Feeling Through Spacesuits:
Application of Space-Resilient E-Textiles to Enable Haptic Feedback on Pressurized Extravehicular Suits

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Abstract—**Extravehicular activity (EVA) spacesuits frequently remain bulky and pressurized, which impedes astronauts' ability to engage with the proximate environment and with fellow astronauts. In this project, a concept prototype for a sensate skin intended for the exterior of an EVA suit is manufactured using commercially available electronic fabric sensors. This prototype is then shown to discriminate between surfaces relevant to space explorers (metallic objects, rocky surfaces, and spacesuit gloves), implying that each surface can be translated into a unique sensory experience. Specifically, haptic actuators flush against the astronaut's biological skin can transduce sensory data from the external environment through the pressurized suit, allowing the astronaut to feel touch input right through the spacesuit. The key contribution of this work is to introduce a plausible application area for space-resilient electronic textiles using commercial off-the-shelf fabric sensors for demonstration.**

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1. Introduction

As humanity seeks to establish a more significant presence in Low Earth Orbit and beyond, human explorers will bridge the gap between quantitative scientific inquiry and keenly experiential discoveries. Indeed, NASA's famous *Visions of the Future* [1] convey humanity's hunger for rich, thrilling, and immediate sensory experiences of a cosmos filled with worlds that can be known and explored.

The direct engagement of explorers with their proximate environment is crucial for promoting both maximum situational awareness and vivid sensory feedback. However, the protective pressurized spacesuit worn by astronauts creates a thick boundary between the wearer's biological skin and the suit's space-exposed surface, isolating and impeding the wearer from engaging with the intuitive sensory and tactile functions of human biological skin.

SpaceTouch is a conceptual application area for fabric sensing on the spacesuit exterior. An implementation overview and a set of broad potential use cases for this concept are summarized in Figure 1a. This spacesuit composition enhances the safety of pressurized suits while reinstating a biological sense of touch. To do so, touch input from the protective suit's exterior layer is detected, identified, and mapped to a haptic feedback system on the wearer's biological skin, 'conducting' sensory data from the exposed skin to within the spacesuit.

2. Project Overview

To date, little has been done to augment the performance of the exterior fabric on spacesuits, despite this material offering key real-estate for distributed sensing in the vicinity of the astronaut. Recently, our group has been developing space-resilient smart textiles to one day enable a variety of applications on habitat and spacesuit exteriors, ranging from scientific characterization of interstellar space dust, to systems that inspire deeper connection between astronauts and their environments [2], [3].

In this work, we assess the technology requirements for effective human-computer interaction within a spacesuit by creating and evaluating a prototype of an external sensate skin capable of multimodal sensor measurements. Eventually, this external layer can be used either as part of a closed-loop haptic feedback system for astronauts in order to boost situational awareness in a variety of operational environments, or as an open-loop data source for remote monitoring of extravehicular astronaut activities.

Electronic textiles incorporated into spacesuits can also enable more descriptive remote-monitoring capabilities for mis-

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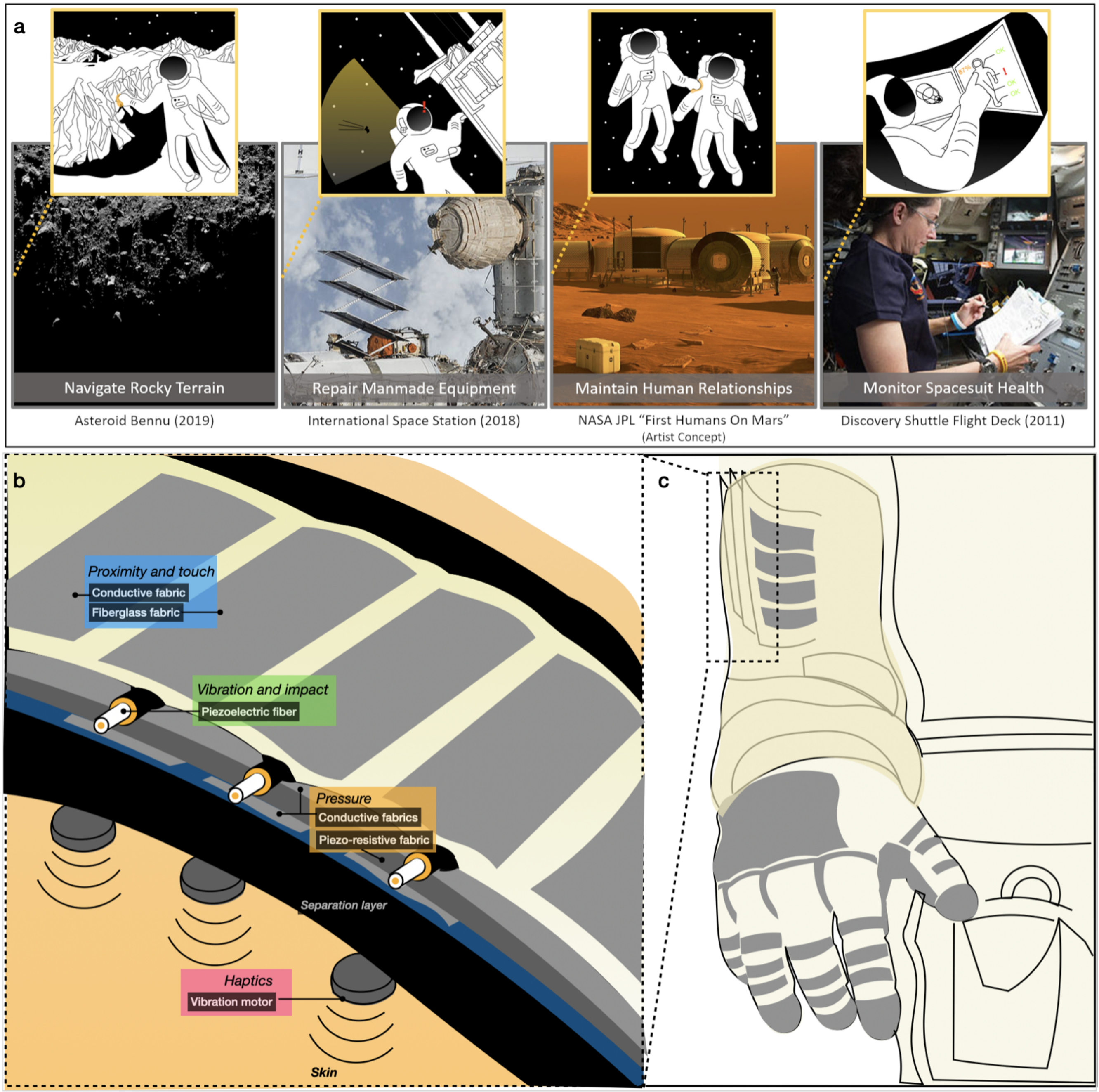

Figure 1. **a) Representative environments encountered by astronauts informing the current study, and b,c) exploded view of multi-modal e-textile spacesuit skin.**

sion control centers and other remote entities. In particular, it becomes possible to augment virtual renderings of astronaut EVA with data derived from the astronaut's proximate environment for real-time safety-monitoring and enhanced mission tracking purposes, as well as for astronaut training.

