Data collection in Svalbard, Norway to test the use of virtual reality for Lunar and planetary surface exploration

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As part of MIT's work with the Resources Exploration and Science of OUR Cosmic Environment (RESOURCE) project with NASA Ames and the Solar System Exploration Research Virtual Institute we are testing both the scientific and operational usefulness of a virtual reality environment for local, small-scale (< 5 m) geological analysis for Lunar and planetary surface exploration missions. Specifically, we are testing a virtual reality (VR) environment developed using a low-cost commercial off-the-shelf combination LiDAR/RGB camera for geological exploration. We incorporate local environmental data such as temperature, luminosity, humidity, and pressure as well as drone-collected photogrammetry. The data was collected in Svalbard, Norway, from three locations near Longyearbyen. The sites were selected based on their distinct geological features including 1) a riverbed in a glacially carved valley (<10 cm-scale features), 2) a permafrost feature (>1 m) and 3) the base of a recent glacial retreat (last 100 years, 10-50 cm. This data is being rendered in VR and will be used to assess scientists' abilities to answer questions about the relevant local geology for differing feature scales (<10 cm, 10-50 cm and >1 m). The VR environment will be compared to a traditional desktop application in 2-dimensions and geological field notes taken on an app developed by the University of Western Ontario for geological field work. Here we discuss the data collection techniques used in Svalbard as well as the lessons learned from this field work. Data processing techniques are presented, as well as the preliminary VR rendering capabilities developed for this work. The low cost of the technologies provides an opportunity to develop immersive environments not only for Lunar and planetary surface exploration, but also for remote or environmentally sensitive locations on Earth where research is lacking and human presence should be minimized.

I. Introduction

USING Svalbard, Norway as a Martian analog, we are testing both the scientific and operational usefulness of a virtual reality platform for local, small-scale (< 5 m) geological analysis for Lunar and planetary rover exploration missions. Specifically, we will be testing a virtual reality (VR) environment developed using a low-cost commercial off-the-shelf (COTS) combination LiDAR/RGB camera for high-resolution, near-field geological exploration. We will incorporate local environmental data such as temperature, luminosity, humidity, and pressure as

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well. In addition to the camera, a DJI Phantom 4 Pro V2 drone was used to gather aerial photography of each field site. The data was collected in Svalbard, Norway, from three locations near Longyearbyen. The sites were selected based on their distinct geological features including (1) a braided stream in a glacially carved valley (<10 cm-scale features), (2) a permafrost feature (>1 m), and (3) the base of a recent glacial retreat (last 100 years, 10-50 cm). This data will be rendered in VR and will be used to assess scientists' abilities to answer questions about the relevant local geology for differing feature scales (<10 cm, 10-50 cm and >1 m). The VR environment will be compared to a traditional desktop application in 2-dimensions and geological field notes taken on an app developed by the University of Western Ontario for geological field work.

Perceiving scale on the lunar surface is very challenging because of the lack of atmosphere and scale reference. Having high resolution depth data available for scientific analysis, or later for situational awareness as humans return to the moon, will be invaluable. The use of stereoscopic imagery to create 3D environments in virtual reality for surficial geological analysis was demonstrated with the Mars Curiosity rover for the Kimberly outcrop in the Gale Crater on Mars[1]. However, using stereophotogrammetry in concert with multiple overlapping image sources led to challenges with calibration and large data sets. Given the challenges associated with exploring craters and lava tubes, regions of interest for in-situ resource utilization, enabling exploration through VR could allow for safer methods for astronauts to train for upcoming missions, such as the Artemis missions, and for robotic data collection to supplement astronaut exploration in challenging areas. These methods can also be expanded to sensitive environments on Earth providing a methodology to create a virtual environment to give access to areas like the Galapagos or the Antarctic to scientists around the world without increasing our environmental impact.

With the growing number of COTS depth-cameras available, MIT's RESOURCE team is exploring new methods for low-cost depth-data collection and integration into VR for future exploration missions. Using low-cost technologies furthers accessibility, opening the scientific exploration of data collected in space and in Earth's fragile environments to a broader range of researchers.

A. Virtual Reality for Lunar and planetary surface exploration

To ensure we are achieving the most science possible within future space exploration missions, human-computer interaction needs to take a front-seat in mission operations[2]. By treating machines as collaboration tools, we stand to improve cross-discipline communication, improve real-time decision-making processes, reduce task loads and provide flexibility in both temporal and spatial planning. Exploration missions will stand to benefit given the specificity of the knowledge required to make decisions around geological data. Providing naturalistic visualization tools that multiple team members can use to analyse, discuss, and interpret data, has the potential to dramatically improve the scientific return on both rover prospecting missions, and later human exploration missions.

