How the Internet of “Space” Things will Disrupt and Transform Astronaut Work-Life

Improving astronaut execution tools to enable crew autonomy in long duration exploration missions through integrated sensor information

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Future long duration exploration missions will require astronauts to work and behave more autonomously. Over the last several years, we have been investigating how integrating sensors into an astronaut’s environment enables crew autonomy. This paper describes the prototypes we have deployed in Earth analogs investigating the concept of the Internet of “Space” Things.

CCS Concepts: • **Human-centered computing → Human computer interaction (HCI)**; **Field studies**; • **Computer systems organization → Sensor networks**.

Additional Key Words and Phrases: procedure execution, internet of things, timeline, space exploration

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1 INTRODUCTION

Astronauts both live and work onboard the International Space Station (ISS). Most astronauts’ missions are around six months long and their time is occupied with a great variety of assigned work. The high profile, safety-critical aspects of spaceflight such as launch/re-entry, extravehicular activities (EVA) or spacewalks, and robotic operations usually capture the attention of the public and media. However, a significant portion of work that astronauts complete are complex tasks that involve completing scientific experiments and maintaining the spacecraft. Preparation for these tasks begins years before flight when astronauts receive training on the various systems and experiments with which they are expected to interact. Unfortunately, astronauts must frequently complete tasks for which they received training months prior, and they are expected to perform these tasks efficiently in a microgravity environment that they have only recently been living and are often still adapting to. In order to facilitate task execution, astronauts receive step-by-step instructions and are often guided in real-time by subject matter experts on the ground. While astronauts continue to work in low Earth orbit, this concept of operations is sufficient, albeit arguably inefficient.

As NASA moves towards long duration exploration missions (LDEM), like those envisioned for Moon and Mars, the present concept of operations will be ineffective. Astronauts and mission control will have to contend with increasingly long communication transmission latencies as well as intermittent communication. Space-to-Ground will no longer be real-time access to experts. Instead, future astronauts will have to work and behave more autonomously, leveraging

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mission control and ground flight controllers only sporadically. We believe that this requires a technological disruption in an astronaut's work-life. Over the last several years, we have been investigating how integrating sensors into an astronaut's environment may enable more autonomous task completion, improving work in space. This paper describes the prototypes we have deployed in Earth analogs investigating the concept of the Internet of "Space" Things for crew autonomy.

2 CURRENT TASK EXECUTION TOOLS

Astronauts are assigned work and can keep track of task assignments through timeline tools, which include a sophisticated, shared calendar for multiple users (both in space and on Earth). Each assigned task in the timeline is called an activity and each activity has a set of corresponding instructions called procedures. Activities have a status, indicated by color, and an astronaut can mark an activity started or completed by changing its color. A change in color is visible to everyone with access to the timeline, communicating start and completion of tasks. Currently, OPTIMIS Viewer is used for ISS, while Playbook [8, 9, 11] is used for most analogs, including NASA Extreme Environment Mission Operations (NEEMO) and Human Exploration Research Analog (HERA).

Currently onboard the ISS, astronauts use the web-based tool known as International Procedure Viewer (iPV) to view and complete their procedures [12]. These procedures provide step-by-step instructions for everything astronauts do onboard the ISS, including tasks ranging from science experiments to basic maintenance. The basic elements of these procedures include text and images, and can also link to videos and other related procedures. Additionally, there is a comprehensive list of supplies (and corresponding locations on ISS) required to complete the assigned tasks. Compared to the paper-based procedures that were used for the Apollo and Space Shuttle missions, synchronization between iPV clients allows ground support to follow along with astronauts as they complete procedures, reducing the time it takes for them to jump in and provide assistance.

3 INTERNET OF "SPACE" THINGS

The Internet of Things (IoT) has recently become an ubiquitous technology. The Internet of Things is a term which describes a "network of sensors and actuators within or attached to real-world objects" [1]. IoT is commonly used on Earth to enable smart home devices such as virtual assistants (Google Home, Amazon Echo), to control lights (Philips Hue), temperature (Nest Thermostat), monitor for smoke (Nest Protect), and provide home security with monitoring (Ring Doorbell) and smart locks (August). Additionally, IoT has also recently begun to enable topics essential to future space operations such as habitat monitoring [14], precision farming [13], robotic movement planning and execution [4], and maintenance procedures for monitoring and safety systems [2]. Its application to NASA and directly to human spaceflight operations, however, is novel.

As we consider how to implement an Internet of "Space" Things, we offer a framework for the levels of interactions astronauts have when they work in space (see Fig. 1). Most work conducted by astronauts in space can be characterized in this framework. An astronaut must interact with a procedure viewer to receive instruction and then interact with some hardware to complete the assigned task within an environment. The hardware may be items like tools, experimental hardware, vehicle subsystems, or even the spacecraft itself. All of these levels (hardware, astronaut, procedure) reside within an environment, like a spacesuit, spacecraft, or space itself. For example, an astronaut conducts repairs on the treadmill (hardware) onboard ISS (environment), guided by procedures. At each of these levels of interactions, sensors can be placed and provide a unique value. We hypothesize that the integration of a sensor suite will enable more efficient and effective astronaut work.