A representative prototype for this external skin is manufactured using primarily commercial off-the-shelf (COTS) fabric sensors integrated into an external armband representative of suits used for EVA and exploration. The sensors integrated into the suit's outer skin layer include capacitive proximity detection, piezoresistive pressure detection, and piezoelectric vibration detection (see Figures 1b-c). We assess this design by detecting and differentiating between textured end-effectors on a robotic manipulator, and show that it is possible to differentiate between environmental stimuli encountered by astronauts operating in different environments, allowing for unique haptic mappings associated with each stimulus.

The system architecture introduced in this paper can also be applied in hazardous aerospace or terrestrial environments where humans must perform dangerous operations. In such environments, electronic textiles and suits that sense environmental stimuli, protect occupants, and alert operators to any present dangers can provide intelligent protection and awareness, enabling greater degrees of operational efficiency and safety. Figure 2 shows a graphical interface that highlights regions of the spacesuit experiencing events of interest, such as tactile pressure on the spacesuit textiles, or the detection of an air leak.

3. Related Work

Conductive textiles date back to at least the 17th century - gold and silver yarn have been woven into ornate clothing and tapestries around the world [4], [5]. In recent decades, textile designers and engineers have started to take advantage of the conductive, resistive, and capacitive properties of these centuries-old fibers in order to create electronic textiles [6]. More sophisticated multi-material fibers are also now being designed. To provide some examples, these multilayer fibers may achieve piezoelectric properties [7], or contain microchips to confer sensory capabilities to digital platforms [8]. In general, advances in electronic textile technology have yet to be leveraged for space exploration, particularly in the case of space-exposed fabrics.

Multi-modal sensing for Human-Computer Interaction

In the field of Human-Computer Interaction (HCI), e-textile sensors for pressure, stretch, or touch detection are often fabricated by combining layers of conductive and piezo-resistive materials [9]. Both knitted constructions and embroidered constructions have been utilized in some of our research group's previous work exploring the use of e-textiles for music creation [10], [11], clothing-based sensing [12], and human-computer interfaces [13], [14].

Multimodal sensing has been used in HCI systems to incorporate sensory and emotional perception into devices through haptic feedback systems. For instance, inflatable actuators have been paired with force-sensitive resistors and air pressure sensors for haptic feedback on the torso similar to that of a hug [15], [16]. We derive similar functional principles, but gear our implementation and evaluation towards fabric-based systems augmenting personal protective equipment (PPE) within aerospace environments. By adapting fabric sensors in a way that they can be embedded within a pressurized EVA suit, the physical protective functions of the textile construction can be supplemented by digital safety-monitoring functionalities and the heightened situational awareness from sensory conduction.

E-textiles for Space Exploration

Despite exciting progress in electronic textile technology, today's spacesuits are not so different from the one that Alan Shepard wore inside Freedom 7 in 1961. The primary focus of NASA, SpaceX, and others in recent suit designs has been on improving astronaut mobility; at best, touchscreen-compatible fingertips have been incorporated as a modest nod to opportunities available for fabric functionalization [17].

There has been growing interest in porting e-textile technology to the internal construction of spacesuits for measurement of astronauts' health and wellness. MIT's Human Systems Laboratory and the University of Minnesota's Wearable Technology lab have studied strain sensors and other internal biological sensors to improve spacesuit fit and monitor human health in microgravity [18], [19]. Both ESA and NASA have also contracted with textile manufacturing companies over the years to develop adaptive textile technologies for astronaut wellness, such as carbon nanotube fibers that conduct heat to regulate astronaut temperature (NASA/NanoTex,

Figure 2. **Illustration of SpaceTouch Graphical User Interface (GUI) for real-time physical interaction visualization and safety assessment.**

2001) and fabric electrodes that keep track of muscle health (ESA/Aarhus, 2009) [20]. These public-private partnerships demonstrate interest in the potential aerospace applications of E-Textiles.

While astronaut health sensing will remain an essential application for e-textiles in spacesuit design, the construction and evaluation of these materials has been similar to that of Earth applications; since the fabrics are buried within the spacesuit, they do not need to survive extreme conditions, nor can they tell us anything about the space environment.

Meanwhile, when it comes to fabric on the spacecraft or spacesuit exterior, emphasis to date has been on engineering the material's intrinsic protective properties – UV and particulate radiation, atomic oxygen erosion, extreme thermal cycling over 90-minute orbital periods, outgassing under vacuum, and penetrations from impact are all risks in Low Earth Orbit. Besides passive protection, there is an isolated concept prototype for a pressure-sensitive helmet lighting control switch integrated into NASA/ILC Dover's 2001 I-Suit prototype [21]. In sum, the space-exposed fabric material has been largely untouched.

Haptics for Personal Protective Equipment

Haptic feedback systems are frequently considered as subsystems on robotic structures for human-robot interaction or human-human interaction over significant distance. For example, [22] describes a pair of haptically connected levers linking the International Space Station with Earth, enabling a virtual handshake to be performed at a round-trip distance of 163,000 kilometers within <20ms delay. Remote tactile contact for establishing shared presence at a distance has been long explored in the HCI community, for example the 1998 'In-Touch' project which explored haptics as a mode of interpersonal communication at a distance [23].

Concurrently, there has been a growing appreciation for the benefits of direct integration of feedback systems on extreme environment suits. The benefits of biological touch sensitivity during EVA was first established in a user study conducted in 2015 at the Mars Desert Research Station, in which a glove was equipped with an array of passive plastic pins embedded in silicone, and an internal transduction layer with electrically controllable stiffness was used to tune the coupling between interior and exterior layers [24]. In 2017, a multidisciplinary team of designers and aerospace engineers built the Enhanced Space Navigation and Orientation Suit (ESNOS) as a demonstration of the use of haptics for orienting astronauts in microgravity [25]. Then in 2019, the benefits of touch response in space were further studied from a physiological perspective, suggesting that sensory feedback may support psychological and social well-being, in addition to heightening experiences and promoting occupational safety [26].

4. CONTRIBUTION

We note a few central benefits to an all-textile, electrically coupled design approach for haptic feedback on spacesuits:

- Directly leverages the existing space robust textile substrate on the spacesuit
- Suitable for delivering haptic responses on pressurized regions of the suit, since layers are electrically rather than mechanically coupled
- Possibility for an enhanced sensing experience driven by a multimodal sensor suite, including sensing of surfaces proximate to the suit, light touches, or wind conditions on planetary bodies with atmosphere.