Critical to this development is understanding if virtual reality can be leveraged to improve analysis for increasing science return. VR is an exciting technology which has gained traction as a tool for space applications in recent years. The Mars Curiosity Rover team used VR to explore geological sites on Mars[1]; NASA uses VR for both astronaut training[3] and as an outreach tool; the entertainment industry has developed immersive games such as Mission ISS for the Oculus Quest. Additionally, there are numerous analogue missions developing VR tools for mission operations, be it human or robotic[4]. Lacking, however, is the defined demonstration of why such a tool is beneficial. And if it is, for what mission operations does it provide the most return. These questions should be answered before investing in the development of VR as an operational tool. Here we focus on the use of VR for geological analysis of Lunar and planetary surfaces using Svalbard, Norway as a Martian environmental analog.

B. Relevant environment – Svalbard, Norway

Svalbard is a particularly fascinating location for geological study because the majority of its long geologic history is both preserved and exposed. The igneous and metamorphic basement rocks show a history of mountain building, with the most recent during the Early Paleozoic (410-440 million years ago). This was overlain by unaltered sedimentary cover rock, masses of sand, gravel and mud, followed by limestone deposits and layers of sandstone-shale deposits up until 40 million years ago[5]. Alpine glaciers carved the terrain into sharp mountains and U-shaped valleys after the retreat of the late Pleistocene ice sheet. Fjords were left by these glaciers as they withdrew from Svalbard's sharply indented coastline leaving a beautifully exposed geologic history[6]. The lack of vegetation, lack of soil and the mountainous terrain provide excellent access to study much of Earth's history. These conditions also mimic what we might expect to find on planetary surfaces.

The Svalbard location provided multiple environmental advantages as a Martian analogue including 1) low azimuth sun angle 2) minimal vegetation, 3) low temperature conditions and 4) desert conditions (low humidity and precipitation). The Martian south pole has low-azimuth sun angles, which, mid-to late-October in Svalbard can mimic these conditions. We also tested the camera capabilities with minimal ground ice (reflectivity of regolith with water ice content will impact the depth-of-view of the LiDAR camera). The lack of soil and forests in Svalbard provide exposed and identifiable rock formations. The naked landscape permitted clear insight into its geological structure and better represented the Martian environment. This provides more realistic depth data and imagery allowing the scientists to better assess the VR tools. The geological questions we selected made use of the local geology that required use of both surface structure or texture (depth data) and color (RGB imagery).

