Holo-SEXTANT: an Augmented Reality Planetary EVA Navigation Interface

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Future planetary exploration for teams of astronauts and rovers can be enhanced through the use of augmented reality (AR) for the purpose of navigating a planned traverse. We present Holo-SEXTANT: a proof of concept AR navigation system tested during simulated Extravehicular Activities (EVA) during the Biologic Analog Science Associated with Lava Terrains (BASALT) exploration field campaign in November 2017, at Hawai'i Volcanoes National Park. Wrist displays and tablets have long been standard tools for navigation and used for analog planetary EVA traverses. However, they distract the astronaut from their environment as the astronaut repeatedly has to look at the display leading to the potential for loss of situational awareness. More primitive navigation methods, such as guidance through voice commands from mission control can also take up mental resources and remove the focus from exploring the environment. Holo-SEXTANT introduces a new approach that allows traverse plans to be overlaid on the terrain in the display, enabling the user to view their environment while always keeping track of the location of the path. The system has geolocation awareness and thus relies only on geographic coordinates of the path as an input, allowing for the display of any arbitrary traverse path. It can be actuated by voice control and includes real-time information displays relevant to the user's location. During the BASALT deployment, the Holo-SEXTANT system was tested in hazardous terrain where no natural or visually obvious paths exist, making the tool essential. We present data on the quality of the navigation achieved with the AR display and prove that this is a viable solution for navigation. We highlight limitations observed during our in-field testing and feedback from the analog astronaut crew involved in the BASALT 2017 campaign. We conclude with a set of recommendations for future development of more advanced AR navigation interfaces.

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I. Introduction

SINCE Ivan Sutherland published his influential paper outlining the first 3D head-mounted display[1], researchers have strived to enhance human capabilities using virtual environments (VEs). The release of the Nintendo Wii in 2006 was a game changer in commercial adoption of 3D user interfaces (UI) and spatial devices, but it wasn't until 2016 that the world saw the first widely-adopted consumer virtual reality (VR) head-mounted devices (HMDs) and augmented reality (AR) HMDs. Researchers have been fascinated by the potential of 3D interaction paradigms to accomplish tasks in VEs to make a real-world impact. Most notably, research on performing tasks in VEs have led to the development of many simulators, including flight simulators and surgical simulators. In one study of flight simulators, users were more engaged when trained in a specialized VE simulator compared to users trained in a commercial flight simulator[2].

Augmented reality could also enhance future manned missions to the Moon and Mars. Mission duration for both destinations will be longer than experienced during Apollo missions: proposed Lunar exploration architectures have suggested 180 days[3] and Martian architectures up to 500 days[4]. Extravehicular activities (EVAs) during Apollo were heavily scripted and controlled by Earth mission controllers, but with longer missions, this responsibility will have to shift towards the surface crew. This is especially critical in the context of a Mars mission; significant latencies of up to twenty minutes one way would make it impossible for any Earth supporting crew to quickly react. Developing the combined concept of operations and software tools that can handle the delays and bandwidth limits is a subset of the work investigate by the BASALT (Biologic Analog Science Associated with Lava Terrains) research project led by NASA. BASALT explores these questions within the limited scope of Mars EVAs for science and exploration. Yet, many of the tools and operations developed can also be applied to Lunar missions, prioritized by the recent Space Policy Directive 1, and for which requirements are currently under development. One of the capabilities researched for use in the context of general planetary EVAs is SEXTANT (Surface Exploration Traverse Analysis and Navigation Tool): a tool to plan traverse paths for astronauts in terrain lacking any trafficability infrastructure such as roads or natural paths. The path planning tool uses data elevation models (DEMs) of EVA regions to optimize the plan based on a metric defined by the user: distance, time, or metabolic energy consumption. It also takes into account obstacles and waypoints. The capability of automated traverse planning is only useful if the output can be followed by the extravehicular astronaut crew during their traverses, whether that involves navigating with a map (digital or analog), or by landmarks and guidance from a support crew over audio. Both methods offer their set of challenges, ranging from distracting the crew to the potential of miss-interpretation of guidance instructions and an added feeling of dependency on ground support when given audio queues.

Analog EVA missions executed in a terrestrial environment commonly rely on GPS displayed on a 2D digital interface to track position. The most commonly used 2D interfaces used for such missions include tablets and wrist-attached displays. Using a digital map with the traverse path displayed, it is relatively straightforward for a user to stay on the path by keeping the GPS track aligned with their current position. Digital maps afford many advantages for reducing the cognitive load during navigation compared to a paper map and landmark navigation. However, digital maps still keep one of the key issues of map-based navigation: the user needs to constantly evaluate the offset between the path and their estimated position (either from landmarks or GPS). This action requires regularly looking at the map, which takes the astronauts' attention away from their surroundings. This, in turn, is a lost opportunity for observing the environment, but could also translate to a loss of situation awareness. This problem calls for an interface that marries both specifications: increased spatial awareness and decreased cognitive load on the user. We propose AR as a candidate medium for our navigation tool, focusing on the feasibility and potential to enhance astronaut performance for EVA navigation capabilities. This paper limits itself to exploring the feasibility question and demonstrates that AR can be used for navigational purposes. We hypothesize that AR should seamlessly provide key navigation information without distracting the user from the environment, allowing the user's cognitive load to be dedicated to other tasks. This leads to the question of how this navigation method compares to others. We try to argue based on the literature, that there should be a good reason for AR to enhance astronaut performance in an EVA compared to conventional methods. Chiefly, we argue that AR also improves EVA traversal efficiency, allows the user to remain focused on their real-world environment (thus increasing safety), and provides a more organic mapping of digital data to the real-world environment. The AR solution developed is a Microsoft HoloLens application that serves as an extension to SEXTANT, thereby giving it the name: Holo-SEXTANT. SEXTANT computes an optimal path between target waypoints, while Holo-SEXTANT conveys this information to the user via HoloLens with the goal of allowing intuitive interaction between the user and the environment.

II. Background

A. Spatial Understanding and Navigation Interfaces

To inform navigation interface designs for Mars EVA missions, we must explore existing navigation tools, including paper maps and 2D digital interfaces. Human navigation, orientation, and positioning rely on a feedback loop that takes in various proprioceptive and environmental cues to build a mental model of a space and orient themselves within this mental model. Humans rely on visual feedback, vestibular feedback, and kinesthetic feedback to position themselves within their mental model of a space[5]. Environmental features can serve to support or reject where a user thinks they are within their mental model, thus refining the accuracy of the mental model and organizing the relationship between said features. The process of building up a mental model of a space can be described as building a configurational schema[6,7]. Although using a configurational schema is a natural approach to navigation, it is not necessarily stable or coherent due to limitations in human memory. Furthermore, building configurational schema relies heavily on noticing environmental cues. Without sufficient cues, humans cannot create an accurate or useful configurational schema. Relying solely on a configurational schema is therefore often insufficient for navigation, and humans, therefore, must utilize tools to aid the process.