As illustrated in Figure 1b-c, the SpaceTouch multi-modal design consists of three main layers: an outer proximity and touch sensing layer containing conductive patches integrated onto a base fiberglass fabric, vibration and impact-sensitive piezoelectric fibers woven into channels in the fiberglass fabric, and multi-layer pressure-sensitive piezoresistive fabrics just below the outer layer. Capacitive coupling between an object as a virtual ground and charged conductive patches reflects touch and near-proximity. An intermediary foam layer separates the aforementioned layersfrom the inner layers of the spacesuit. An actuation layer that is coupled to the skin can provide closed-loop haptic feedback based on the sensor data. Our fully-textile-based sensor design and integration will enable future realization of single-layer capacitive, piezoresistive, and piezoelectric e-textiles that can sense and respond simultaneously to a variety of stimuli.

5. PROTOTYPE MANUFACTURING

First prototype

Two prototypes were constructed (see Figure 3). The first is primarily intended for conceptual demonstration purposes. Piezoelectric fibers were weft-inserted into a Beta cloth fabric simulant (a space-resilient material used on the exterior of the space station and Apollo-era Spacesuits) to serve as an exterior layer of an arm band (Figure 3a-c). The specifications for this representative Beta cloth material are detailed in [2], [3]. Eccentric rotating mass (ERM) motors are mounted on the inner layer of the band, with a thick foam used to isolate the two layers. The piezoelectric signal response directly drives the ERM motor vibration profile. Commercially available piezoelectric copolymer coaxial cables were sourced from TE Connectivity, with an internal construction consisting of multi-filament copper wire core with PVDF-TrFE dielectric and outer copper wire braid, sheathed in rubber cladding. The woven piezoelectric fiber (Figure 4) was fabricated by

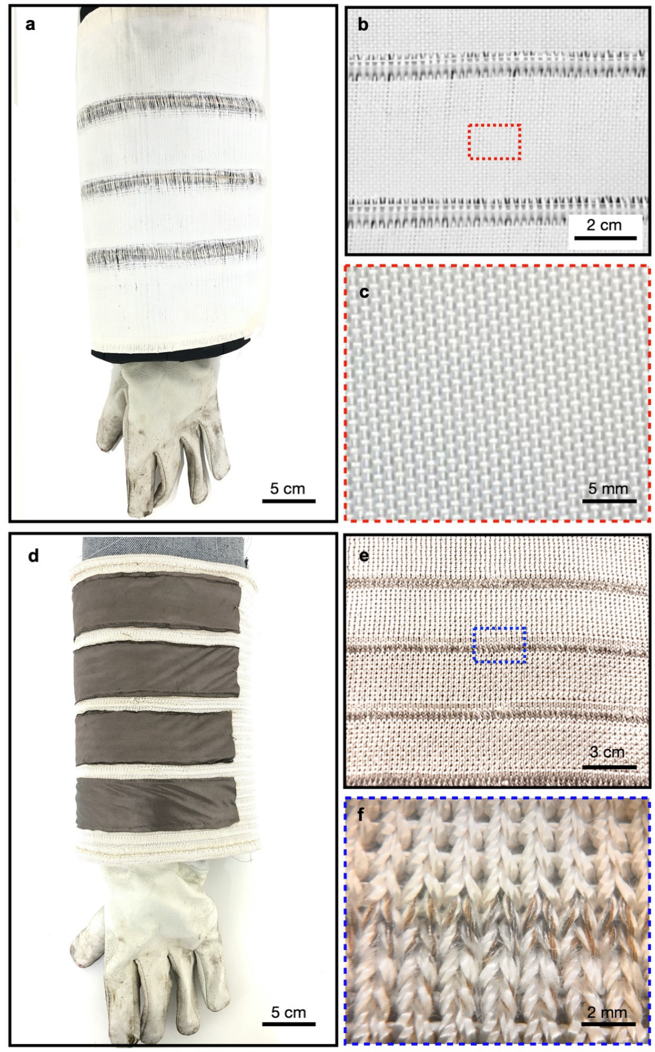

Figure 3. Prototypes of the e-textile spacesuit skin: a-c) Woven piezoelectric Beta cloth. d-f) Knitted fiberglass with conductive yarns and multi-modal embedded fabric sensors.

stripping the external rubber cladding and coating the PVDF-TrFE surface with conductive elastomeric ink (CI-1036, Engineered Conductive Materials). The coated fiber (Figure 4c) was then cured on a hotplate for 12 hours at 90 °C. The fiber sensors and Beta fabric used in this space-exposed material are currently under study on-board the International Space Station for robustness to the space environment. This prototype acknowledges the eventual need to ensure that materials used on the suit's exterior are compatible with the atomic oxygen erosion resilience, outgassing, thermal cycling, and abrasion resilience requirements for a space-exposed substrate. It also implements the full sensor-actuator concept.

Second prototype

For the purpose of increasing the channel count and multi-modal sensing capabilities of the prototype, as well as for the purpose of conducting quantitative sensory detection testing, a second prototype was constructed (Figure 3d).

We knitted fiberglass yarns (ET9, Jiangxi Glass Fiber Co., Ltd.) with a flat, two-bed digital knitting machine (Super-NJ