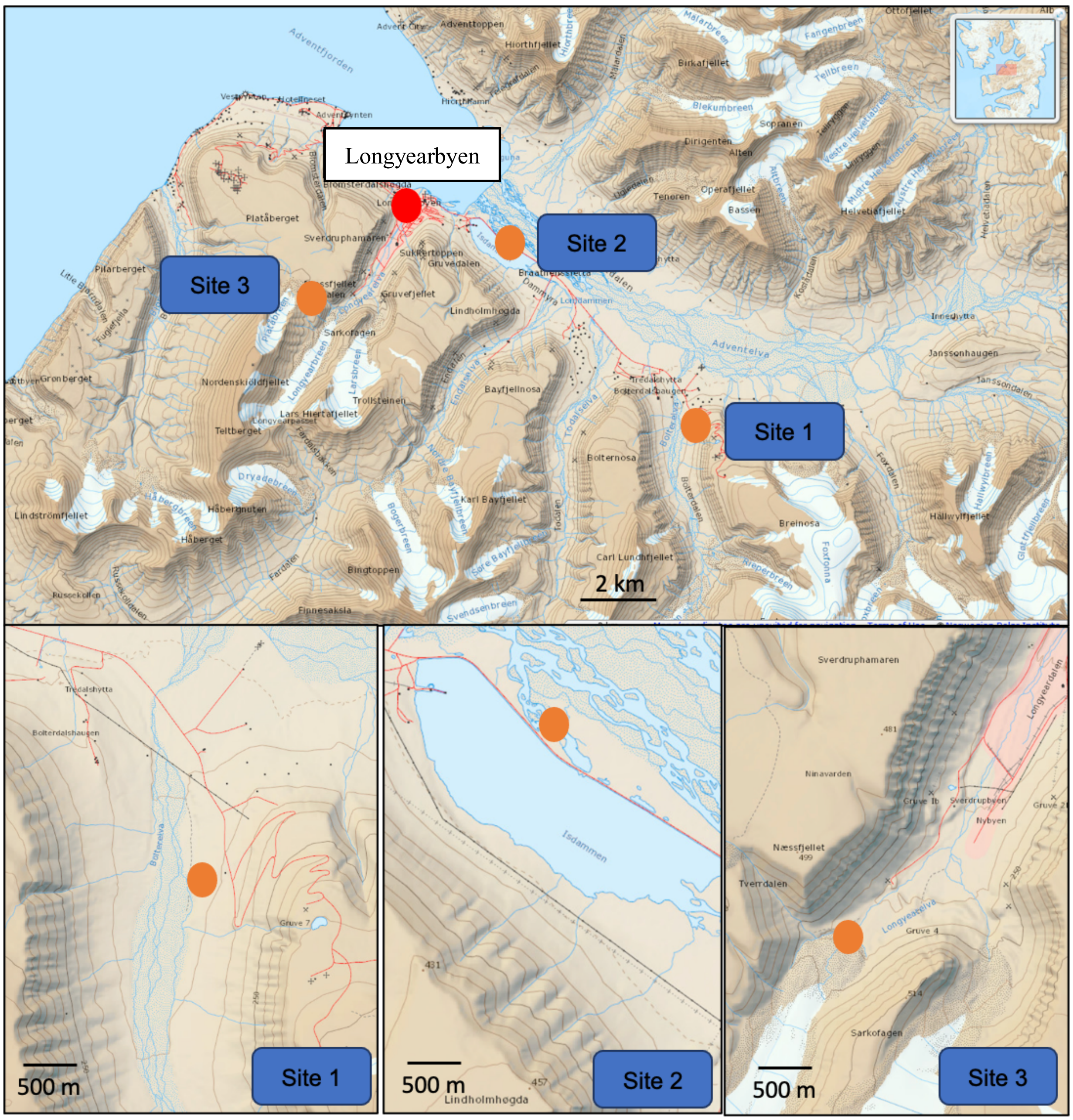

Figure 1: Topographic map of sites near Longyearbyen, Svalbard, Norway. Site 1 is a river bed at the base of a glacial valley, site 2 is a permafrost feature, and site 3 is a recently exposed glacial moraine.

The mission was conducted from October 1 to October 13th of 2022 near Longyearbyen in Spitsbergen on the archipelago of Svalbard, Norway. The average temperature in Longyearbyen is -2℃ (high) to -7 ℃ (low) with an average of 25% chance of rain (1.1 inches) and 7% chance of snow (5.5 inches). We required no snow cover at the selected locations. The lack of snow cover was also critical for the lighting conditions as the Azure Kinect does not work well on highly reflective and white surfaces.

The three field sites where all of the datasets were collected are depicted in Figure 1: Topographic map of sites near Longyearbyen, Svalbard, Norway. Site 1 is a river bed at the base of a glacial valley, site 2 is a permafrost feature, and site 3 is a recently exposed glacial moraine.

B.1 Site 1 – Glacial till incised by a riverbed

Site 1, Figure 2, is a glacial moraine incised by a braided riverbed in Bolterdalen Valley. Two outcrops were selected for this site, 1) the top of the moraine with no river cuts and 2) the bed of the braided stream. Outcrop 1, Figure 2, Left, the top of the moraine, was covered by a layer of moss with relatively few pebbles or cobbles. Outcrop 2, Figure 2, Right, was formed by directionally sorted pebbles and cobbles (1-10 cm) with areas of fine-grained sediment. The riverbed was at the base of a fjord inlet (Figure 1, top) with a coal mine to the East of the field site. Deposits of coal were visible at both outcrops.

The site requires the scientist to identify small scale (<10 cm) features such as pebbles, cobbles and surface texture to identify the directionally sorted rocks and to use the RBG imagery to identify moss on the upper surface indicating an older surface. Finally, we will be able to assess if the VR makes it easier to find the relationship between the two outcrops using visual cues compared to a 2D application.

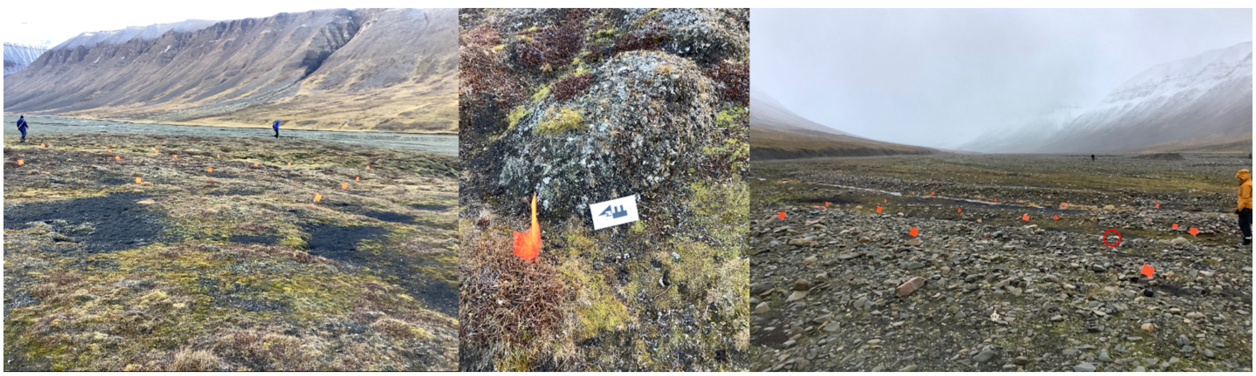

Figure 2: Site 1 - Bolterdalen Valley, glacial moraine incised with braided river. Left: Outrcrop 1, top of moraine, Middle: Outcrop 1, close-up of moss covered mound, Right: Outcrop 2 - base of river bed in fjord.

