From UbiComp to Universe—Moving Pervasive Computing Research Into Space Applications

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Humanity's burgeoning crewed and uncrewed presence in space is creating increasing opportunity for ideas and approaches gestated for terrestrial use to be adapted and deployed in space applications. To illustrate this from the perspective of the Pervasive Community, this article overviews a selection of recent and ongoing space-oriented projects in the MIT Media Lab's Responsive Environments Group, and chronicles the roots that most of them had in our prior Pervasive Computing research program. These projects involve wearables, smart fabrics, sensor networks, cross-reality systems, pervasive/reactive displays, microrobots, responsive space habitat interiors, and self-assembling systems for in-space infrastructure. Many of them have been tested in zero-gravity and suborbital flights, on the International Space Station, or will be deployed during an upcoming lunar mission. Assessed together, this portfolio of work points forward to the broad role that some of the tenets of Pervasive Computing (e.g., novel sensing technologies, "smart materials," and best-in-class modern HCI infrastructure) will play in our near-term space future. This work marks an important inflection point in the space industry, where academic research experiments are rapidly maturing—on the scale of months, not years—to influence the products, tools, and human experiences in low earth orbit and beyond.

As humans and the engineered systems they construct venture increasingly into space in upcoming years, they will bring and send along the technologies that evolved with them on Earth. Space technology has become associated in the popular imagination with engineering pushed to extreme lengths to solve very difficult problems, generally with custom solutions that engage limited numbers of systems and users. The technologies developed for space applications are assumed to be esoteric and particular, thought as a driver for technical advance rather than vice-versa (witness, for example, integrated circuits, which found their first heavy exploitation in the Apollo program and went on to transform the electronic industry[1]). Since the original Space Race of the 1960s and 1970s, however, computing technologies and applications have advanced enormously in terrestrial applications, and we have seen profound impact, especially in areas where humans contact computation, such as human–computer interfaces, pervasive computing, and the Internet of Things. This transformation is spreading to spacecraft; for example, the maze of switches and controllers dominating 1960s manned capsules and the Space Shuttle cabin recently yielding to an array of touchscreens in the SpaceX Dragon.

Astronauts on the Space Station rely on laptops they bring from Earth for much of their work rather than running on computers embedded in the spacecraft. For example, the station's flight and systems control computers tend to be locked into the earlier processor generations because of the rigor of fault-tolerance and space qualification as well as restrictions put on code that can run on them, hence

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FIGURE 1. Smart textiles for space. (a) SpaceSkin with electronics (left/center) and passive sample flying outside the Space Station [right], (b) under TVAC Test, and (c) conceptual layout for SpaceSkin strips with opposing tactile actuators for the "Sensory Conductor" in a spacesuit arm. Peristaltic Suit layout (d) and working prototype during 0–G test flight.

commercial terrestrial computers (albeit they still require some qualification for outgassing, safety considerations, etc.) can be significantly more capable. Looking forward, especially as more people work in space over the upcoming decades, the transformative technologies under development in the Pervasive Computing research community (such as elucidated in the sections that follow) that people on Earth are increasingly living with, will find ample application in space.

For the last 25 years, the Responsive Environments Group at the MIT Media Lab has focused much of its research around aspects of Ubiquitous and Pervasive Computing. However, playing host to the MIT Media

Lab's Space Exploration Initiative over the last five years has provided us an impetus to pivot many of our Ubicomp projects into space applications. Indeed, as our Space Initiative and other opportunities have provided a regular "conveyor" of opportunity[2] to run experiments on periodic zero-G parabolic flights, suborbital rockets, Space Station deployment, and even impending delivery to the Lunar Surface, ideas we have gestated within the Pervasive Computing Framework have been pushed into actual space-related test and deployment. With increasing interest in the Pervasive Community toward space applications (e.g., the SpaceCHI workshop[3] starting a couple of years ago, which some of us have participated in setting up), the evolution of pervasive projects into space is of increasing relevance. Accordingly, this article traces several research threads and projects in our group boosted from their UbiComp roots into Space application and deployment. Table 1 summarizes the key works introduced in this review, and Figure 4 includes a conceptual image of a space habitat leveraging several of these capabilities.

ELECTRONIC TEXTILES, WEARABLE SYSTEMS, AND SURFACE DIAGNOSTICS

Dating to the 1960s, spacesuits, at least in terms of their monitoring and control capability, were predecessors to wearable computers.[4] These ideas came back to Earth, as wearable systems and smart apparel became a tenet of Pervasive Computing decades later.[5] Our group has been working at the integration of computation, sensing, and fabric/material for the last two decades in what we call *Sensate Media*,[6] which bears promise for a variety of space applications. As we have progressed from designing fixed sensor nodes on rigid substrates to dynamic nodes on conformal surfaces, and sensing capability of fabric has improved with better-integrated electronics,[7] it becomes increasingly of interest to consider the fundamental properties of the material in relation to its operating context. Hence, we have moved increasingly toward resilient textiles, inert silicones, and eventually more exotic substrates as we develop such pervasive media. This evolution is important in designing for the harsh space environment, where atomic oxygen erosion, radiation, hypervelocity micrometeoroid impacts, and extreme thermal cycling all wear on external systems.

The International Space Station (ISS) currently depends upon gas leak sensors, external robotic arms, extravehicular space walks, and visual observation for locating damage caused by debris. Indeed, in August 2018, the Russian segment of the ISS began to slowly depressurize. Suspicious of penetrative debris impact, astronauts searched for external holes from the cupola using zoom lenses and binoculars, representing the state of affairs when it comes to damage detection on the ISS.