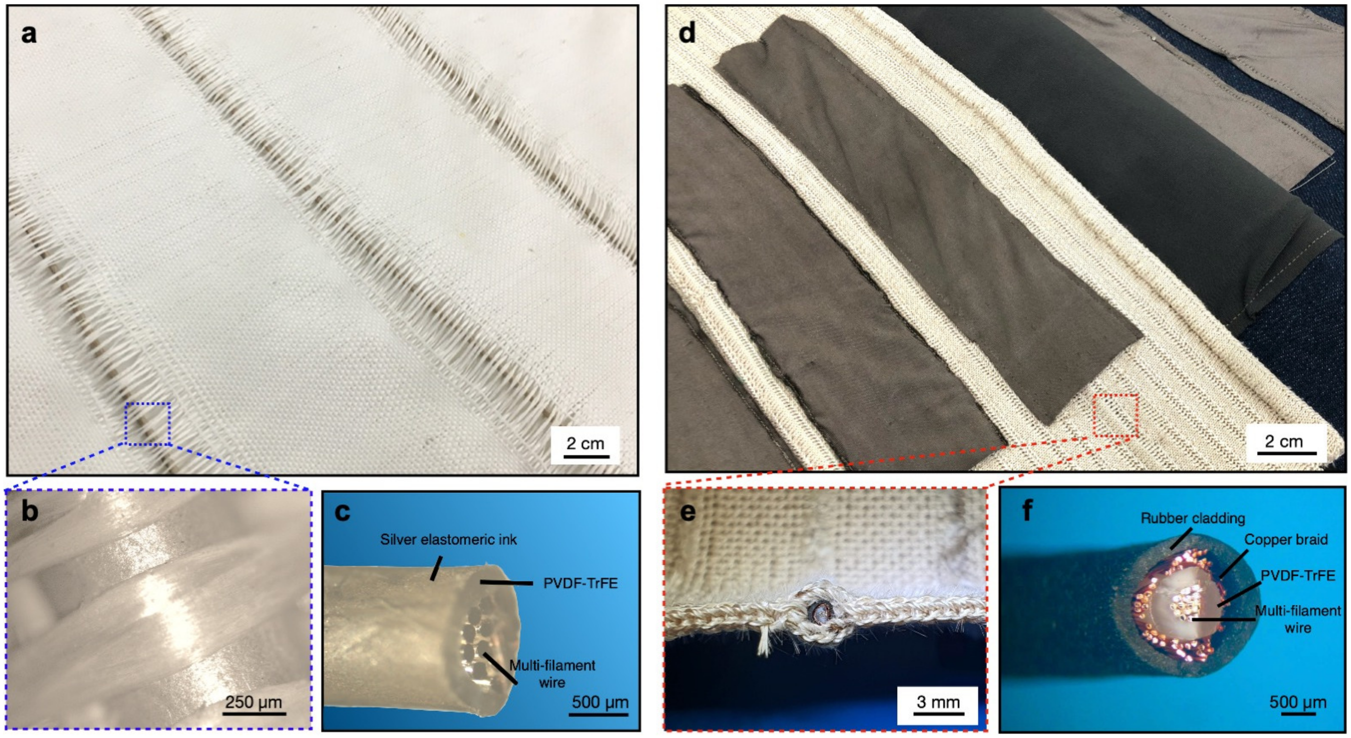

Figure 4. **Magnified images of piezoelectric fabric (top) and fibers (bottom). a-c) Piezoelectric fiber with silver elastomeric ink woven into a Beta-cloth, and d-f) multi-layer configuration of conductive and piezoresistive fabrics with piezoelectric cable in-lay in a knitted fiberglass fabric.**

212, Matsuya). Two yarn carriers were employed in order to develop two layers of weft-knit fabric. An interlocking mechanism was programmed to fuse two fabric layers into one. This was done by performing knitting sequences so that the front and back loop interchanged with each other. Hollow textile channels for threading piezoelectric fibers (Piezo Copolymer Coaxial Cable, TE connectivity) were knitted by programming front-knit and back-knit to loop independently on each side of the channel. As demonstrated in Figure 3e-f, we fed a combination of fiberglass and conductive yarns (Weiwei Line Industry) into one of the yarn carriers to develop a fiberglass fabric with seamless conductive patterns that could form electrical connections with the conductive fabrics shown in Figure 3d.

We then sewed four knitted conductive fabric patches (Stretch, LessEMF) onto the fiberglass fabric using a sewing machine (XL150, Singer) and wove three piezoelectric fibers into the knitted channels. For pressure sensing layers, we stacked two conductive fabric layers: one for grounding and the other layer for discretization into four patches. In between these layers, we embedded a knitted piezoresistive fabric (LG-SLPA-20k, Eeonyx Corporation). These layer configurations can be observed in Figure 4d. Figure 4e shows how the piezoelectric fiber is woven into one of the knitted textile channels.

6. Robotic Test Apparatus

System Implementation

To evaluate this design, textured end-effectors on a robotic manipulator are brought in contact with the fabric sensor suite in order to qualitatively assess that actionable environmental data can be collected and eventually transmitted through haptic interfaces to wearers.

In order to create sufficiently repeatable inputs simulating a variety of space-relevant stimuli, a robotic test apparatus was devised and implemented to evaluate sensor inputs from the e-textile. As seen in Figure 5, the test apparatus contains an actuating component, consisting of a 5-degree-of-freedom robotic manipulator (AL5D, Lynxmotion) and various end-effectors representing multiple surface types, and a sensing component, which is a representative sample of a sensate e-textile spacesuit skin.

In this test setup, the robotic arm is controlled by a computer issuing pre-programmed motion inputs. Three distinct end-effectors are mounted on the manipulator. During testing, the setup (Figure 5, and 6) was mounted on a table using sticky rubber padding under the manipulator for improved adhesion between the manipulator base and the underlying table. The fabric test sample (left, Figure 6) is also mounted on rubber padding to provide vibration isolation from the robotic manipulator.

This SpaceTouch prototype has a total of four piezoresistive patches for pressure sensing, four capacitive patches for touch and proximity sensing, and three piezoelectric fibers for vibration and impact sensing (Figure 5b). Sensor data generated by the fabric sensors are collected by a microcontroller (Teensy 4.0) using a set of mixed-mode analog/digital readout electronics: an MPR121 capacitive sensing board for capacitive proximity and touch detection, amplifiers to read out signals from the piezoelectric fibers for vibration sensing, and voltage dividers and voltage-followers for the piezoresistive fiber sensors. The MPR121 Proximity Touch Controller is utilized for capacitive sensing with thresholding

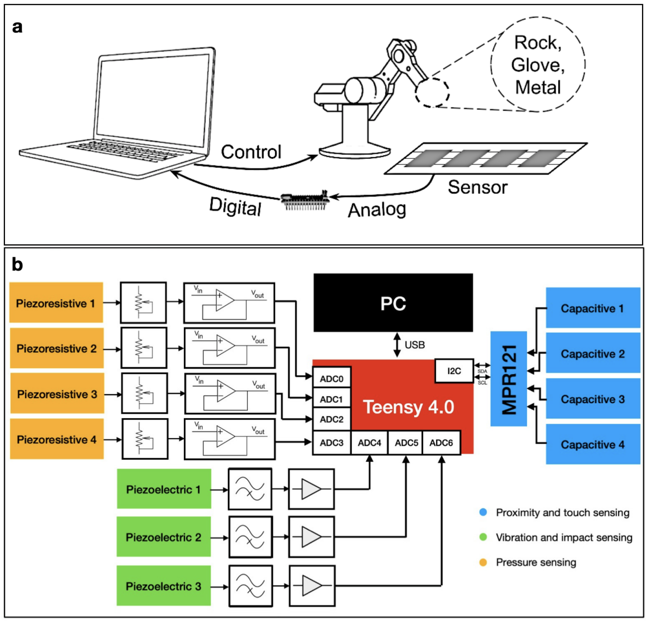

Figure 5. a) Test setup: a robotic arm actuates on the sensor with various end-effectors. b) System interface diagram of multi-modal e-textile.

to accurately detect discrete touch and an aggregate or multiplexed capacitive sensing for near-proximity detection. It has 12-channel input and measures capacitance by charging and discharging each electrode and measuring the voltage simultaneously to detect capacitive coupling from the approach of a finger or conductive object. The microcontroller combines these sensor data inputs and relays a serial data stream to the computer, where incoming data is collected and analyzed.