Perhaps the most widely adopted pedestrian class of navigation tools are 2D interfaces that rely on GPS. Not only is GPS cost-effective, but it provides real-time data on where the user is positioned so that the user does not have to rely solely on a configurational schema. Unlike paper maps, digital interactive map displays (like common car GPS devices or mobile map applications) rotates the map frame of reference to the user's world perspective, removing the cognitively demanding task of matching these frames of reference[8]. It better focuses the user's attention on relevant aspects of a navigation task[9], such as faster vehicle driver response time[10] which improves efficiency navigating to a destination[11].

Although digital interactive map displays are widely they fall short on certain aspects compared to traditional paper maps. Oulasvirta established that when users were given either a paper map or a digital device to navigate, users given a paper map developed a better mental model of the journey ahead of them whereas users given a digital device developed dependence on their device[12]. In another study, users told to navigate an environment using a digital mobile map proved to be worse at estimating the route distance compared to users told to navigate with a paper map. This was credited to the fact that "mobile map users acquire a more fragmented and regionalized knowledge representation based on strong connections between locally clustered landmarks along the route."[13] Although there is little current literature on navigation aspects of modern AR interfaces due to the novelty of the hardware, we propose that an AR navigation tool could address the specific challenges encountered when using paper and digital interactive maps by circumventing the need for a mental model.

In the context of planetary surface missions, we only have navigation experience from the Apollo missions. This pre-date the availability of robust digital displays, and required the use of paper-based maps, as seen in Figure 1a. These missions required landmark-based navigation and reference frame rotation by the astronaut to align their environment with the map, thus demanding a high cognitive load. Navigation by paper-based maps and landmarks also proved to be challenging in certain occasion, as illustrated by the second EVA of Apollo 14. Pilot Ed Mitchell had to execute a significant traverse of 1.5km without the Lunar Rover to the rim of Cone Crater. However, on the way, they struggled to estimate distances to nearby landmarks such as craters and rocky features, which made it hard for them to triangulate their own position. After extending the EVA for 30 minutes, they failed in finding the goal location and missed their final target by less than 100m. Due to the lack of atmosphere on the Moon, it is much harder for the human eye to judge distances, and thus triangulate the position with respect to nearby landmarks. Carr[14] did a visibility analysis of the terrain to show that many landmarks, such as the edge of the cone crater were not observable. The experience with the Apollo 14 mission highlights the critical need for updated paradigms for navigation tools as we look towards future Mars EVA missions.

Figure 1a. navigation during Apollo 14 with paper-based maps. **Figure 1b.** Wrist attached digital display through a smartphone used during BASALT. **Figure 1c**. The tablet-based digital display used during BASALT.

Since Apollo, the closest experience the EVA community has come to planetary surface missions are analog missions on Earth. Here, GPS combined with digital interactive map displays have become the standard tool for navigation (giving the advantages it offers over paper-maps). Figure 1b and 1c show examples of digital displays: a wrist-mounted smartphone and a tablet, respectively. These were both used during the BASALT deployment. The wrist-mounted map display was used in-simulation by the extravehicular (EV) crew, while the tablet display was used for research purposes but was never used in any simulated EVA. Initially relying on Google Earth for navigation, a custom application was developed which could run both on the phone and the tablet. This was motivated by the lack of certain features that would improve navigation abilities, such as automatically aligning the map with the orientation of the person, or adding a fluid planning and re-planning interface.

B. SEXTANT

SEXTANT (Surface Exploration Traverse Analysis and Navigation Tool) is a decision support aid for path planning. It incorporates an automated path planning algorithm that avoids obstacles in the terrain, while optimizing one of several candidate cost functions: total traverse distance, time, or astronaut energy consumption. The user can control the path by introducing waypoints, which makes the tool a decision support tool, as the user does not have to blindly trust the solution but can control the outcome of the planning tool. Obstacles are based on the slope of the terrain, where steep terrain, such as boulders or crevasses are avoided. SEXTANT requires two types of dataset. The first is a DEM, which then gets further processed within SEXTANT to generate internal slope maps from which obstacle maps are derived based on user defined thresholds for maximum allowable slope. The second consists of cost function curves, which describe the cost associated with traversing the terrain, such as average ambulation

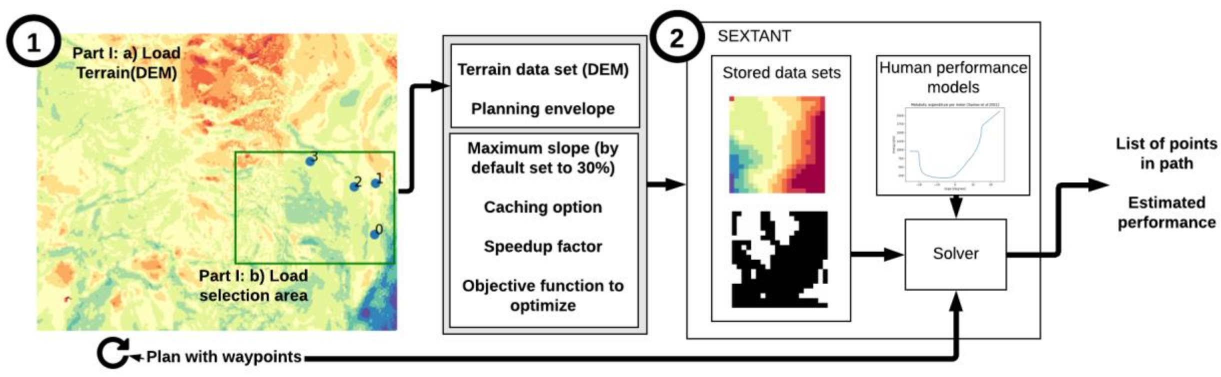

Figure 2. SEXTANT Architecture, as outlined by Norheim[15]

speed as a function of slopes. Figure 2 outlines SEXTANTs architecture. SEXTANTs path planning algorithm is similar in nature to those used in the domains of robotics or computer entertainment. However, it is unique as the method has not been applied to human navigation. Although solutions exist for planning hiking traverses in a terrestrial environment, they rely on trail network data and not on the topology of the terrain.

Originating from a traverse plan analysis tool developed by Carr, a planetary EVA traverse planning support tool was first introduced by Marquez[16]. The tool was further refined by Lindqvist[17], Essenburg[18], and Johnson[19], improving both the performance of the automated planning algorithm and the user interface. In its most current version, Norheim[15] decoupled SEXTANTs planning algorithm from the user interface, thus giving its user much more flexibility, and allowing several interfaces to use the planning capability as a service. Supplying a DEM, a human performance model, and several parameters that affect the performance of the path generated, the user can submit queries to compute traverses between waypoints. As part of BASALT, a custom web-based application was developed for the digital interactive map interfaces, and the planning service was integrated into NASA's Exploration Ground Data Systems, which was used for EVA planning.