B.2 Site 2 – Permafrost feature

A large (5 m diameter) permafrost feature was identified in the drained Adventdalen Valley next to a road cut opposite the ground water reservoir, Figure 3. This was identified as either a small pingo or a frost heave. Pingos are formed in areas with continuous permafrost by pressurized groundwater freeze/thaw cycles forming an ice lens under the top sedimentary layer. This lens deforms the surface and creates a mound. These are generally multiple meters in diameter forming over multiple years. Frost heaves form in a similar fashion but over a period of months instead of years, are generally only a few meters in diameter and only last for one season[7,8]. Additional identifying features are radial cracks on the surface of the mound and polygonal cracking or channel-like features around the base, which can be seen in Figure 3, Left. Similar features can be found on Mars providing an intriguing Earth analog that can be used to identify subsurface water on Mars[9–11].

The permafrost feature site focuses on mid- (10 – 50 cm) and large- (>1 m) scale features, requiring the scientist to assess whether the feature is a pingo or frost heave, identify key features such as the radial cracks, and make inferences as to the feature's formation due to its location, such as the requirement that it form in sediment, near groundwater, and near an area of significant relief.

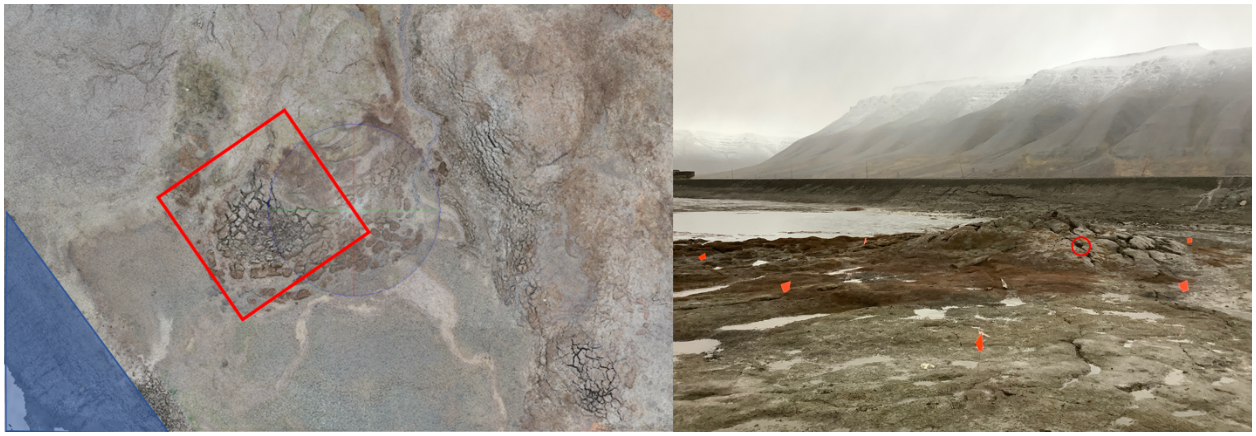

Figure 3: Site 2 - Adventdalen Valley, permafrost feature. Left - overview of the site location with the 10 m x 10 m site highlighted in the red square, data taken with drone. Right - ground view of Site 2.

B.3 Site 4 – Recently exposed glacial moraine

Site 3 was in Longyearelva, the glacially carved valley where the town of Longyearbyen is at the mouth of the valley. The site was approximately 500 m from the base of the Lonyearbreen glacier on the recently exposed (last 50 years) moraine. The moraine was made up of large (5 – 50 cm) angular rocks with a smaller (0.5 – 5 cm) rock and sediment matrix. The site was at the base of a steep scarp and at the head of the braided stream region below the recent retreat. Based on the angularity of the rocks and what appeared to be local origin of the material, this is a cold-based glacier. There are both warm- and cold-based glaciers in the Spitsbergen region of Svalbard[12].

Here scientists will need to focus on the mid-range (10-50 cm) scale looking at the rocks and pebbles within the field site to determine whether the retreating glacier is warm- or cold-based using the angularity of the rocks. Again, the VR environment may provide an easier method of interpreting the location as a moraine as scarp's size and steepness may be more pronounced.