To provide a set of representative interactions with stimuli in aerospace contexts, the following motion sets were implemented with the robotic testbed:

- Impact (vertical motion directly onto the fabric)
- Stroke (side-to-side translational motion)

End-Effector Design

End-effectors were mounted onto the end of the robotic arm in order to simulate different objects that might come into contact with spacesuit fabrics. These end-effectors vary in surface texture as well as various material properties, including composition, weight/density, compliance, and conductivity.

To decide on a set of end-effectors to use for testing the sensitivity and characteristic signals generated by the sensate spacesuit skin, characteristic scenarios were considered that astronauts might encounter in space exploration applications. These scenarios were categorized into three key types: astronaut-astronaut interactions, astronaut-spacecraft interactions, and astronaut-environment interactions.

The following end-effectors were subsequently chosen as analogs to simulate these use cases due to their ubiquitous nature in space applications:

- Spacesuit glove
- Metallic object (representing components on a spacecraft structure)
- Rocky aggregate (representing Lunar/Martian rocks, or the surface of an asteroid)

Figure 6 shows the different end-effectors and depicts some characteristic motion profiles, such as increasing proximity, horizontal stroke, and perpendicular impact.

For the spacesuit glove, a leather work glove was used to reproduce the compliant yet form-fitting nature of spacesuit gloves. Support material was inserted within the glove to incorporate a degree of partial rigidity, similar to that of a hand with outstretched fingers. This allowed the "impact" motion to simulate an example case of an astronaut pressing buttons on a spacecraft or spacesuit interface, or poking another spacesuit, such as to get the attention of another astronaut. The glove was mounted onto the robotic arm, anchored onto the "gripper" portion of the manipulator to allow for wrist mobility, and reinforced in place for testing.

To simulate a metallic object, a stainless steel cup was mounted onto the robotic manipulator. When brought close to the fabric, it mimics the capacitive signature of an astronaut moving near to a metallic object, such as a spacecraft structure or metallic tools. While mounted on the manipulator, the cup is grounded to ensure an accurate representation of large space structures that can be detected with a large capacitive signal.

In addition, a rocky surface was imitated using assorted rocks mounted onto a polymer base using thermoplastic adhesive. These rocks, of various textures, sizes, and mineral composition, represent a variegated mineral landscape, such as rocky artefacts on lunar and Martian surfaces, as well as rocky aggregates that form the surface of asteroids. This end-effector also provides an example of a high-abrasion material that astronauts may interact with, and can further be utilized to evaluate the robustness of aerospace-grade e-textiles.

7. Results & Discussion

Findings / Impact

In Figures 7, 8, and 9, we visualize data from multiple datasets, highlighting the multimodal sensing capacity of the SpaceTouch sensate suit architecture. Piezoelectric fibers change detected vibrations, piezoresistive fabrics provide pressure readings, and conductive fabrics allow capacitive touch detection.

In the stroke motion from a glove and rocky surface (Figure 7), we observe that the end-effector creates oscillation signatures as it passes over discrete piezoelectric vibration sensors. In the case of the rocky surface, sequences of multiple oscillations are observed as multiple rocky pieces separately stimulate piezoelectric vibration signatures as they pass over the piezoelectric fibers. This is consistent with physical manipulation and the sensations that an astronaut may encounter as their suit rubs against a rocky surface or another astronaut touches their suit. The piezoresistive pressure sensors also demonstrate sequentially peaking values, with pressure curves unique to the amount of time that the manipulator spends on each patch as it moves sideways across patches on the fabric sample.

In the stroke motion using a metal surface (Figure 8), this horizontal translation is also represented in the capacitive touch data: while contact with a conductive surface is detected, the capacitive touch channels report a binary "1"; when there is no surface conductivity, a binary "0" is returned. Capacitive

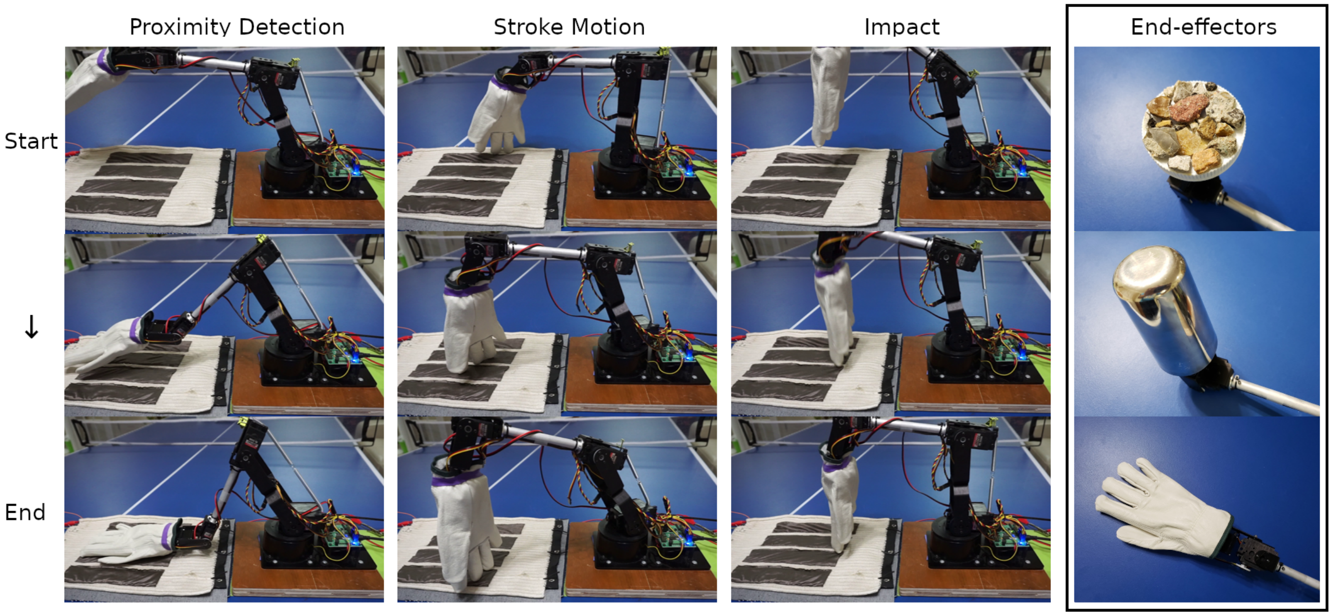

Figure 6. **The robotic test setup with glove arm motions (left) and end-effectors (right).**