C. BASALT

BASALT is a NASA research project exploring new operational concepts and hardware systems within the limited scope of Mars EVA for science and exploration. To this goal, three analog campaigns, consisting of ten mission days each, were carried out by a team of analog astronauts and a backroom science support team. The first, during the summer of 2016, was carried out in Craters of The Moon National Park in Idaho, the second and the third, during the fall of 2016 and 2017, both carried out in Hawai'i Volcano National Park, on the Big Island of Hawai'i. The work described in this paper was part of the 2017 campaign, conducted in the *Kīlauea Iki* crater and *Keanakako'i* Overlook area.

BASALT's high-level architecture separates the mission teams into two extravehicular (EV) astronaut crew and two intravehicular (IV) crew members that can communicate in real time on what is referred to as "Mars time." Additionally, there is a science support team (SST) operating on "Earth time" that can only communicate under delay. EVA missions extend over the period of 4 to 5 hours and are split into several phases with different durations: approach, contextual survey, sampling site selection, presampling survey, and sampling. The navigation is mostly of interest in the approach phase. The approach phase covers the traverse from the starting point of the EVA to the vicinity of a general area of scientific interest. During the 2016 campaign, the area of interest consisted of up to three science stations in close proximity of one another, whereas during 2017 campaign it remained a significantly large area. For the 2016 deployment, the second and third stations were normally within a close distance of the first station, making the traverse planning and navigation an area of application for the approach phase, which would generally last about 20 minutes. Compared to Apollo, where traverses were as long as 1.5km(during Apollo 14) and previous analog missions, the traverse paths for BASALT were significantly shorter, ranging from several hundred meters, to a maximum of around 1km. Although the traverses were short, they were executed in challenging terrain with steeper slopes and rougher terrain texture than encountered during Apollo. The terrain encountered could vary from flat and solid to rugged and unstable. Representative terrain is depicted in Figure 3a and 3b. This latter type of terrain included *a'a*, a type of cooled lava forming small sharp rocks, and *shelly pahoehoe*, a smoother looking terrain, but crusty, and with a large chance of collapse under the weight of a person. Therefore, the challenging terrain still made the approach an important part of the mission, where path planning and navigation were critical to the success.

The BASALT framework set a strict set of field operation rules, both for in-simulation(in-sim) and out of the simulation, limiting several aspects of the testing. Deadlines to be out of the terrain by the early afternoon excluded any chances to test the setup in dimmer evening lighting environments that might have been favorable to the display interface. Safety constraints limited the extent of terrain in which Holo-SEXTANT was tested in the field out-of-simulation(x-sim). The experimental aspect of Holo-SEXTANT also limited the number of times the system could be tested in-simulation.

Figure 3a. Hawaii 2016 deployment lava terrain. Figure 3b. Idaho 2016 a'a lava terrain.

III. Methodology

The methodology section describes the hardware utilized, data flow architecture, software development, user interface and field use. The user interface development will describe the different components of the interface that the user interacts with. The field use section will outline the experience the EV crew has while using Holo-SEXTANT in a mission, as was done in the 2017 NASA BASALT analog mission in the Hawai'i Volcanoes National Park.

A. Hardware

1. HoloLens

The most crucial hardware component of Holo-SEXTANT is Microsoft's HoloLens. HoloLens is an AR smart-glasses Head Mounted Display (HMD) with 6 degrees of freedom (DOF), an estimated 30° x 17.5° field of view (FOV), stereoscopic display with 1268 x 720-pixel resolution per eye, spatialized audio technology, Wi-Fi and Bluetooth wireless connectivity. The HMD has an onboard computer consisting of a general-purpose processor as well as a custom Holographic Processing Unit (HPU). HoloLens uses user gaze, hand gestures, and voice as user interface input. HoloLens' AR and Mixed Reality (MR) capabilities allow images to be projected on the optic wave lenses in front of the user's eyes and appear to the user as holograms in their environment. HoloLens creates a sparse 3D map of the room around the user through its sensors and can "place" holograms on physical features. These locations are also preserved in a cache allowing users to return to previous locations and find the holograms persisting.

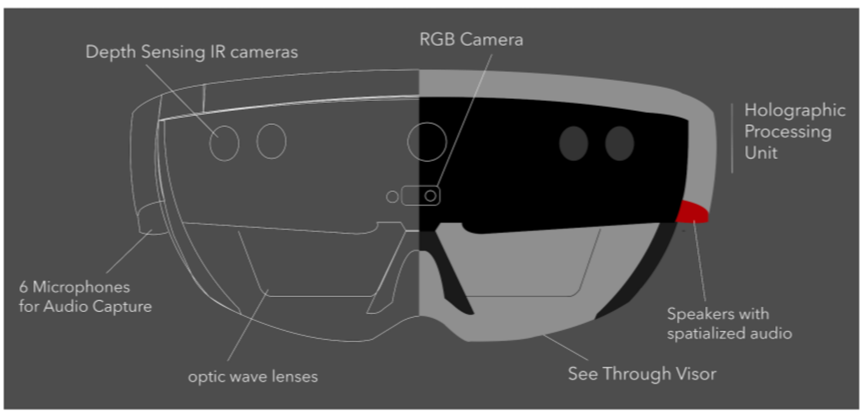

Figure 4. Microsoft HoloLens hardware front view, with components, highlighted

When choosing the medium of communicating information for the next generation of navigation tools, it is important to leverage the best features of past navigation tools. For the purposes of this tool, HoloLens was chosen for its state-of-the-art capabilities for augmented reality and its easily-accessible developer platform and projection technology. Additionally, HoloLens handles relative position and rotation using its Inertial Measurement Unit (IMU) and sensors and visually represents the information, which alleviates the physically and mentally taxing responsibility of orienting and visualizing from the user[20,21]. HoloLens also allows the user to transform their view within an environment simply by rotating their head in the HMD, which is a lot more intuitive than having to use or learn an additional input mechanism to perform the same task on a 2D screen. Ruddle et al. noted that users navigating using an HMD also spent less time stationary trying to work out where to move next compared to users navigating using a desktop display[22], allowing the users using an HMD to navigate more efficiently. Lastly, since HoloLens has onboard computing, it is untethered and can be used independently and easily.

Augmented reality allows users to keep their eyes on the terrain, environment, and world around them while being able to view informatics displays. Research utilizing 2D displays for navigation when driving have shown that drivers relying on a mobile phone may experience attention overload causing a safety concern[23] especially given that the risk of a traffic accident is significantly increased with a driver distraction of more than 2 seconds[24]. An AR navigation tool allows the user to focus on the environment while consuming navigation information and provides the added benefit of the user being able to see their body, providing kinesthetic and vestibular feedback not available on a 2D display. Although Holo-SEXTANT relies heavily on visual cues, Bakker et al. have shown that kinesthetic feedback provides the most reliable feedback for users to orient themselves[9].