We approached disrupting the work conducted in spaceflight operations carefully, as it is a safety-critical domain. We began by first identifying the most applicable tasks to start introducing the Internet of Space Things (IoST). We have explored integration of a variety of sensors to enable proximity detection, such as RFID, Bluetooth, Wi-Fi, and contact sensors. Our initial work focused on tasks that are assigned to astronauts but do not command the spacecraft, like experimental setup activities. In this paper, we highlight three prototypes which were evaluated in either Earth analogs or in a laboratory setting: 1) modeling and tracking astronaut position within the environment to communicate timeline progress, 2) integrating hardware tracking and communicating real-time locations, and 3) combining various sensors on hardware and astronauts to confirm procedure progress.

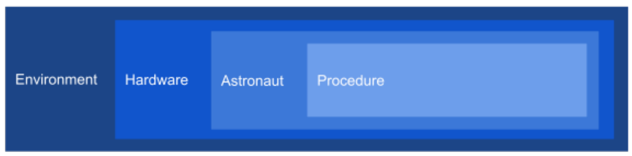

Fig. 1. Framework for levels of interaction between astronaut with procedure and work.

4 ARTIFACTS WITH ASTRONAUT EXECUTION TOOLS & INTEGRATION OF SENSORS

4.1 Avoiding Congestion

NEEMO missions use Aquarius, a habitat located about 60 feet underwater. With only 400 square feet of work-life space, understanding where work is conducted allows for efficiencies, avoiding interruptions and congestion while protecting crew privacy. In order to manage the numerous experiments conducted in a short two-week mission, the timeline included a model of each activity's location. Within Playbook, if activities were assigned to different crew members at the same time but used the same space, a warning or violation is shown. Real-time tracking progress on these activities was also essential in order to avoid upcoming conflicts. If crew were taking longer than expected, planners had to project if future assigned activities would create congestion, potentially indicating rescheduling was necessary. While the activity's status was leveraged, astronaut position (in this case, video as a proxy to sensors) also confirmed which activity crew was completing. Future extensions of this prototype would include independent, autonomous tracking of astronaut position, cross-referencing with modeled or expected position, in order to automatically status activity progress.

4.2 Finding Supplies

On NEEMO missions, we partnered with the commercial RFID tracking company AllTraq in order to integrate location data capabilities into Playbook. AllTraq RFID tags were placed on crew members, equipment, and supplies, which allowed them to be location-tracked within Aquarius in real-time. This data was then displayed within the Playbook user interface (see Fig. 2), allowing all crew members and mission control to easily see where various items were located. This functionality proved particularly useful for crew members as activities planned in Playbook showed all the relevant supplies and equipment along with their locations inside the habitat, simplifying the setup process for many experiments. On the mission control side, support personnel benefited from having a bird's-eye view of all tagged items. Not only did this give ground support another data point when guiding crew members in experiments, but it also eliminated the frequent need to directly ask the crew about specific equipment location. Given the usefulness of only one data type (location), the addition of more sensor information to various equipment and tools could have even greater benefits in analog environments and various types of tasks.

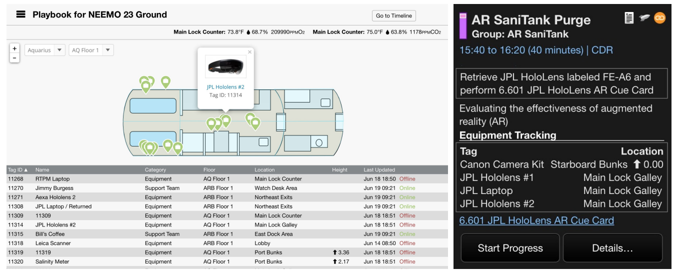

Fig. 2. Displayed in Playbook, all equipment and personnel locations (left) and detailed equipment tracking within activity (right) during NEEMO 23.

4.3 Successful Confirmations

Our ongoing laboratory experiments at NASA Ames have focused on using IoT sensors and devices to enable just-in-time training for procedure execution and have specifically focused on maintenance and assembly tasks [5]. Our early work showed that procedures could be replaced by a basic combination of LEDs and connection sensors, enabling the construction of simple electrical circuits. Through the integration of small, low-powered chipsets such as ESP8266s with sensors, we have demonstrated that naive users can quickly and correctly complete procedures which would otherwise require additional training. By measuring the Received Signal Strength Indicator (RSSI) between IoT equipped tools, hardware, and user worn wristbands, we have guided novices to specific work areas and tools. This sensor data has also been fed directly into our prototype procedure execution tools, providing feedback to users when they correctly (and incorrectly) follow procedure steps and automatically tracking progress through the procedure. These sensor-enhanced procedure execution tools were selected to be deployed at NASA Johnson Space Center HERA for their upcoming missions, where they will be evaluated in an analog operational environment.

5 FUTURE WORK

NASA is currently investigating ways to improve operations in future exploration missions. We propose that further developing these IoT concepts will enable crew autonomy. Our future work will focus on other IoT applications, centered around improving procedure execution as well as aiding timeline tracking [7]. Aside from our upcoming work in HERA, we plan to expand our IoT concepts to address future challenges with EVA (i.e., planetary spacewalks) in analog conditions like Biologic Analog Science Associated with Lava Terrains (BASALT) [3, 6, 10].

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