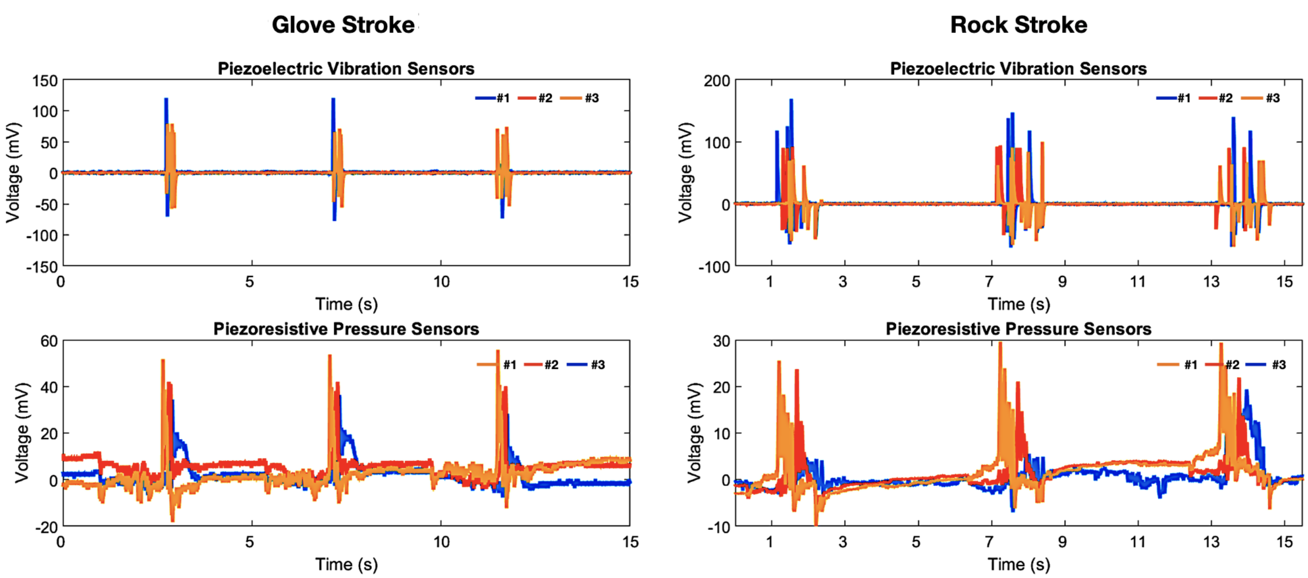

Figure 7. **Comparison between piezoelectric and piezoresistive response for a glove stroke motion vs. rock stroke motion. While the piezoresistive data is qualitatively similar, the rocky surface induces longer duration piezoelectric ringing.**

touch contact with a metallic surface also corresponds across multimodal channels, to the detected piezoresistive pressure. For example, capacitive touch is detected while force is also detected on the corresponding piezoresistive patch. As the end-effector moves across the fabric, different segments report detecting a touch. In this way, the motion of a conductive or capacitive surface can be "tracked" across the textile, and used in conjunction with piezoresistive pressure sensing to form a human-computer interface through the textiles integral to the suit.

In the impact motion from metallic and rocky surfaces (Figures 8 and 9), we observe that short, high-amplitude impulses create uniform pressure signals, focused on one main pad segment (red line) but also providing transient signal spikes in multiple channels. There are low levels of ambient piezoelectric vibration, with observed spikes consistent with brief impacts. Uniquely, the "bounce" from a falling object in a gravitational environment creates a dual-spike signature for strong impacts. Such signatures can be used to additionally characterize environmental properties as well as the physical properties of stimuli experienced by astronauts.

For the rocky surface, as expected, there is little variation in the capacitive touch detection, in the absence of any large ferromagnetic occlusions. Such signatures can be utilized to further detect and differentiate between different forms of stimuli, and provide a basis with which to automate stimulus-