AR brings together the best of existing navigation tools like paper maps and mobile 2D displays. Not only does an AR tool offer the affordance of being able to constantly display information without distracting from the environment, it can also selectively show the user what's most important at any given phase during their EVA mission. Augmenting the information available in acrew member's field of view through AR not only reduces cognitive load required to perform the navigation task but also prevents the user from having to juggle route navigation with another task (which the intended user on an EVA mission will be performing). This, therefore, allows said cognitive load to go towards common EVA tasks like rock sampling while navigating and keeping track of their location[25].

Despite the advantages HoloLens brings to our application, the hardware and industry overall have limitations. First and foremost, HoloLens is an indoor AR headset, and its core technology is designed for that. It uses Wi-Fi signals to localize, Time of Flight IR sensors to map the room, and maintains a display brightness suitable for use under artificial lighting. Utilizing HoloLens outdoors means all of the previous attributes have to be adapted. The IR cameras are sensitive to sunlight and need to be shielded. The decreased brightness and visibility of holograms outside also had to be accounted for. Next we describe the set of modificatins carried out to adapt the HoloLens for outdoor use and extend it beyond its usual operational range.

2. Hololens Modifications

The first modification was adding a polarized tint on the visor to increase the visibility of holograms outdoors. Tinting film typically used for car windows was cut to the appropriate size and applied. Both 20% and 50% Visible Light Transmission (VLT) polarization films were tested. Intense sun at Kīlauea required the use of the darker 20% VLT film. With the film applied, holograms were significantly more visible outdoors. Additional hardware modifications to HoloLens included an umbrella hat and a solar fan. Both of these were attempts at dealing with HoloLens' sensitivity to high temperature, heat, and sunlight. An umbrella hat was used to shield the headset from the sun's heat and sunlight. A clip-on solar fan was also added to the front of the umbrella hat to help cool HoloLens in the event of over-heating. Earlier field tests showed us that when used in direct sunlight, internal components including the battery would heat up causing a shutdown of the system. To account for the high wind at the open landscape of Kīlauea, an in-line microphone was used for higher accuracy voice commands. A high-amperage portable power bank was also utilized for extending the battery-life of HoloLens, especially when used in higher than normal temperatures which decreased its battery life.

3. Other Hardware

The GlobalSat BT-821C high accuracy and high-performance Bluetooth GPS receiver was used because HoloLens does not have any GPS receiving capabilities built in. This model has a 24 hr battery life, 2.0 M accuracy, as well as 35 second signal acquisition time making it durable, accurate, and fast for Holo-SEXTANT's geolocation awareness. Aside from the modified HoloLens, a rugged industrial-grade tablet with the SEXTANT web-app was used to guide testing and test the accuracy of the Holo-SEXTANT application.

Figure 5. Holo-SEXTANT hardware

B. System Data Flow

Holo-SEXTANT receives its data from SEXTANT. However, since our application was offline and locally run, the paths were preloaded. A comma separated value(CSV) file with latitude, longitude, and altitude data was generated and exported from SEXTANT. This path is then uploaded to HoloLens prior to the mission. As many paths as desired can be uploaded to a pre-designated folder. Files can also be added at runtime on the field through a computer wirelessly uploading files to HoloLens. The Bluetooth GPS receiver connects to the Holo-SEXTANT app immediately after starting the application and sends GPS data constantly to Holo-SEXTANT providing it with geo-location awareness. With the path loaded and the GPS information streaming, Holo-SEXTANT can locate the user and render the holographic path relative to the user after some rotational calibration.

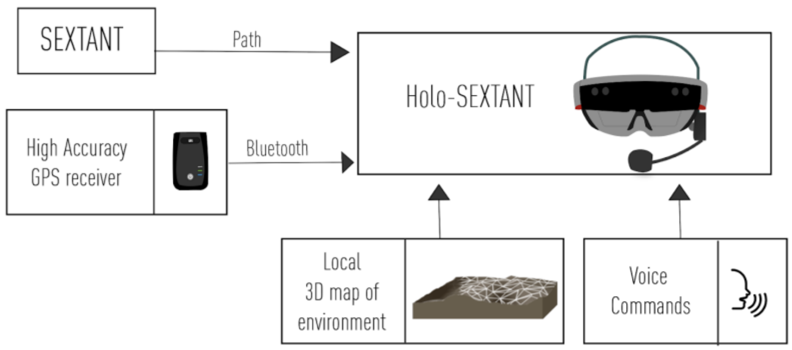

Figure 6. Holo-SEXTANT data flow chart

C. Software Architecture

Holo-SEXTANT runs the Unity 3D game engine to visualize and render on top of the real world environment. The application was built using the Unity framework and C# as the scripting language along with the open source Mixed Reality Toolkit. The Mixed Reality Toolkit is an open source collection of scripts, components, and tools for input for accelerating development. This section will detail some of the technical implementation methods and challenges. Bluetooth communication is a foundational requirement for Holo-SEXTANT to receive GPS data. This was custom built for HoloLens to interface with the BT-821C receiver. In the background, a multi-threaded process searches, connects, and receives GPS data from the BT-821C. After parsing the NMEA 0183* GPS formatting, Holo-SEXTANT uses the data to update the current position of the user.

Next, the SEXTANT path needs to be converted into the HoloLens coordinate system. HoloLens uses a coordinate system with the headset start position as the origin (X to the right, Y upwards, Z towards the user). The path and the Bluetooth GPS receiver both use a global georeferenced coordinate system. Holo-SEXTANT takes the initial GPS coordinate of the user and uses a transformation matrix to convert any globally georeferenced coordinate, such as GPS coordinates or path points, to HoloLens coordinates at runtime. Since the path and many other components are world-locked content† , these GPS points are converted to distance measurements to place in HoloLens world. After identifying the transform, the path can be generated by transforming all of the coordinates from the SEXTANT generated path into relative distances and initialized where needed.

After converting to distance measurements, translational calibration of the path is complete, rotational calibration is still needed. Sensors in HoloLens ensure the calibration of the z-axis and x-axis rotations, however, the y-axis transformation is needed to properly place the path. To address this, an automated process was investigated using a series of GPS coordinates to estimate bearings of the user and rotate accordingly. However, a manual method proved

* NMEA 0183 is a combined electrical and data specification for communication between marine electronics, sonars, anemometer, gyrocompass, GPS receivers and many other types of instruments

† World-Locked content specifies holographic content that does not move with the user. These holograms are spatially anchored to real world locations.

sufficient and was ultimately implemented: the user identifies the start of the path and rotates the path until the path start and the actual start of the path align.