We have redesigned a habitat's protective thermal blanket to simultaneously operate as a dense sensate skin by weaving a variety of piezoelectric fibers (which respond to impact shock) and plasma sensing electrodes (which detect charge created by high-velocity impacts) into standard white "Beta Cloth" spacecraft wrap,[8,9] shown in Figure 1(a). Following an impact event, the skin would localize (and ideally characterize) damage and strategically summon optical or other kinds of imaging free-flying or crawling nodes for further appraisal. This aerospace architecture emulates the coordinated nature of a biological pain response in the sense that we reflexively mitigate uncertainty in what is felt on our skin by summoning the attention of our eyes.

ACCORDINGLY, THIS ARTICLE TRACES SEVERAL RESEARCH THREADS AND PROJECTS IN OUR GROUP BOOSTED FROM THEIR UBiCOMP ROOTS INTO SPACE APPLICATION AND DEPLOYMENT.

In contrast to typical electronic textile projects in the HCI community, such an augmented fabric sensor system designed for the extravehicular space environment must eventually undergo shock/vibration testing (for launch survival), thermal vacuum testing (for robustness to the relevant space environment), and ground characterization (to justify launch in the first place). Pictured in Figure 1(b) are two fabric swatches undergoing thermal vacuum testing ahead of launch to the Space Station's exterior walls, where one of them is currently residing and taking data.

Once such sensate space-ready materials are designed and well understood, they can also be considered for other applications. In this case, we have been building out a conceptual framework called a "sensory conductor," in which this skin would serve as a robust exterior to pressurized spacesuits and map external stimuli to the wearer's biological skin. In other words, this enables astronauts to feel through the walls of their extravehicular spacesuits. A basic scheme is shown in Figure 1(c) and described by Payra et al.,[10] which details

TABLE 1. Outline of projects presented in this article.

Project	Long-term Vision	Phase of development	Key technical or conceptual challenge
Electronic Textile Enhanced Thermal Blanket	Fabric walls of spacecraft can track damage and sense interstellar dust impact	Demonstrated impactor sensitivity thresholds using ground-based accelerators. Sensor performance maintained following 15-month LEO exposureperiod	Improve mechanical resilience of fiber sensors to thermal cycling and ambient vibration/ charge.
SpaceTouch	Astronauts will vividly feel touch and texture through walls of pressurized suits	Conceptual prototype	Sleek integration between interior and exterior suit layers
Peristaltic Suit	Wearable telemedicine system and real-time intervention for cardiovascular deconditioning and microgravity adaptation.	Demonstrated in a zero-gravity flight to study the effects of microgravity and active compression to various physiological markers.	Miniaturization of skin-contact hardware and their seamless integration into a spacesuit.
SpaceShoe	Intelligent dynamic foot restraint that enables walking on ferromagnetic surfaces.	Early electromagnet- based sole retrofit tested in zero-gravity flight.	Adopt electropermanent magnets w. intelligent controller to anticipate gait, and low-mass attachment surfaces.
SpaceHuman	Controllable appendage for dynamic hands-free grappling.	Pneumatic soft-robotic version 2.0 tested in zero- gravity flight.	Develop automatic/guided higher speed grappling control.
AstroAnt	A swarm of AstroAnts build a dynamic extra- vehicle sensor network for space station, gateway, Lunar rovers, etc. The AstroAnt swarm can help with inspections and diagnostic sensing with different sensor payloads.	Finished design and tests of the proof-of-concept on four parabolic flights, and finished design, development and tests of a flight hardware unit for lunar surface testing in 2023/2024.	Efficient energy harvesting approaches, accurate tracking techniques, and mobility on nonmagnetic materials.
TESSARAE	Scaling humanity's presence in orbit through autonomously self- assembling space infrastructure	Prototype hardware, code, and mission conops (Concept of Operations) tested successfully on two parabolic flights, one suborbital launch, and two ISS missions	Transitioning hardware electronics and controls from test-prototypes to the first human-scale tiles for self-assembly of a human-rated space station.
LunarWSN	Build wide-spanning Wireless Sensor Networks (WSNs) on the Lunar surface to study properties of regolith in areas-of-interest and do long-term Lunar environment monitoring.	Finished design and tests of the proof-of-concept.	Lunar dust impact on solar energy harvesting and long-term operation in shadowed areas.
Cross-Reality Mission Operations	Represent all aspects, assets, and players in space operations through diverse mixed reality immersion	Developed for terrestrial environments and demonstrated using a variety of rovers with data from simulated missions	Refine frameworks for scalable presence and human/robot control at various delays.
Mediated Atmospheres In Space	Automatically adapt the sensorial environments of long-term space-farers to keep them focused and restored.	Demonstrated in terrestrial rooms—conceptual "pods" for space applications designed, prototyped, and exhibited.	Prototype realistic MA pods and habitats, test in space analog missions.

preliminary tests. This work is still at the stage of a conceptual demonstration with partial prototypes.