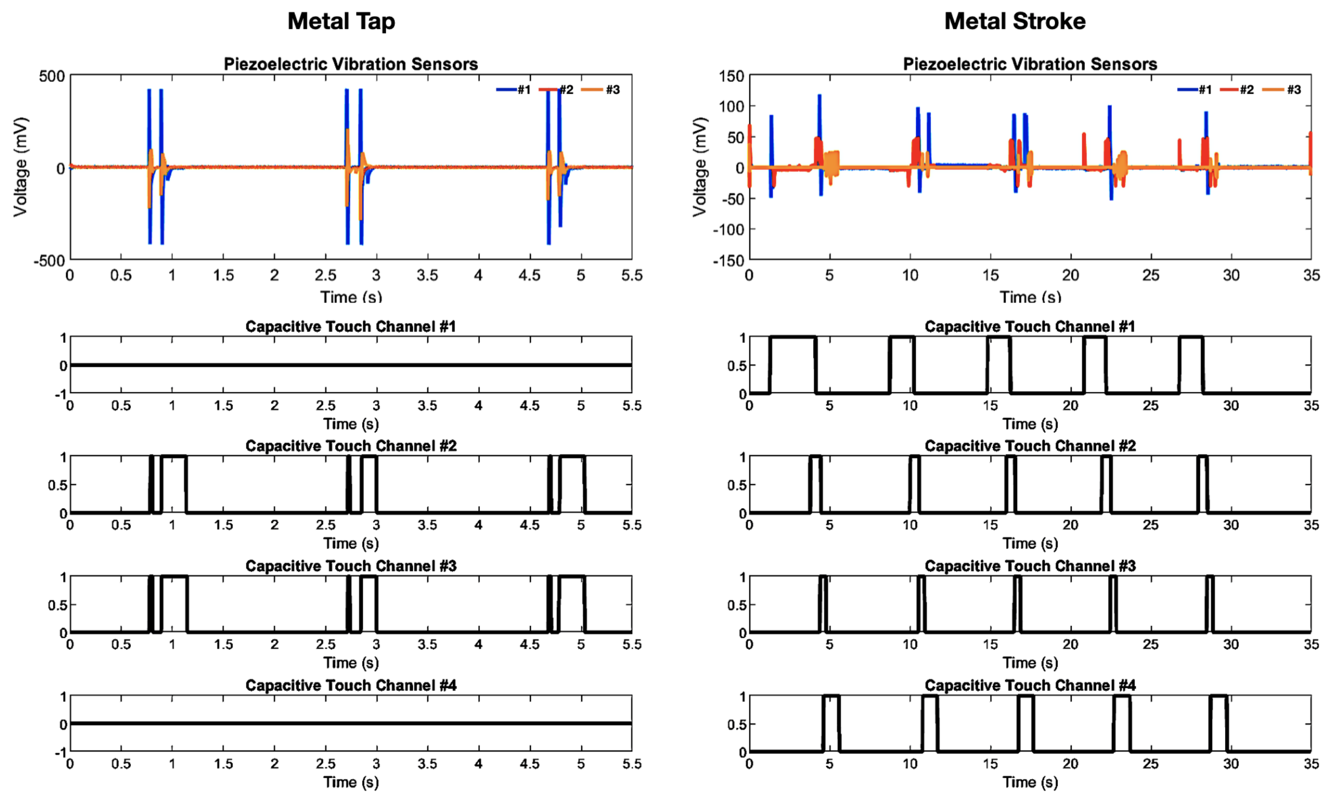

Figure 8. **Comparison between tapping and stroking gestures for metallic surface. A tapping gesture induces a higher amplitude piezoelectric response and more localized capacitive response across two channels, whereas the stroking gesture results in a smaller amplitude piezoelectric response and time-delayed capacitive response.**

detection algorithms in an intelligent SpaceTouch sensate skin.

To provide estimates of the sensitivity of the SpaceTouch textile-based sensors to different forms of stimuli, reference data for the lower bounds of successful proximity and pressure detection were collected from each of the end-effectors. This data, shown in Table 1, highlights the sensitivity of the multimodal sensing approach: capacitive and metallic objects can be detected in proximity to the astronaut and contact detected at zero nominal force; even light touches with low force can be detected from other stimuli such as rocky surfaces and gloves. In the appendix, we additionally provide reference data on manual stimulation using a bare human hand. We show that the e-textile can detect hand approach from up to 10 cm away, as well as detect a hand sliding over the textile through the subsequent touch (capacitive) and pressure (resistive) change (see Figures 10 and 11).

Haptic Actuation Strategies

Continuing the integration of haptic actuation as offered in our first prototype, we have identified factors to optimize for improved haptic sensory conduction, including:

- mapping of sensing modalities to unique haptic signatures
- differentiation of haptic signatures for disparate stimuli
- optimal distribution and localization of haptic actuators for different locations on the skin

We propose a modality-to-actuation mapping scheme that controls the intensity of vibration from an eccentric-rotating-mass (ERM) motor as a function of multimodal sensor inputs, as follows:

$$I(v,r,p) = \begin{cases} \textit{taps} \text{ where } T \propto \dfrac{1}{p}, & \text{if not touched } (r = 0 \text{ or } p > 0) \\ C_1 * v + C_2 * r, & \text{when touched } (r > 0 \text{ or } p = 0) \end{cases}$$

where

$$I = \text{intensity of vibration}$$
$$v = \text{piezoelectric vibration signal}$$
$$r = \text{piezoresistive pressure measurement}$$
$$p = \text{capacitive proximity measurement}$$
$$C_1,\ C_2 \text{ are scaling constants}$$

Using this scheme, gradually increasing proximity of a capacitive or metallic object can be represented as a series of "tap" sensations (achieved with short-duration activation of the motor for brief impulses) where the frequency of the taps increases as the object comes closer to the skin, similar to the auditory indicators of ultrasonic obstacle-proximity warnings in automobiles. Once a stimulus is in contact with the spacesuit, haptic actuation can be comprised of vibration impulses/fluctuations based on piezoelectric vibration impulses, combined with a consistent baseline vibration intensity proportional to the pressure intensity detected by the piezoresistive textile sensors.

Following established two-point discrimination guidelines that outline spatial acuity of differentiating haptic stimuli across the human body [27], we propose the placement of

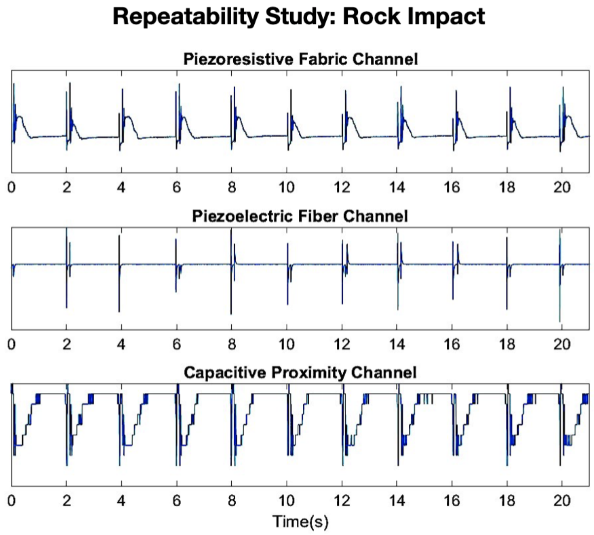

Figure 9. Repeatability study for 10x trials showing the similarity of multi-impact data from piezoelectric, piezoresistive, and capacitive proximity channels. Minor variability in the data can be attributed to wide tolerances associated with robotic arm motion.

Stimulus Type	Proximity Threshold	Pressure Threshold
Hand	10cm	0N*
Glove	0.2cm	0.3N
Rocky	0.7cm	0.3N
Metallic	1.8cm	0N*

* capacitive touch detection at zero nominal force

Table 1. Sensor calibration: reference for proximity and pressure detection for different end-effectors.

haptic actuators with interstitial distances of 2-5cm in areas of tactile significance, such as the forearm and upper arm. Such placement can also facilitate the utilization of semi-rigid liquid cooling channels to aid in vibration conduction over a larger surface area, or the placement of wiring and electrical connections in lines of non-extension throughout the suit [28].

8. Future work / Vision for Textiles

Implementation Steps

The current prototype is estimated to match a NASA Technology Readiness Level (TRL) of 3: an experimental proof-of-concept of characteristic technologies. In order to reach flight qualification (TRL 8), any fabric sensor mounted exterior to the suit will require demonstrated robustness to the relevant environment. In Low Earth Orbit, any exposed electronics should fulfill the following suggested guidelines:

- Ensure sufficient shielding from noise induced by the highly charged environment, such as by using shielded cabling.
- Ensure grounding of any exposed electrically conductive material, to prevent voltage-biasing of the suit or sensors.
- Ensure that materials used are characterized in a vacuum chamber for their vacuum outgassing properties, both in order to meet NASA standards and to ensure that outgassing does not substantially alter the functioning of the sensors over time.
- Ensure that exposed materials are resilient to atomic oxygen erosion while remaining mechanically flexible. If necessary, surfaces can be coated or covered with resilient materials.
- Ensure that sensor function is characterized as a function of temperature: maximum and minimum operating temperature should be specified and referenced relative to expected temperature exterior to the suit, where temperatures can reach extremes (-150 °C to 120 °C at worst) and fluctuate quickly as the spacecraft enters and leaves sunlit regions.