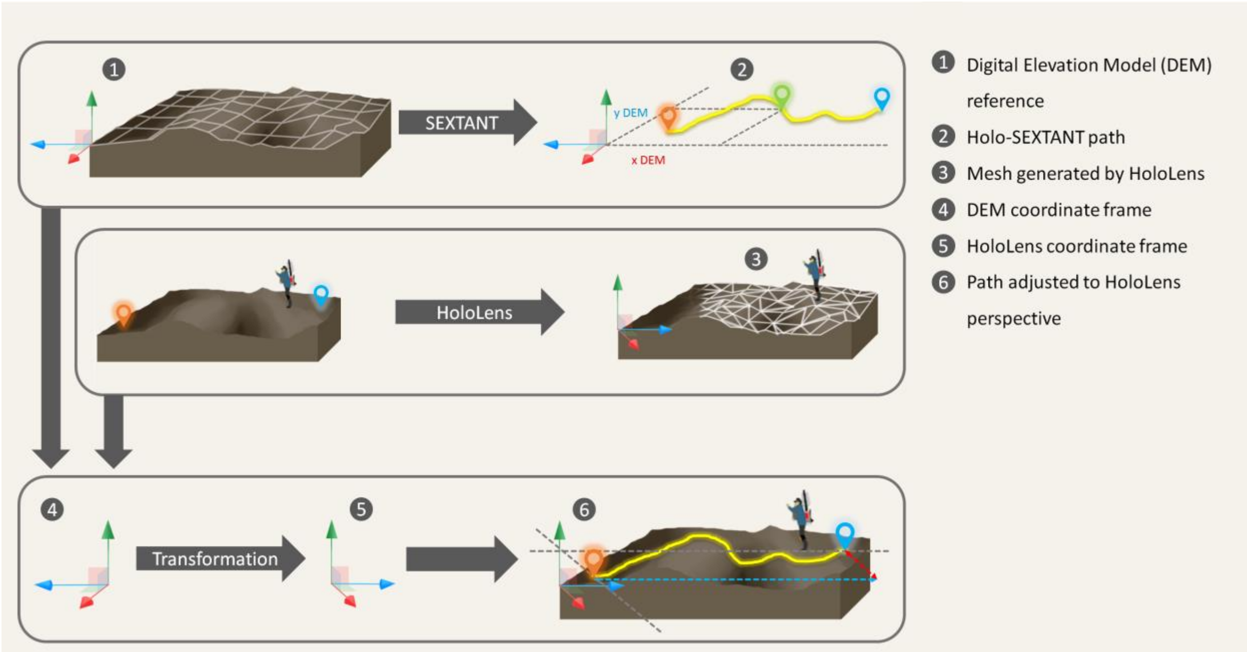

Figure 7. Transformation framework

D. User Interface

When designing a user interface for navigation to be used in hazardous terrain, several aspects have to be kept in mind: the user, the user's cognitive load, intended interactions, and the user's surroundings. By keeping these in mind, potential harm, and additional complications can be avoided. This section provides some of these guiding principles behind Holo-SEXTANT. First and foremost, the interface should not obstruct the user's field of view nor distract the user from their environment, since the environment is dangerous and simple distractions can cause slips, falls, and injuries. Distractions could include colorful objects, large and obstructive elements obstructing the field of view, or animations. All of the components should be simple, easily visible, and intuitive. Since the interface is *aiding* the user to perform their task, it must play a supplementary role. The user cannot direct full attention to the application since they will also be walking, working with team members, and performing tasks. To prevent from distracting the user, Holo-SEXTANT has a simple, vivid, and intuitive interface. Holo-SEXTANT consists of a 2D screen locked user interface and a 3D UI (holographic elements). The 2D UI is layered close to the user so that the 3D objects in the user's view do not interpenetrate each other, and the menu displays were made translucent and take up minimal screen space. All of the text is bright white for optimal visibility.

1. 2D Static Display

The 2D static display is overlayed on top of all other elements, virtual and physical. It includes the primary information needed for the user. A small circular indicator shows the current GPS status, in three states: red when the BT-821C is not connected, orange when it is connected without satellite uplink, and green when connected and receiving. A direction indicator shows what direction[‡] the user is facing. This feature uses a GPS bearing estimation that works based on the starting bearing of the user. On the right side of this heads-up display is an overall status indicator showing whether Holo-SEXTANT is calibrated, showing the path, or not initialized. This heads-up display

[‡] One of the 32 Cardinal compass directions

follows the gaze of the user as head-locked content. To reduce the visual clutter in the 2D static display, several extra features were removed such as time, and current GPS location, leaving only the most important information: bearing, system status, and system mode.

2. Holo-SEXTANT 3D User Interface Design

The 3D UI consists primarily of a holographic path that follows the route generated by SEXTANT. The path is rendered in vivid blue to ensure maximum visibility under the harsh lighting conditions Holo-SEXTANT must operate in. It has simple geometries and therefore low visual fidelity, which allows for better spatial awareness of 3D objects[26] and encourages the user to focus on the position of the path without being distracted by visual complexities (eg. texture or specularity). Using simple geometries also reduces the cognitive load required to visually scan the environment to locate the path. With an omnipresent overlaid path, no recall or memorization is required, and the cognitive load is reserved for navigation and motor control for traversing through the terrain. To make navigation even easier, several distinctive waypoints were added to the path at varying locations. These allow the user to deviate from the path if needed, yet be able to identify the waypoints and walk towards them and continue following the path.

Perspective and occlusion are the strongest depth cues when manipulating and observing objects beyond an arm's length[24]. HoloLens handles perspective view but is not suited for handling occlusion for far away objects. For instance, the end of a path that curves around a hill should be hidden to the user, but HoloLens does not know that such a hill exists because its depth-sensing cameras do not have a long enough range (unless it has been pre-emptively recorded, placed in the Unity environment, and overlaid on the terrain, which would have allowed for significant positioning error since these hills are far away). Therefore the part of the path that should intuitively be occluded the hill is still visible to the user. The holographic path does appear relatively thinner the farther away it is from HoloLens, allowing the user to judge distance, but unless the user is concerned about gauging the route ahead, the user is almost always more immediately concerned with what is right in front of them.

Aside from the heads up display and path, there is also a status display panel. The status display is locked to the user's view. This means that while not in the field of view of the user, it will always follow along with them wherever they walk. The display is located to the right of the user, such that they can always look over 90° to the right and see the display. This display is an auxiliary information panel showing the following: GPS coordinate values, altitude, distance traveled, time, and distance to start or end position. A help display can also be brought up if needed to give a reminder of the voice commands and interactions possible. Both menu displays are located at a comfortable distance from the user and never take up the entire field of view. Linear interpolation and slight delays are used for controlling the displays movement as the user moves without being jarring or disorienting.