Sensate vests for monitoring cardiovascular performance and respiration have been under development in the wearables community since the late 1990s and although they continually improve with technology, some have already been productized. Applications in space health suggest prophylactic actuation as well, since prolonged exposure to microgravity induces various acute health risks, including muscular, vestibular, and cardiovascular dysfunctions.[11] Without the influence of gravity, bodily fluid hydrostatic pressure gradients vanish, and blood distribution shifts from the astronaut's legs toward their upper body. Providing continuous medical monitoring and intervention for astronauts throughout their journey in microgravity and after their return to Earth is, therefore, imperative. Along with exercising machines, compression systems such as

FIGURE 2. Dynamic astronaut restraint systems: SpaceHuman (a) tail linkage skeleton, (b) deployed with active pneumatics during 0–G test flight; and active magnetic outsole, (c) in prep, and (d) during 0–G Test Flight.

orthostatic intolerant and passive antigravity skinsuits have been commonly used as countermeasures.[12] However, these garments do not adapt to the astronauts' physiological and physical changes and cannot exert controllable pressure throughout the body. Inspired by the Peristalsis phenomena, which is the propagation of contraction and relaxation of muscles in our gastrointestinal tract, we have developed the Peristaltic (PS) Suit [see Figure 1(d) and (e)] by embedding soft, textile-based actuators and sensors into an intravehicular activity garment with miniaturized and wireless sensing-actuation control hardware.[13,14] It consists of an array of air pouches that can be individually controlled for dynamic pressure or compression gradients across the body through a wearable, compact, and light-weight pneumatic system.[15,16] It is also equipped with multiple wireless skin-contact compression pressure sensors, inertial-measurement units, and physiological sensors that constantly measure heart rate, respiration, blood pulse transit time, temperature, and blood oxygenation level of the wearer. Incorporating both sensing and actuation systems enables us to

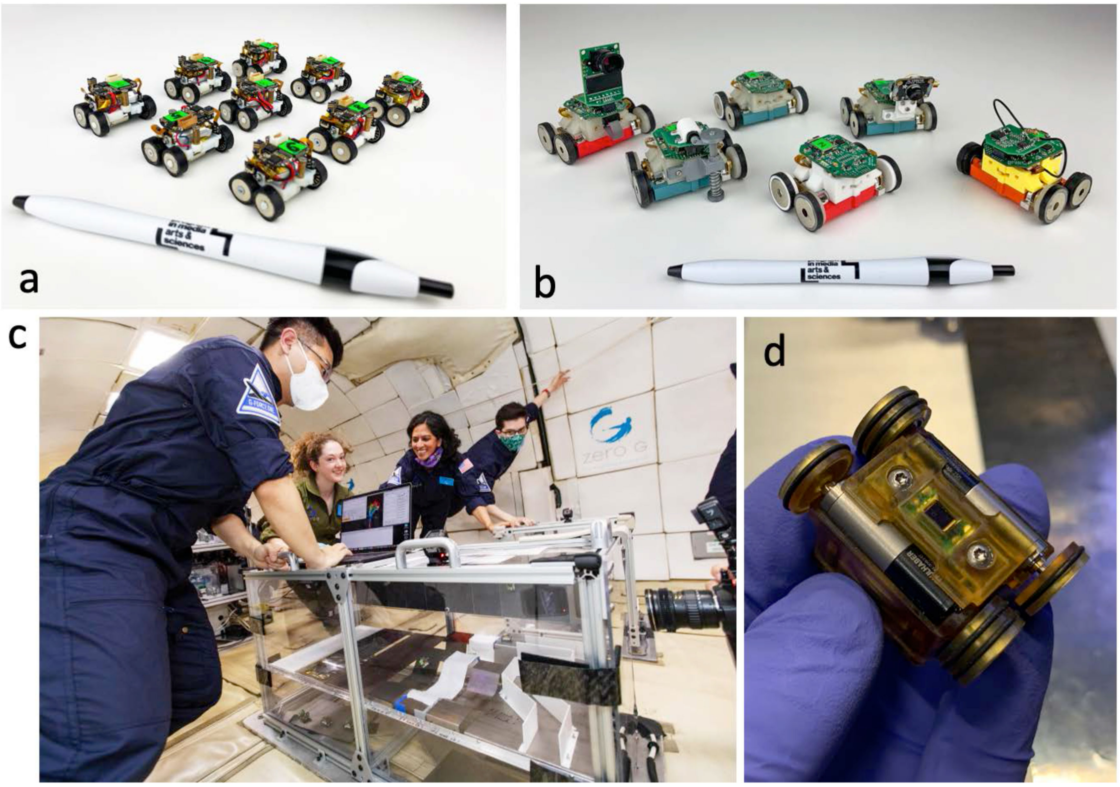

FIGURE 3. AstroAnt MicroRover for Spacecraft Inspection. (a) standardized rover set, (b) customized set with diverse sensing, diagnostic and servicing capabilities, (c) 0–G testing atop various surfaces, and (d) AstroAnt designed for deployment atop the Lunar Outpost Rover—bottom view showing thermal sensor, space-qualified motors, and magnetic wheels.

perform closed-loop intervention and study the direct influence of active compression on various physiological markers.

The PS-Suit platform can not only allow remote diagnostics and better regulation of cardiovascular health and body fluids of astronauts, but also augment their physical training through active muscle compression, plus provide emotional support and physical feedback through embodied haptic transfer, as well as monitor and prevent other microgravity adaptation health risks such as osteoporosis, skeletal muscle atrophy, spatial disorientation, and motion sickness. The design and control framework of the PS-Suit will also be applicable in other health, rehabilitation, or soft robotics applications not only in outer space, but also on the Earth in the form of hyper-gravity(G) suits, athletic or lymphedema compression garments, shapewear and corsets for exoskeletons, and surgical tourniquets. Wearable telemedicine systems integrated into spacewear will ultimately help preserve and maintain astronauts' and space explorers' health and well-being seamlessly and comfortably during and after long-term spacefaring or lunar or other low-gravity operations.