Under such harsh environments, materials with superior temperature resilience are preferred; thermally absorptive or emissive coatings can help to regulate internal temperature. Active thermal control systems may be integrated, e.g. using resistive heating elements and thermal radiators to regulate the external suit's temperature. For spacesuits operating on rocky surfaces, abrasion resilience is a critical additional consideration.

While the Beta cloth fabric used in prototype #1 is regularly used on persistent orbital spacecraft and on Apollo-era suits, Ortho-fabric (a Nomex, Gore-tex and Kevlar blend that balances mechanical flexibility and resilience) is also currently commonly used as a spacesuit outer layer. Further characterizations can explore tightly-coupled integrations of textile sensors with alternative base layers constructed of materials such as Ortho-fabric, especially in conjunction with haptic actuation.

Further work in haptic actuation can include the development of textile-based haptic actuators to complement our prototype, as well as implementing and characterizing proposed haptic actuation strategies. We also aim to further explore various sensor-actuator integration strategies, networked in-fabric communication, and flexible power distribution techniques and textile topology to realize a large-surface-area sensate skin that can cover an astronaut's whole body [29], [30].

9. Conclusion

SpaceTouch is a conceptual prototype motivating the use of electronic textile technology for enhancing the situational awareness, operational safety, and general wellbeing and connectedness of astronauts. We have described some of the key technical considerations and candidate sensing modalities in service of this vision, and have further demonstrated this concept by constructing an e-textile sensate skin prototype and validating multimodal sensing capabilities as they correspond to human touch sensations. In this way, SpaceTouch reflects and seeks to advance the mission to augment human spaceflight by enhancing human sensory capabilities and counteracting the sensory insulation of conventional pressurized spacesuits.

Acknowledgments

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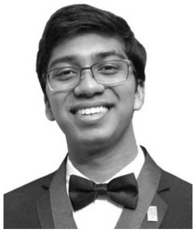
BIOGRAPHY



Syamantak Payra *is an MIT undergraduate studying Electrical Engineering and Computer Science. His interests lie at the junction of science, engineering, and human experiences, and he is passionate about creating technologies with human impact. His previous research has included developing robotic orthotic devices for gait rehabilitation, biomedical sensing for health monitoring, and computational fibers for intelligent fabrics, with additional interdisciplinary work across fields like materials science, microbiology, and public policy. He is a US Presidential Scholar, and the MIT Lincoln Laboratory has named Minor Planet 33610 "PAYRA" in recognition of Syamantak's international-level awards for scientific research.*

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Joseph Paradiso *is the Alexander W. Dreyfoos (1954) Professor in Media Arts and Sciences, where he serves as the Associate Academic Head and directs the Media Lab's Responsive Environments group, which explores how sensor networks augment and mediate human experience, interaction, and perception. Paradiso worked as a Tufts undergrad (where he received his BS in electrical engineering and physics summa cum laude in 1977) on precision inertial guidance systems at Draper Lab, then completed his PhD in physics at MIT in 1981, while working with Prof. S.C.C. Ting's group at CERN in Geneva as a K.T. Compton Fellow. After two years developing precision drift chambers at the Lab for High Energy Physics at ETH in Zurich, he joined the NASA-affiliated group at Draper Laboratory, where his research encompassed spacecraft control systems, image processing algorithms, underwater sonar, and precision alignment sensors for large high-energy physics detectors. He joined the Media Lab in 1994, where his current research interests include wireless sensing systems, wearable and body sensor networks, energy harvesting and power management for embedded sensors, ubiquitous/pervasive computing and the Internet of Things, human-computer interfaces, space-based systems, and interactive music/media. He has written over 350 publications and frequently lectures in these areas. In his spare time, he enjoys designing/building electronic music synthesizers, composing electronic soundscapes, and seeking out edgy and unusual music while traveling the world.*

APPENDICES

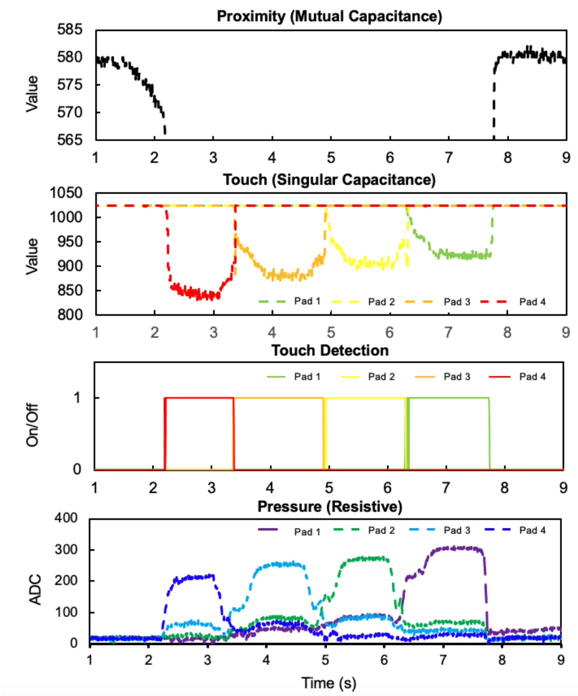

Figure 10. **Manual stimulation: horizontal stroke motion.**

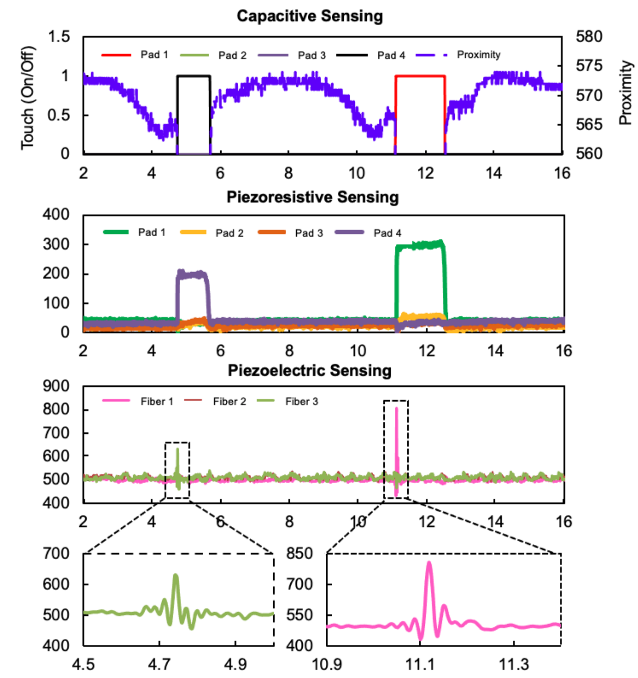

Figure 11. **Manual stimulation: tapping.**