Figure 8. First person view of UI. *Include, path, waypoint, and status display*

3. Holo-SEXTANT Interaction Design

User selection in many HoloLens applications relies on carefully positioning the small HoloLens cursor on a point in the UI with the user's gaze and then using a hand gesture to select. Although ray-casting selection techniques are precise on HoloLens, accurately placing the cursor on the desired UI object requires high precision, which requires more time and a higher cognitive load on the user. Furthermore, the cursor is not always easy to locate when HoloLens is used under harsh lighting conditions. For our use case, the user must perform crucial tasks with their hands, requiring a hands-free interface. To circumvent this, Holo-SEXTANT makes use of voice commands, which allows the user to actively provide input to the system without having to worry about turning their head or focusing on cursor position accuracy. During the November 2017 BASALT campaign, users previously unfamiliar with HoloLens demonstrated difficulty recalling hand gesture commands to operate an independent HoloLens application, in this case *Skype* for HoloLens, but recalled Holo-SEXTANT voice commands with ease, enforcing our hypothesis that voice commands are more intuitive to use. Additionally, Holo-SEXTANT includes a 2D holographic panel that displays the voice command options so that the user simply has to recognize instead of recall. These commands were created using a custom Speech Recognition Grammar Specification (SRGS) [§] and the underlying Cortana Voice Engine as part of Windows 10 on HoloLens.

E. Holo-SEXTANT Field Use

Holo-SEXTANT is ran executing the following procedure: first, the user preloads paths obtained from SEXTANT prior to the mission. Then they start the GPS module and the application on HoloLens. Once the user sees the green light indicating GPS signal reception, Holo-SEXTANT is connected to the GPS receiver and ready to be calibrated. The voice command *Show Path* will generate the path and place it the appropriate distance away from the user. Now the user can perform the rotational calibration by verbally commanding the system *Rotate (-)[½, 1, 5, or 10] degrees* to respectively rotate the path about the user's origin point. They can rotate until the first point of the path in the HoloLens display (portrayed by a large box that plays the role as a virtual waypoint) aligns with the correct position in the real environment. The status display indicates the distance from the user's porition to the start of the path. After arriving at the start point, the user can raise or lower the path as needed to fit their comfort level. All that is left is to follow the path to the destination. If needed, the user can re-calibrate the path either raising, lowering, or rotating it at any time during the traverse. They can always refer to the status display to see their bearing, GPS, distance traveled, and distance from start.

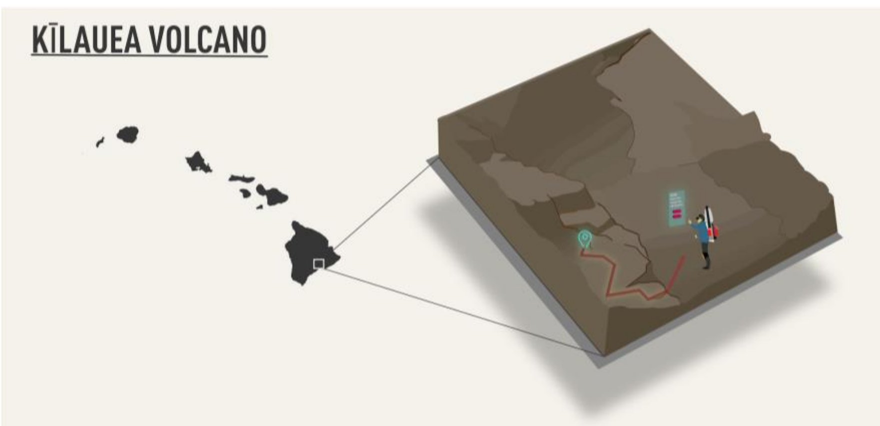

Figure 9. *A third person view of an EVA crew member navigating through the Kīlauea terrain with Holo-SEXTANT. Holographic path, waypoint, and menu are shown on the terrain as well*

IV. HoloLens Field Results

A. Field Results

Due to the novelty of AR interfaces, the EV crew were put through training to familiarize themselves with Holo-SEXTANT prior to field testing. Three full field tests were executed with EV crew members previously unfamiliar with HoloLens. The first field test was executed by the EV crew in x-sim environment, during the return traverse from the end of the mission. The other two field tests were done in-sim for the 20-minute approach path into the region of interest for that day's mission. The short approach times limited the amount of in-sim we could collect. Additional technology testing and assessment were also carried out x-sim by the authors of the paper. A representative x-sim traverse in the *Keanakako'i* overlook area is displayed in Figure 10. The GPS track was generated by following the planned traverse through the AR display as closely as possible. Although there are

[§] **Speech Recognition Grammar Specification** (SRGS) is a W3C standard for how *speech recognition grammars* are specified. A speech recognition grammar is a set of word patterns, and tells a speech recognition system what to expect a human to say. https://www.w3.org/TR/speech-grammar/

offsets between the GPS track and the planned path at a smaller scale, the paths match qualitatively well at the larger scale, indicating a good agreement of the location and orientation of the virtual path rendered by HoloLens in the real world with respect to the actual location and orientation the planned traverse.

Figure 10. SEXTANT web-based application view. *In orange: planned path, in yellow GPS tracks from Field Test Day 1.*

B. Calibration

After implementation and arriving in the field, our assumptions about calibration, environmental factors, and accuracy were tested. We found the GPS receiver to have accuracy problems at times –while the advertised 2.0 m accuracy was exhibited most of the time, there were instances when the GPS would be inaccurate. This would lead to incorrect calibration. Discounting this occasional hardware issue, our translational calibration was very accurate providing 1-2 m accuracy. Our automated rotational calibration mechanism was not accurate enough to test or use in the field. Manual calibration, however, was efficient enough to not be cumbersome. With less than 5 voice commands issued, the path can be calibrated completely. Sometimes, however, recalibration was needed during the middle of the path, if the path required precise traversal. For this reason, a tablet was running the SEXTANT web app showing the path on the terrain, allowing the user to re-calibrate if needed to align the path displayed in the HoloLens with the path's real orientation on the map.

C. Environmental Factors

Performance of HoloLens in the outdoors was surprisingly robust. Anticipated fragility due to rain was not a problem, as was discovered during the second in-mission field test. HoloLens operated reliably through windy conditions with fluctuating rain as long as the screen was dried off regularly to clear the sensors and the user's view. The head umbrella was not very effective in windy conditions, as it would have been hard to keep it in position, making HoloLens' inherent robustness to rain a significant advantage. Sun and heat also proved to be less of a challenge than expected; IR reflection on the rocky terrain rarely confused the HoloLens sensors, and the mesh accurately captured the surroundings when visualized. As a result, holograms were stable during most of the tests. However, we noticed that if HoloLens was pointed directly at the sun at any point it would either shut down or lose track of its surroundings. We believe that overexposing the IR sensors for sufficient time causes HoloLens to lose track of its orientation and position in the current mesh, and as a result, loses the capability to extend the mesh further. Although the windy conditions rendered the head umbrella to be of little use in the rainy conditions, it was useful in sunny conditions as it would serve as a visor to keep the HoloLens IR sensors from being directly exposed. We also observed that rebooting HoloLens could often lead to an incorrect interpretation of the location of the user, as the path would no longer be in the same location and orientation, indicating an incorrect load of the previously existing mesh. Visibility of the holograms was clear, thanks to the darker lighting offered by the tinted layer applied on HoloLens. In artificial lighting conditions, the tint was even enough to make the holograms occult the surroundings. This made for a clear visual of the path even in sunny conditions, while offering the tinted functionality of polarized sunglasses, which the crew would have required anyways.