For most crewed operations, it is crucial to anchor an astronaut properly in zero-gravity—especially if both hands are involved in a task, without proper attachment, one hand is often dedicated to holding on to a rail or handle. Current solutions include tethering astronauts to fixtures or attaching to foot restraints. As our group has a long and early history of developing shoes equipped with wireless sensors for electronic dance and gait analysis,[17] or outfitted with power generating elements for energy harvesting,[18] it is only natural that we had turned our attention again to shoes, but here prototyping a favorite fantasy of science fiction, the magnetic boot. Although passive magnetic boots are commercially available (e.g., for roofing) and some variations have been suggested for spacecraft,[19] more conventional restraint systems have proved practical and adequate for current space work. With new developments in space operations involving more people in larger habitats, the time is ripe for developing new adaptive astronaut restraint systems, and as improved magnets and more control options have become available, we have revisited this idea. Our initial proof-of-concept design is an outsole retrofit using standard double-sided Velcro strips to strap on different types of shoes, regardless of their size, with two powerful remotely-actuated flat electromagnets (WF-P70/9, rated at 12 V DC each, capable of maintaining 250 N stiction while activated) that pull against a thin magnetic steel strip fixed to the spacecraft "floor." We have recently tested a very early prototype [Figure 2(c) and (d)] on a zero-gravity flight, and are refining our design to use energy-saving electropermanent magnets (that are only pulsed for release) and will feature an automatic mode driven by sensors that anticipate that a foot is pulling up to actuate its release, adapting gait prediction techniques that researchers are pursuing in smart robotic prosthetic limbs.[20]

Another approach that we have explored to securing astronauts involves a strap-on robotic appendage. These have been explored before in HCI, for example, as extra assistive arms.[21] But in our case, the seahorse's unique tail structure provided inspiration for the overall biomimetic design that we adopted. Indeed, among all the marine creatures that use their tail for swimming, seahorses make particular use of their flexible and resilient tail to grasp objects in their environment. Our prototype, *SpaceHuman 2.0*,[22] shown in Figure 2(a) and (b), is a wearable soft-robotic additive prosthetic that can move around the body to grasp objects and handles in microgravity through an object tracking camera, protecting the wearer from injuries that might occur while floating in a confined habitat, while providing an adaptable and kinematically stable base. *SpaceHuman 2.0*, has been developed via different computational design methods, and tested at a basic level (without active tracking) in different gravity conditions (microgravity, lunar gravity, and Martian gravity) on two Zero-G flights [see Figure 2(b)]. Through 36 pneumatic actuators specifically designed to be shape-changing and bend along a reinforcing rib of the material, astronauts and space tourists can use *SpaceHuman* to cling to useful surfaces inside orbital housings. The augmentation of human performance through wearable soft-robotics solutions could be integrated with fashion aspects of spacesuit design and the architectural aspects of responsive habitat interior design. Adapting the tail to vacuum operation would require more robust materials or a mechanical approach.

MICROROVERS AND SWARMS

Inspired by the "Selfie Drone," a conceptual design where a drone resting on your wrist would fly up to take a "selfie" photo then return to its perch,[23] we began thinking about how robotic systems could fuse with Wearables. This enquiry resulted in the development of our *Rovables* microrobots, which were designed to traverse clothing to serve a variety of novel user-interface functions.[24] The *Rovables* design was subsequently adapted to serve a series of space projects starting with a version that would traverse a net anchored to a microgravity object of interest (such as an asteroid). The net provides a stable infrastructure that would allow robotic assets to reliably move to particular locations in order to conduct exploration and other operations. We have also made and tested initial prototypes of autonomous grapplers located at several points around the net that could grab onto surface features and thus help to anchor it there.[25]

After preliminary development, aspects of this project pivoted into a related space application through the NASA Tech Flights program—e.g., traversing the outside of spacecraft to determine vehicle integrity and assess any potential damage. Traditionally, when damage or an exterior anomaly is assumed, a camera (perhaps on a robotic arm) or astronaut on an EVA would be dispatched to investigate. EVAs are complex and risky operations, however, and cameras are limited in what they can assess, and may not have access to the entire spacecraft.

Robots have long been used for on-orbit servicing, such as Canadarm 2 and the ERA systems[26] that serviced the International Space Station. Platforms that apply robotic systems to implement on-orbit serving have recently been designed and/or tested, such as the OSAM-1 (On-orbit Servicing, Assembly, and Manufacturing 1) for on-orbit assembly, manufacture, and refuel,[27] and MEV-1 (Mission Extension Vehicle 1) for repositioning satellites.[28] The on-orbit service provided by these platforms can extend satellites' lifespans. Most of these robotic systems are fixed, large, and cost-intensive platforms. The motion of these heavy and bulky robotic systems are coupled into the base platforms, which makes the dynamic and kinetics analysis of the system more complicated during on-orbit service.[29] Smaller, autonomous robots can provide better mobility and greater functional flexibility, such as inspecting narrow spaces that are not accessible or hard-to-reach for human astronauts or large robotic systems. Building on the knowledge we obtained from our *Rovables* project, we expanded the applications of the miniature rolling robotic swarm to space—which we term *AstroAnt*.

The *AstroAnt* [Figure 3(a)] is a miniature robotic swarm aimed at servicing the outside surface of a spacecraft or systems working on planetary surfaces, such as rovers or landers, for inspection and

FIGURE 4. TESSARAE test tile, circuitry (top left) and in active deployment on a 0–G flight (top right); and on the International Space Station (middle); conceptual view (bottom) of the interior of an assembled structure depicting several Space Initiative projects, including some described here, in action.

diagnostic tasks. With magnetic wheels, the robots can attach to ferromagnetic surfaces.