Figure 4: Site 3 - Longyearelva, recently exposed moraine. Left shows site location (orange dot) and distance to Longyearbreen glacier. Right shows the field site marked by orange flags.

II. Hardware

Using the results of a previous analog environment experiment[13] we first selected an optimal low-cost camera that would provide high resolution near-field depth and RGB data. Preliminary testing was done with the Boston Dynamics Spot robot and the Intel RealSense L515 camera in August of 2021 in Marblehead, MA, to assess the combination LiDAR/RGB camera in daylight and night conditions[13]. Experiments were conducted under the MIT RESOURCE project in collaboration with SSERVI and NASA Ames. Due to a lack of commercial availability and support for the Intel RealSense L515, a comparable COTS camera was selected – the Microsoft Azure Kinect.

A. Microsoft Azure Kinect

The Microsoft Azure Kinect is a LiDAR depth-camera with integrated RGB imagery. The camera, Figure 5, has two separate systems for LiDAR and RGB. The LiDAR camera uses modulated near-IR (NIR) light to process and generate a depth-map of a scene. This is created by measuring the time it takes for the NIR light projected by the camera to return to the camera sensor. The amount of NIR light returned from the scene is also recorded providing an IR image alongside the LiDAR image. The LiDAR camera has different modes (narrow field of view, wide field of view, binned and unbinned) to allow for customization of the X- Y- and Z-axis range. The LiDAR camera has a resolution range of 320x288 to 1024x1024 pixels and a Z-range of 0.5-5.5 m depending on the settings used. The 12-MP RGB camera provides aspect ratios of 16:9 and 4:3. In order to have the RGB image completely overlap with the depth map the 4:3 aspect ratio is used with the narrow field of view LiDAR setting. For the data collection completed in Svalbard, this meant recording for a maximum depth of view of 3.86 m with a 75° x 65° field of view.

The data collected on the Microsoft Azure Kinect was captured as a .mkv video file containing both LiDAR and RGB data on Open3D, an open-source library that supports rapid development of software that deals with 3D data[14–16]. To use the data in a virtual environment, a 3D rendering was required. This was also done using Open3D with the commands detailed in Section VI below. This provides a .ply 3D reconstruction of each video. These are then stitched together in Unity.