One larger unforeseen challenge was using voice commands in wind; users had to raise their voice and repeat commands before HoloLens registered the input. This would be frustrating and distracting from a user perspective, but also offers a simple solution: connecting a boom microphone covered in sound mufflers to the HoloLens. Another proposed solution for the future is using bone conduction microphones.

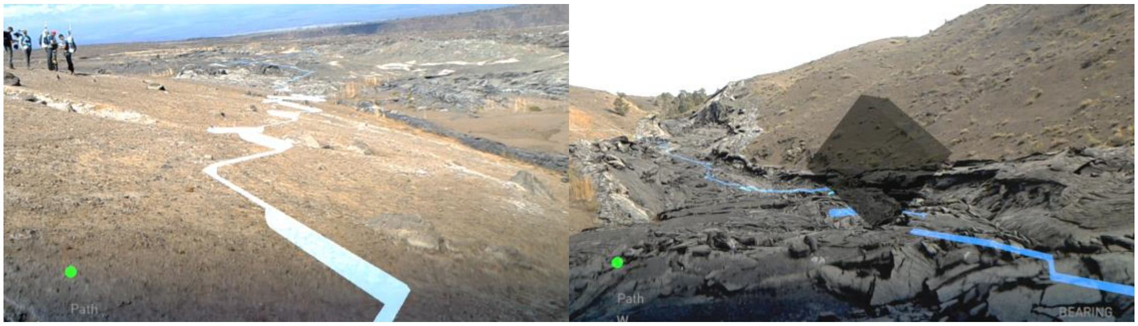

Figure 11. Screenshots taken from HoloLens showing path and waypoint

V. Discussion

Despite several key assumptions and limitations in the hardware such as the tracking, mapping, and robustness, HoloLens had sufficient hardware capabilities for this proof of concept navigation assistant. Some of the limitations, such as drift, re-calibration, and error did hinder the EVA experience. To re-calibrate, the EVA crew member would have to stop, assess where they were and rotate or translate before proceeding. One method of increasing accuracy and preventing such recalibration is a dynamic updating and localization mechanism. First, an automated orientation estimation is needed. Second, with the GPS data stream, the application should assess the rendered path accuracy at some nominal update frequency to ensure that the path remains calibrated. While design ideas were outlined, such dynamic updating functionality has not yet been implemented.

Implementing an automated orientation estimation was one of the challenges that we faced. Orientation estimation requires some sort of compass information or user input. One method that we explored was using a straight line of GPS points recorded at initialization to estimate the true bearings of the user. Based on this, the path can be initially rotated in the right orientation. However, this proved quite difficult to implement, and is not a robust enough method to perform re-calibration during a mission. It requires user input making it non-ideal. Integrating a digital compass is another option, but this poses its own challenges with accuracy. A third more novel approach could be a larger architectural change for future research. One could mimic the spatial mapping technology that HoloLens uses to localize itself indoors. Aside from using Wi-Fi, HoloLens generates a sparse map of its immediate surroundings and compares that with a global mesh that it has stored to find a match and locate itself in the global mesh. Mimicking this method, an external LiDaR or depth sensing camera alongside a wearable computer could be used to generate dense 3D maps and match them with the bigger DEM that was already acquired. Using GPS to localize on the terrain, and using a dense 3D map to identify the user orientation in the terrain, can lead to an efficient and automated calibration mechanism. The current point cloud and resulting mesh generated are far too sparse for this method. A denser, more detailed depth map would be required to capture the features of the terrain and provide detailed localization. Thus, this method would require additional hardware for capturing as well as processing this information. However, we think that exploring methods to automate calibration and localization are crucial for future research to make an augmented reality navigational application robust.

We proposed that an AR navigation interface would provide several advantages over existing navigation interfaces. Since HoloLens automatically handles the map's frame of reference and updates the position of the user's view, it eliminates the need for the user to manage this cognitively heavy task explored by Thorndyke and Hayes-Roth[21]. HoloLens overlays map information on the environment through holograms and therefore circumvents the limitation proposed by Collins et al.[9] by allowing the user to better focus on relevant aspects of the navigation task.

A concern of existing 2D navigation interfaces is that users may develop a reliance on the tool and distract from the environment. Holo-SEXTANT's design intentionally aims not to detract from the user's spatial awareness by being mindful of removing visual complexities from the user's view. Although Holo-SEXTANT doesn't necessarily prevent the user from relying heavily on it to navigate, it eliminates the disadvantages of reliance proposed by Oulasvirta[12] and Willis et al[13].

Some other challenges were errors in conversion between systems. At each stage of the data flow, the error propagates and accumulates. The initial DEM used to generate the SEXTANT path has an inherent error. SEXTANT has some tolerance for error as well, particularly because minute terrain features cannot be captured in SEXTANT. When this path is converted to the Unity coordinate system, there is more error introduced. However, for an EVA mission, the region of interest is typically larger in radius than a specific, precise GPS coordinate. This allows for Holo-SEXTANT or any other EVA navigational tool to tolerate such errors. Despite this, some terrain and pathways will require much more precision. In our field test, we found one location with only a single naturally formed channel to be traversable. And there was a single accessible entry point into this channel. Because of this, Holo-SEXTANT had to be quite precisely calibrated to not lead the user astray drastically.

Through the field testing at Hawai'i Volcanoes National park, we found it hard to identify key metrics to test the efficacy of a navigation interface. Paths are not repeatable by the same user because the user now has a memory of traversing it. The speed of crew members traversing had quite a large spread. Comparing the planned path with the traversed path might seem to be an obvious choice, however following the path exactly is unfeasible and unnecessary to the goal of the EVA. Furthermore, one of the goals of Holo-SEXTANT is to enable EVA crew to safely and willfully deviate from the path to explore if they wish to and return to the path with ease. Further investigation is needed to identify the best metrics to test such an AR navigation interface.