Four zero-gravity flights have been conducted to test their mobility (speed and obstacle- overcoming ability) and sensing capabilities in microgravity environments through the NASA Tech Flights (REDDI) program. During these flights [Figure 3(c)], the mobility mechanism enabled the robot to reach ~8 cm/s on low-carbon sheet steel, aluminum sheets with magnetic paint, and beta cloth simulant (in this case, with the use of a magnetic pinch roller on the opposite side of the beta cloth, as in the original fabric-traversing *Rovables*). In a zero-gravity environment, the robots can round a corner of 70° in pitch, which ensures that they can overcome ramps and corners enroute to an area-of-interest on the external surface of spacecrafts, rovers, or landers.

With a modular design, each *AstroAnt* robot can carry different sensor payloads, which can be tailored based on different inspection tasks and diagnostic missions [see Figure 3(b)]. The sensor payloads we developed include a visual camera for optical inspections, a thermopile for contactless temperature measurement, a thermal camera to obtain a thermal map of an area-of- interest, and an eddy current sensor for metal flaw detection.

Built on this work, we designed another model of the *AstroAnt* robot that will be sent to the Lunar south pole with Intuitive Machines and Lunar Outpost as early as 2023. This microrobot will be working on the MAPP1 rover's top surface, which is the radiator of the rover's thermal system. Equipped with a thermopile on the bottom [Figure 3(d)], the robot can make contactless temperature measurements of the radiator and help monitor the performance of the thermal system.

Although there are some improvements needed, such as better tracking mechanisms, building a mesh network for multihop communications within the swarm, and viable energy-harvesting approaches, the *AstroAnt* robots have promising potential to support future deep space exploration.

AUTONOMOUS ROBOTICS AND SELF-ASSEMBLY FOR SPACE HABITATS

Cooperative and reconfiguring robot swarms have been used in various projects related to the Pervasive Community,[30,31,32] and it is only natural that spacecraft exploit this capability. We already see the beginnings of this with dynamic spacecraft docking and ensemble control.[33,34] Our TESSERAE (Tessellated Electromagnetic Space Structures for the Exploration of Reconfigurable, Adaptive Environments) Project[35,36] builds on this tradition via self-assembly of large space habitats from discrete smart tiles that can be launched in a compact flat stack, thereby fitting into existing spacecraft fairings. This endeavor anticipates the need for modular, reconfigurable infrastructure in orbit—from self-assembling habitats, to parabolic mirrors, to dynamically evolving multiunit satellite buses.

The TESSERAE project charts a multiyear research effort to study, characterize, simulate, prototype, and test quasi-stochastic self-assembly in microgravity environments. The component tiles are tuned to autonomously self-assemble into a particular geometry—in our initial prototypes [see Figure 4(a)], we have focused on the buckminsterfullerene (20 hexagonal tiles, 12 pentagonal tiles). During assembly, tiles autonomously assess their bonding status and can separate and rejoin via applying current pulses to magnetic joints, to form a more perfect target geometry. Each tile, at minimum, includes a rigid outer shell, responsive sensing and control code for bonding diagnosis, wireless communication via Bluetooth Low Energy modules (supporting both mesh and central-station configurations), electropermanent magnets for dynamically controllable bonding actuation, and an on-board power management system. TESSERAE hardware has flown on two parabolic flights [see Figure 4(b)], one suborbital flight, and two ISS missions [CRS20 and Ax1—Figure 4(c)] and is currently being spun out of the MIT Media Lab for habitat-scale applications.[37]

WE ALREADY SEE THE BEGINNINGS OF THIS WITH DYNAMIC SPACECRAFT DOCKING AND ENSEMBLE CONTROL.

The "TESSERAE" name and multitile structure hearken to the small, colored tiles used in Roman mosaics, where many standard pieces, or "tesserae," interlock to form a larger creation. We make this reference to ancient history when designing an artifact of our space exploration future to tie architectural elements together across scales and across millennia. We aim for TESSERAE to function as multiuse, low-cost orbiting modules that supply a critical space infrastructure for the next generation of zero gravity habitats, science labs, staging areas for on-surface exploration, and more. TESSERAE should be thought of as flexible and reconfigurable modules to aid in both small-scale, agile mission operations and grand-scale, iteratively expanding space architecture. Our mission concept focuses on supporting LEO, Lunar and Mars operations, with dual-use orbit and surface capability:

- Tiles are packed flat and condensed for launch;
- Tiles are released after orbit insertion to quasi-stochastically self-assemble into the target geometry, while floating in microgravity;

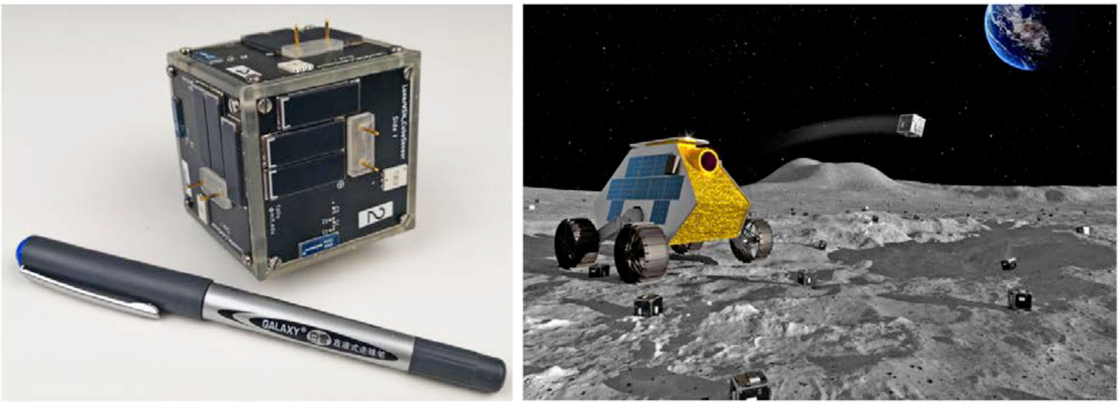

FIGURE 5. Lunar wireless sensor node, working prototype (left) and conceptual ballistic deployment from a rover (right).