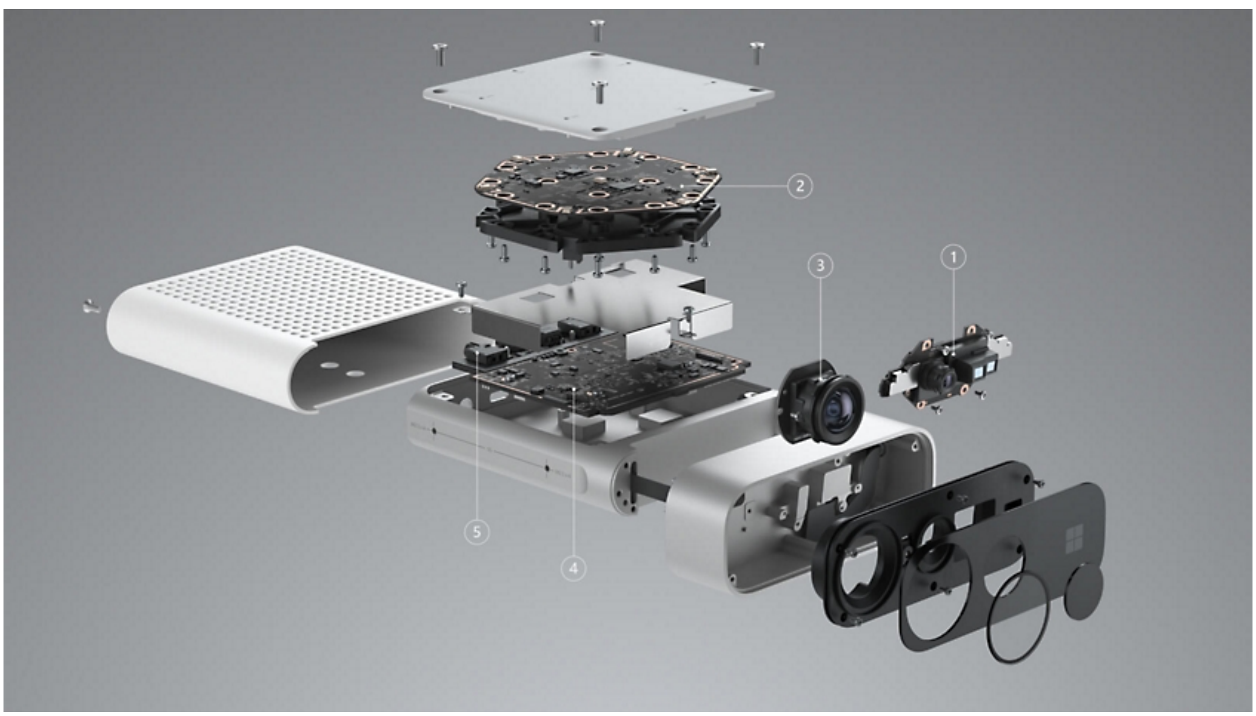

Figure 5: Microsoft Azure Kinect internal hardware – 1) 1-MP depth sensor with wide and narrow field-of-view (FOV) options, 2) 7-microphone array for far-field speech and sound capture, 3) 12-MP RGB video camera for an additional color stream that's aligned to the depth stream, 4) Accelerometer and gyroscope (IMU) for sensor orientation and spatial tracking, 5) External sync pins to synchronize sensor streams from multiple Kinect devices. Image and descriptions from azure.microsoft.com.

B. DJI Phantom 4 Pro V2 Drone

Aerial photography was gathered for each field site using a DJI Phantom 4 Pro V2 drone, a COTS, low-cost drone platform commonly used by amateur drone pilots and videographers. The DJI Phantom 4 drone is equipped with a gimballed 12.4 MP camera and can be operated via an iPad app, which is used to design raster patterns over each field site. The drone was flown in a preprogrammed trajectory to gather high resolution aerial images with complete coverage of the field site.

C. Arduino Nano 33 BLE Sense – Environmental Sensor

The Arduino Nano 33 BLE Sense is a complete environmental sensor package. The sensor records colour (brightness and proximity), sound, motion (vibration and orientation), temperature, humidity and pressure. This is recorded as a .CSV file which can later be calibrated. The sensor uses a small Li-Ion battery (1800 mAh) and records data to a micro SD card.

D. Tablet Application – Field Notes

Field notes, observations collected by hand by the geologist in the field, were done using a custom tablet application designed and built by Dr. Gordon Osinski and his team at the University of Western Ontario for analog missions[17]. The tablet allows collection of annotated images of the site, field notes, voice recordings, and mapping of multiple locations throughout an expedition. A screenshot of the application with field notes is shown in Figure 6. Samples may be recorded within annotated images of the site as well as separately for a location. The data collected can then be collated and exported. The application allows use of camera, audio recording, and sample identification (top symbols in). Also available are the site's location on a map, with GPS location available and compass heading. All expedition sites are located on a top-level map (bottom symbol, left) and in list form.

Figure 6: Tablet application showing Site 1, Outcrop 1 image and initial field notes.

III. Concept of operations development

From fieldwork done in Marblehead, MA, we first assessed the data types that were best suited to near-field exploration of remote environments for scientific return. This was reported at the IEEE Aerospace Conference in 2021[13]. A combination RGB and depth-imagery camera was selected to allow for depth-data functionality in low- and no-light scenarios while also providing colour when possible. The Microsoft Azure Kinect was tested at the Marblehead site in 2022 using the software that came with the camera and manual manipulation of camera position to assess the baseline concept of operations for data collection expected in Svalbard, Norway. The data was collected by manually rotating the camera on a marked platform in 60° increments (to allow for 5° of overlap on each side of the image for the narrow field-of-view setting) and capturing a 10 second video at each position. The camera was moved on a tripod through a raster-style pattern in 3 m increments over a 10 m x 10 m field site. The data collected provided insights into multiple challenges for this style of collection in an extreme environment. The software required long inputs from the user for each capture which needed to be minimized for the freezing temperatures. Additionally, the captured videos required extensive manipulation to stitch into a 3D scene in post-processing, requiring first stitching the 360° rotation images, followed by stitching the raster images. Additionally, using a tripod on the uneven surface was time-consuming and often resulted in loss of stability of the camera and the image. Finally, the 360°-style data capture left a data gap where the camera was positioned.

To address these lessons learned the following actions were taken:

1. Software: instead of the Microsoft Azure Kinect SDK, we would switch to a modified version of the Open3D library and software. The Azure Kinect camera is equipped with a high-resolution depth sensor and a 4k color

camera, which allow it to capture data that can be used to generate a 3D point cloud. Open3D is an open-source library that provides a range of algorithms and tools for manipulating and analyzing point clouds. We used Open3D to capture, process and visualize the data recorded by the Azure Kinect camera, enabling us to generate 3D models with a high degree of accuracy and detail from single recordings. The software uses a single video capture in which the camera is manipulated to 'see' the entire 360° of a scene to create a 3D point cloud without the need to manually stitch together individual images/videos. Additionally, the modified version of the software allowed video captures to be started and stopped with single key-stroke inputs to minimize time required without gloves in the field.

