibility Requirements: Decide if flexible sensors are necessary.
- (5) Analyze Energy Constraints: Choose sensors compatible with power availability.
- (6) Review Cost Considerations: Balance performance needs with budget.
- (7) Ensure Durability Demands: Select sensors capable of long-term operation.

5.3. Future directions and sensor development recommendations

Future development of tactile sensors should focus on:

- (1) Enhanced Radiation Resistance: Develop materials and architectures resistant to radiation-induced degradation.
- (2) Adaptive Sensing Technologies: Incorporate adaptive algorithms and machine learning for dynamic sensitivity and calibration.
- (3) Energy-Efficient Designs: Emphasize low-power technologies and energy-harvesting capabilities.
- (4) Integration with AI and Autonomous Systems: Combine tactile sensing with AI for enhanced autonomy.
- (5) Modular and Scalable Sensor Arrays: Design sensors that are easily scalable and reconfigurable.
- (6) Multimodal Sensing Capabilities: Integrate tactile with visual or auditory sensors for comprehensive environmental understanding.

By addressing these areas, future tactile sensors will meet the stringent demands of space environments and advance autonomous robotic systems for space exploration.

CRedit authorship contribution statement

Hadi JAHANSHAHI: Writing – review & editing, Writing – original draft, Conceptualization. **Zheng H. ZHU:** Writing – review & editing, Writing – original draft, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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