- Once assembled, the structure can be reconfigured on demand (e.g., where a berthing port tile was needed yesterday, a cupola tile can be replaced tomorrow);
- Tiles can be disassembled entirely, packed flat again in an EDL (Entry, Descent and Landing) vehicle, and then deployed and "snap-assembled" with astronaut assists on the lunar or Martian surface.

Multiple, interlocking TESSERAE can serve as a larger-volume orbiting base (e.g., "MOSAIC": Mars Orbiting Self-Assembling Interlocking Chambers), in addition to supporting the coming waves of space tourists and space hotels in low Earth orbit.

SENSOR NETWORKS—EXPLORATION SENSING IN EXTERIOR EXTREME ENVIRONMENTS

Our group has been designing, building, deploying, and using a variety of terrestrial sensor networks for 25 years, and we have explored a host of wearable, smart/responsive buildings, and environmental sensing applications with them.[38] The large, outdoor, multimodal, low-power wireless sensor network (WSN) that we designed for deployment at Tidmarsh Farms,[39] a former cranberry bog that has been transformed into a wetland wildlife sanctuary, inspired us to evolve different kind of node suitable for lunar deployment.[40] Taking a modular, configurable approach, such as we used for wearables in the early 2000s,[41] this node has the form factor of a CubeSat (although is only 1/8 the size: $5 \times 5 \times 5$ cm—Figure 5 left) and is designed to be ballistically "shot" out of a launcher on a rover or lander to access lunar terrain that the main platform (such as a single high-cost rover or lander) cannot reach (e.g., rockpiles, craters, etc.)—Figure 5 right. After the nodes are deployed to the lunar surface, they establish a WSN (which we term LunarWSN) with hardware redundancy that can reduce the chance of failure.

Each node is equipped with wireless communication and wireless ranging capability. On each side of the cubic sensor node, there is a wireless communication antenna, a wireless ranging antenna, and solar cells to guarantee powering, functionality, and wireless connection with a communication relay or other sensor nodes, regardless of landing orientation. After the nodes are deployed from a rover or lander, they can be localized and set up as an expandable WSN. With a modular design, each sensor node can carry different sensor payloads for collecting desired scientific data simultaneously from multiple locations. Although other sensing systems were explored,[40] the exemplary functional LunarWSN node of Figure 5 is equipped with electrode probes and an impedance convertor to study the character of the Lunar regolith, where we suspect the existence of water ice.

WSN technology can play an important role in future *in situ* planetary exploration,[42] providing meter-scale spatial sampling that aids in better understanding of dynamic phenomena.

CONNECTION TO VIRTUAL ENVIRONMENTS

Although virtual and augmented reality have had some exploratory use in space mission formulation, for example, with the design and verification of the Perseverance Rover and other projects at JPL and other NASA centers,[43] the frontiers of mixed reality hold enormous potential for near-future hybrid mission operations.

Since 2004, our group has explored various ways spatially tagged sensor information is rendered in