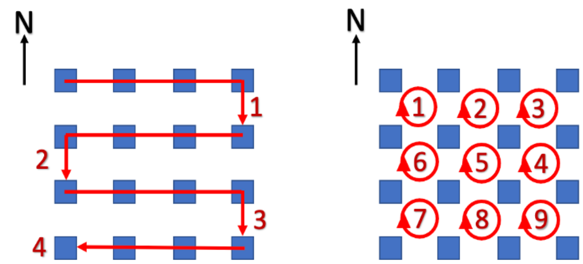

Figure 7: Recording patterns. Left: Raster pattern (better for post-processing) – 4 recordings and Right: Grid pattern – 9 recordings

2. Raster vs. Grid: Using the Open3D software, we created two capture styles, raster and grid, Figure 7, to capture the data in an effort to eliminate blind spots. The raster pattern provides long swathes of data side-by-side, while the grid pattern provides 360° blocks of data with central blind spots that are eliminated by overlapping data from adjacent grids.
3. Uneven ground: Because we couldn't predict the conditions of the ground on which we would be recording, we chose the simplest method to ensure camera stability: manual data collection. The camera was held at an approximately continuous height from the ground and walked in the selected pattern over the field site. This allowed for faster data collection (critical in the low temperatures) and a smoother video recording.

IV. Mission planning

Working in Svalbard, Norway required special planning not only for logistics and concept of operations for a remote location, but also in consideration of the fragile nature of the environment. The government of Norway requires approval of all research being conducted on the archipelago to ensure protection of the environment and historical locations with a focus on minimizing human impact. A detailed application package was submitted to the Governor of Svalbard including all field site locations with access dates, modes of transportation, equipment to be used, data collection methodology and data use. Additionally, because a drone was used, drone licenses were required from the Civil Aviation Authority of Norway and sites needed to be at least 5 km from the airport. Logistics within Svalbard were coordinated by Maggie Coblentz and Sean Auffinger from SEI.

Field work in the Arctic requires unique preparation including both training and specialized equipment considerations for the cold temperatures and high winds. Considerations were made for battery life, hardware use on unstable ground, high winds, and possible precipitation. All electronics were kept in weather-proof cases, including a custom 3D printed housing made for the environmental sensors as they would need to be left overnight. Low temperatures also required all hardware be manipulatable with gloved hands (with exception made for the minimized inputs for the Azure Kinect software operation). The researchers were also provided with an environmental preparedness course prior to the expedition and a polar bear safety course taught at the University Centre in Svalbard (UNIS).

V. Data Collection

At each site a 3-by-3 grid was set up using flags to mark 3.3m x 3.3m grid blocks for a 10 m x 10 m site. Field notes were taken at each site including date and time, GPS coordinates, weather conditions, site name and any distinctive features. This was done using the tablet field notes. This was followed by starting the environmental sensor recording. The RGB and depth-imagery were then collected. Finally, the drone data was collected for the site and the surrounding area. Figure 8 shows the activities being conducted in the field.

Figure 8: Clockwise from top left: Arduino environmental sensor in custom hard-shell case, C. Paige collecting field notes, C. Paige collecting data using the Microsoft Azure Kinect, C. Paige, S. Auffinger and J. Todd preparing a mini rover with the Microsoft Azure Kinect mounted on a custom payload tower for data collection, C. Paige and J. Todd collecting data using a Velodyne puck on a custom 360-degree rotational mount (collection for a separate project, Ward et al., at ICES 2023).

A. Environmental Sensor

The environmental sensor was stored in a custom weatherproof housing, Figure 9, Right, with it's Li-Ion battery disconnected. After the grid was marked, the housing was opened, the battery was connected to the sensor and the Arduino environmental sensor was placed at the north-east corner of the grid, Figure 9, Middle. The sensor was left to passively collect data for 2-3 hours while the field notes, Azure Kinect and drone data were collected. The sensor housing was then closed and left to collect data overnight with a marked flag, Figure 9, Left. The duration of data collection depended on the team's ability to return to the site and the life of the battery – usually 12-15 hours. When collected, the battery was disconnected to ensure no further data was recorded.

Figure 9: The Arduino Nano 33 BLE Sense environmental sensor is contained in a custom weatherproof housing for data collection. Left – sensor is flagged and housing is closed and weighted for overnight data collection, Middle – shows housing opened for researcher-on-site data collection with Li-Ion battery connected and Right shows custom weatherproof housing.

B. RGB and depth-data collection

The Microsoft Azure Kinect camera was then walked in the two patterns described in Section III over the field site: 1) a raster pattern (Figure 7, Left) and 2) a grid pattern, (Figure 7, Right) a 360° rotation within each grid block. This allowed us to assess the ideal traverse path needed to create a complete field site in 3D. The camera was held approximately 1 m above the ground and walked in the selected pattern. This manual method proved particularly important at Site 2, where the ground was very soft and wet and would have proven difficult for tripod use, and Site 3, where the winds were high and would have caused tripod instability.