From user interviews and feedback from users, a couple of key points were highlighted. Visibility was a key feature that users liked. While the holograms were initially difficult to see, our modifications with the polarization, improved it significantly. One EVA crew member mentioned that wrist displays are very hard to see in the sunlight, making Holo-SEXTANT significantly more visible. Another insight was the customizability needed for different users: some preferred the path at ground level, while others preferred it over-head leading us to make the path height customizable. At a high level, different EVA crew members have different roles, and one single interface won't fit all their needs. For example, the lead crew member might navigate for the entire team, while the second crew member oversees other operations. While they could both benefit from an Augmented Reality information display, their needs are quite different. For this reason, we made a highly customizable UI. Any UI component can be hidden if the user wishes so. All the UI components were directly manipulatable allowing the user to design their own "workspace" on the go.

From walking alongside several users using Holo-SEXTANT, we noticed different user application interactions. One user raised the path to render above his head such that he would look up occasionally to gauge his progress and continue onwards independently. Others would place the path slightly above terrain level to be able to see the ground and the path simultaneously. Some users found it uncomfortable to see the world through a polarized HMD especially when the terrain can crack and watching each step is crucial. They would raise HoloLens to walk and lower it onto their eyes occasionally to check the path. This validated our belief that the interface should be adaptable and customizable for different users. Overall, this user interface is safer, more efficient, provides more affordances through natural mapping and ultimately improves spatial awareness.

VI. Future Work

The BASALT mission framework set a strict set of field operation rules, both for in-sim and x-sim, limiting several aspects of the testing. Future work could look to extend testing and push the use of AR to the extremes, testing user fatigue, use over longer traverses as well as in low light environments.

Here we suggest several advances that could augment the capabilities of Holo-SEXTANT. We first discuss developments that are within the scope of current research development:

Alternative path visualization. Holo-SEXTANT makes use of a long continuous holographic path to indicate the route described by SEXTANT, but there are alternative ways of displaying the same information. For instance, placing waypoints in the terrain, using arrows to point towards the next waypoint, making more use of color to convey information.

Measuring biometrics. SEXTANT was designed to calculate the shortest, safest, and most energy efficient route between points on a terrain. Monitoring EVA biometrics (such as heart rate, calories burnt) to display to the user could allow the user to be more aware of how different phases of their navigation in an EVA mission are affecting their body.

Measuring the user's invisible states. Being able to monitor invisible metrics such as intention could provide useful data for planning navigation routes. HoloLens does not currently support eye tracking capabilities but tracking user gaze could build a better picture of what the user is focusing on during an EVA mission.

Displaying distances and current position. Estimating distance without additional tools is challenging for humans, especially in a terrain with sparse landmarks like Mars. In a study where users traveled by following either a paper map or a mobile map interface, subjects from both groups underestimated their travel distance (mean of 98.93 m using a paper map, 135.90 m using a mobile interface)[13]. It's important that the user has a clear idea of what to expect for the terrain ahead of them. This can be accomplished by providing a 2D representation (like a minimap) or a 3D representation (like a hologram of the terrain). Additionally, by including a planning pre-task where a schematic overview of the entire route is displayed and can be referred to during the task, the user not only develops a better understanding of what to expect, but it also addresses the issue of overcoming an unstable configurational schema.

Reviewing completed traversals. Holo-SEXTANT's capabilities end as soon as the user ends the EVA mission. A helpful capability would be to provide a 3D representation of the mission traversal for analysis, noting details such as biometrics, how closely the user stayed on the proposed path, changes in speed etc. This visualizes the data for a remote support team and could help the user mentally compartmentalize and contextualize segments of the EVA mission, which is especially useful if the same environment were to be traversed again. Similarly, pre-mission visualizations can be useful to plan the mission routes, and understand the terrain.

Next, we propose developments that would benefit Holo-SEXTANT beyond the scope of our research:

Increased field of vision (FOV). Navigating with the restricted horizontal FOV on HoloLens increases the angle and frequency at which the user must rotate their head to identify and follow the path. A restricted horizontal FOV (30° on HoloLens compared to 180° on humans) can have a non-trivial effect on task performance. A low FOV hinders performance at visual scanning tasks[25] and can affect distance estimation[26], speed and accuracy when maneuvering through a physical obstacle course[2]. Additionally, a wider FOV will have the added benefit of allowing the user to look ahead and anticipate upcoming parts of the environment[28]. Although the current available AR HMDs do not allow for a sufficiently large FOV, we hope that advances in AR hardware development will make way for HMDs with a larger horizontal FOV.

Adapting for flight-ready hardware. As mentioned before, HoloLens is a general purpose augmented reality HMD designed for indoor use. A next step would be to investigate custom hardware solutions using more powerful sensors, robust physical design, and application specific hardware. Performing power analysis to analyze what requirements an AR display will have is important. Implementing the optics in the helmet visor would be challenging given the distance from the retinas to the display that would be on the visor. Other considerations would be the sensors and mapping cameras on the exterior of the suit to have spatial 3D mapping for localization and world-locked content as well as hand tracking for interaction.

Other applications: Holo-SEXTANT is one part of the larger AR toolkit that EVA missions could utilize. Navigation is a critical component, but an AR assistant can aid with identifying samples, providing suit diagnostics, aiding with tasks, taking notes, communicating with IV or mission control and more. Additionally, such an EVA tool could also have integrated intelligence going beyond simple voice commands. An artificially intelligent assistant would be far more powerful and aid in decision making directly.

VII. Conclusion

We have shown that an augmented reality-based navigation system can be readily developed using off-the-shelf components. We believe that using AR based methods could add significant value for an EVA crew to follow their traverse plan, compared to current methods. It could improve situational awareness and provide insights on the path and the terrain that other digital methods couldn't offer. This work partially fills in the gap that would allow an AR navigation interface to be compared to other methods such as digital display interfaces. Although we don't have any data on human performance using both of these methods we outline the feasibility of this method. We have outlined the setup that would allow future efforts to focus on the comparison of the AR platform with other interfaces. We also outlined the limitations we encountered in our setup and proposed ideas on how to improve this in future iterations of the current AR navigation architecture. These are key to make the system robust enough so that any comparison across information display methods is not negatively biased towards the AR solution due to current limitations in the technology that will surely be overcome in the future.

Ultimately we believe other EVA related capabilities could also be significantly enhanced bys highf the use of AR. Enhancements could come from different stages relative to the EVA, and for a diverse set of stakeholders. Pre-EVA planning for scientist and the operation team could benefit from tools like NASA's Jet Propulsion Lab (JPL) OnSight tool, which can virtually replicate the real environment of proposed EVA areas and immerse the user in this environment in a collaborative manner simultaneously with other users. The same tool could also be used in combination with additional data post-EVA to allow a broader pool of researchers gains access to the mission. Mid-EVA applications could go beyond navigation, which was the main point explored in this paper, and both enhance communication across the IV crew and the EV crew. Such a capability could be provided by a tool similar to *Skype* for HoloLens. Despite the time delay, the science team in the mission support center could also benefit from an AR environment mid-EVA, being able to follow the EV-crew and their interaction with the environment from a virtual vantage point. These tools all show the promise of AR for exploration missions.

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