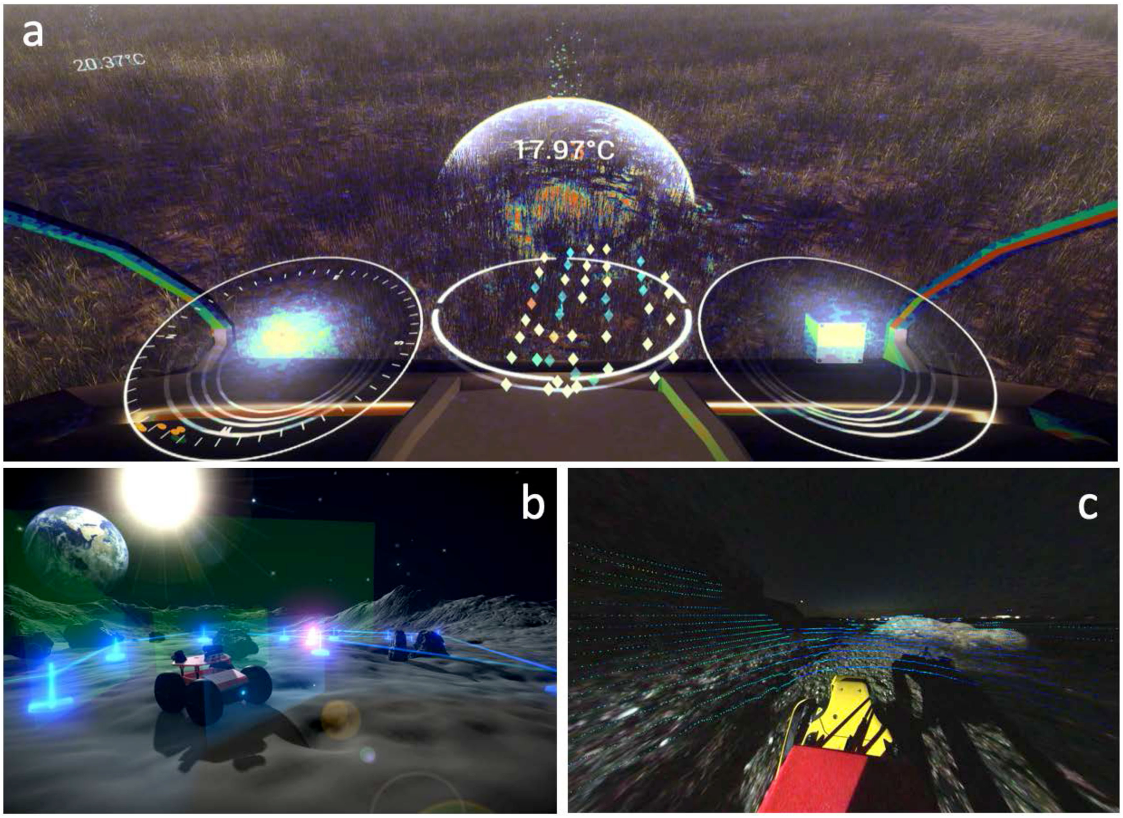

FIGURE 6. (a) Virtual "Rover" control panel run in Doppelmarsh, showing real-time sensor data. (b) VR mission planning for lunar rover. (c) AR overlay of laser ranging data from Spot walking robot.

virtual worlds, making "Digital Twins" that allow users to explore a real environment by navigating engaging "Cross-Reality" analogies.[44] These culminated in our DoppelLab[45] and DoppelMarsh[39] experiences that enable real-time browsing of multimodal sensor data via animations, sensor-driven music, and streaming audio in virtually rendered analogs of our Media Lab building and the Tidmarsh Sanctuary [e.g., Figure 6(a)], respectively. The terrain in Doppelmarsh is generated by LiDAR measurements collected in 2012 by the United States Geological Survey (USGS) at the real site and imported into a custom software developed with the Unity game engine. Real time and cached sensor data from the field are stored in a PostgresQL database and streamed within the virtual landscape through Chain-API,[46] our custom hypermedia web service based on the REST architecture that serves JSON+HAL and WebSockets on demand. DoppelMarsh supported over a dozen projects (see http://tidmarsh.media.mit.edu), and as it ran openly online for many years, it was experienced by many users—we know of several who would just leave it running to enjoy the aesthetic connection to the sanctuary. This suggests another way to connect the general public to space and places where most will never go, namely by aesthetically/artistically interpreting space-related data streams into ambient or immersive experiences that people can enjoy.

In collaboration with the Human Systems Lab (HSL) in MIT's Aero/Astro dept and NASA Ames researchers, we are exploring moving these concepts into space mission ops, where various assets (rovers, sensors, orbital platforms, and even AIs) and personnel distributed across vast distances, diverse time delays, and different degrees of immersion need to blend together.[47] Our current efforts in virtual space presence focus on two applications of human–robotics interaction. The first simulates a virtual space analog containing a digital-twin 3D model of a four wheeled rover (provided by Rover Robotics), deployed in a 60×32 sq. ft room that is mirrored by an artistic rendering of a lunar environment built with the Unity game engine [Figure 6(b)]. The user interface and interaction follow a real-time strategy (RTS) game-like view, giving the user the ability to control a virtual model of

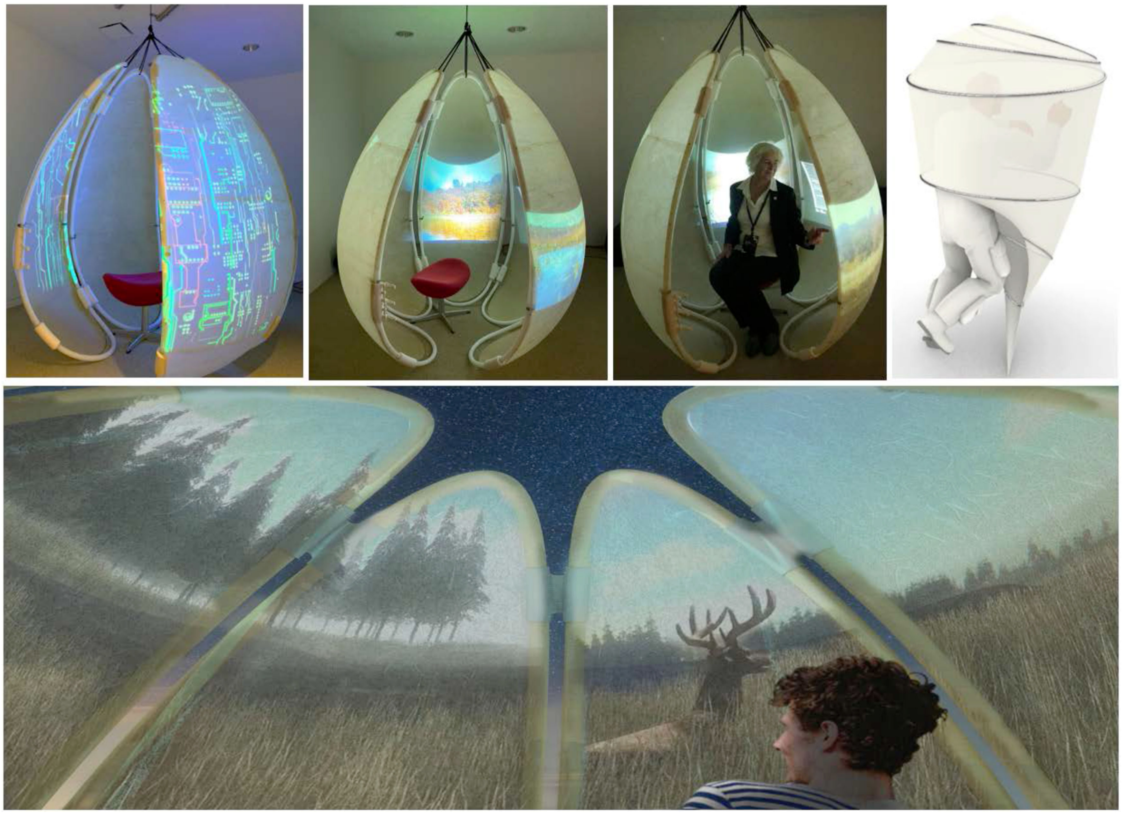

FIGURE 7. Mediated Atmospheres in Space: Top Right, the VR Astropod, a conceptual design for a compact, private immersive facility in space (in collaboration with SEI member Tamalee Basu). Top Left, different views of the Tidmarsh Living Observatory Portal prototype with live video projections (middle images). Bottom, artistic impression of the fully developed Portal in operation.

the rover from within the lunar environment by setting waypoints. The virtual rover will follow the path set by the waypoints, while keeping track of previous traverses through a color scheme reference. In the second experiment, a SPOT quadrapod, provided by Boston Dynamics, was deployed in an outdoor rocky seashore environment [see Figure 6(c)]. The robot was augmented with a Velodyne LiDAR and a custom multipurpose 3D-printed payload, which served as a container for swapping various data-collection cameras and devices (currently a 360° video camera, and higher resolution LiDAR scanners). As seen in Figure 6, the sensor data can appear as a video overlay and in the UNITY visualization environment.

MULTISENSORY INTERIOR EXPERIENCES

In this era of Internet of Things, smart buildings will increasingly become partners, where they can change properties to dynamically suit their users by leveraging context and information coming from wearable and *in situ* sensors. We have realized several projects in this area, including our *Mediated Atmospheres* systems, that explore how indoor terrestrial environments can respond to occupant's physiology and affect their cognition by sensing multimodal signals (including activity level, heart rate, breathing rate, posture, electrodermal activity, skin temperature, and facial gestures) and controlling lighting, projected images/video, ambient sound, and even airflow and smell to keep them in a high focus-restoration state.[48,49] This concept has attracted interest for long-duration spaceflight, where a variety of stressors could cause crew members to experience complex psychological challenges that will likely become more severe as the mission progresses and exposes astronauts to situations of extreme sensory deprivation and loneliness.[50] Moreover, deep space settings might increase the general reduction of stimuli and monotony inside the space habitat, since it is an entirely artificial closed-loop environment.[51] To compensate, perhaps the spacecraft can transform its presentation in accordance with the state of the astronaut. We have focused explicitly here on compact pods and customization of individual habitat modules, where an astronaut can essentially float inside a reactive audio/video display or personalized enclosure module.

Mediated Atmospheres in Space conceives a new experience for space mission workspaces that can self-regulate on the basis of an occupant's activities and perceived affect in a closed-loop fashion. This type of workspace can instantly adapt to users' requests and/or their affective state, and trade, for example, the engaging focus of a library with the liberating sensation of a stroll through the forest. The responsive controller relies on ubiquitous, nonintrusive sensing of the occupant's activity, work habits, and physiological or behavioral reaction to environmental changes. Building on data from realistic work scenarios, it has been possible to create personalized occupant response models for appropriate multimedia response. Dynamic control presents an opportunity to synchronize the workspace experience with the ever-changing requirements of today's workers and future space explorers.

We have prototyped such an experience (Figure 7) in the *Tidmarsh Living Observatory Portal*,[52] which is a compact, individual multisensory experience that generates an immersive physical real-time telepresence into the enchanting natural Tidmarsh wetland by recreating visuals, smells, and sounds representative of the site, and streaming live data as well as past recorded data, thereby also allowing travel across time. For maximizing immersion, the overall experience is tailored for a single user and lasts for a minimum of three minutes, up to half an hour. Leveraging projected graphics or embedded large displays, it avoids the constraints and disorientation that VR goggles can produce. The architectural design of the pavilion is based on a human-centered design approach inspired by the idea of recreating an individual Tidmarsh ecosystem wherever the Portal is going to be located. Inside such a cocoon, astronauts will feel protected and transported into restoring terrestrial environments such as this natural wetland, where they will be able to adopt their own stress–relief activities, like meditation, reading, or relaxing, while being immersed in the beauty of nature.

CONCLUSION

In the bright dawn of this new space age, unprecedented opportunities abound to deploy and test ideas in space. However, to appropriate Heinlein, "Space is a Harsh Mistress," a demanding environment that has always required and encouraged wide-ranging technical advance and adaptation. Yet, as people go into space, they will be transformed by the technology they bring along. The revolutions that the UbiComp/Pervasive/IoT axis bring about on Earth will usher a change in the human (e.g., affecting perception, cognition, even identity as we are increasingly connected and augmented by AI). This will be defining for future spacefarers who will rely on, or even more crucially, be transformed by this technological backbone. it is not yesterday's astronaut that will go out there... And as a research group grounded in Pervasive Computing, we have been delighted to crack open a few views into this quickly moving future and expose new pathways toward Pervasive space implementation.

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