C. Drone depth-data

The drone depth-data was the final set collected at each site. All but the corner flags were removed from the site's grid to minimize visual interferences in the drone field-of-view while still maintaining the site's external parameters. The drone was flown 15 m above the ground in a raster pattern of 1 m by 1 m over the entirety of the site. Additional data was collected at a height of 25 m flying a raster pattern of 10 m by 10 m for a lower resolution of the surrounding area of each site.

VI. Data processing for VR development

A. 3D Reconstruction with Azure Kinect and Open3D

In order to create highly detailed and accurate 3D models of objects or environments, our team utilized 3D reconstruction techniques using the Azure Kinect camera and the Open3D library. 3D reconstruction techniques using the Azure Kinect camera and Open3D can be applied to a wide range of applications, including virtual reality, robotics, and computer-aided design. By leveraging the capabilities of the Azure Kinect camera and the powerful tools provided by Open3D, we were able to create highly accurate and detailed 3D models for our project, Figure 10. The following is a series of commands used to process the 3D reconstruction using Open3D and Python3:

python azure_kinect_mkv_reader.py --input "...\[folder]\[capture].mkv" --output "...\[folder]\[capture]"

Make, Register, Refine, Integrate commands:
python run_system.py --make "...\[folder]\[capture]\config.json"
python run_system.py --register "...\[folder]\[capture]\config.json"
python run_system.py --refine "...\[folder]\[capture]\config.json"
python run_system.py --integrate "...\[folder]\[capture]\config.json"

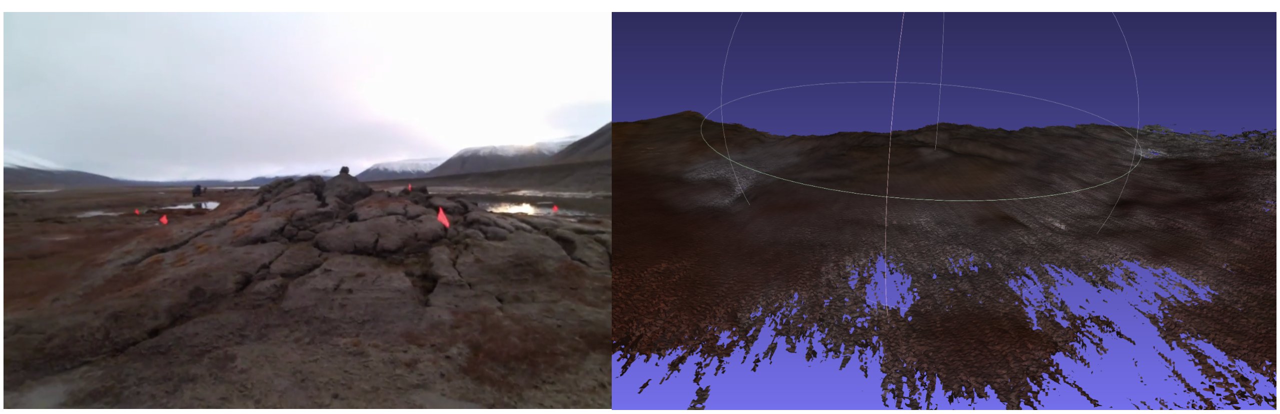

Figure 10: Left: Image of video in .mkv format from Site 2, Right: 3D reconstruction from Azure Kinect video.

B. Drone and Metashape

Agisoft Metashape was used to perform photogrammetry with the drone images, producing 3D point clouds and meshes of the field sites to augment the data gathered with other hardware. Photogrammetry was performed by matching features across images and generating a dense point cloud of the mapped area. GPS coordinates from the

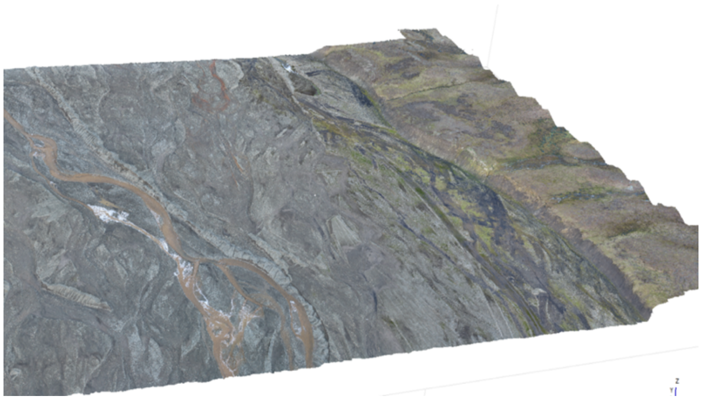

Figure 11: 3D mesh of Site 1 - river bed

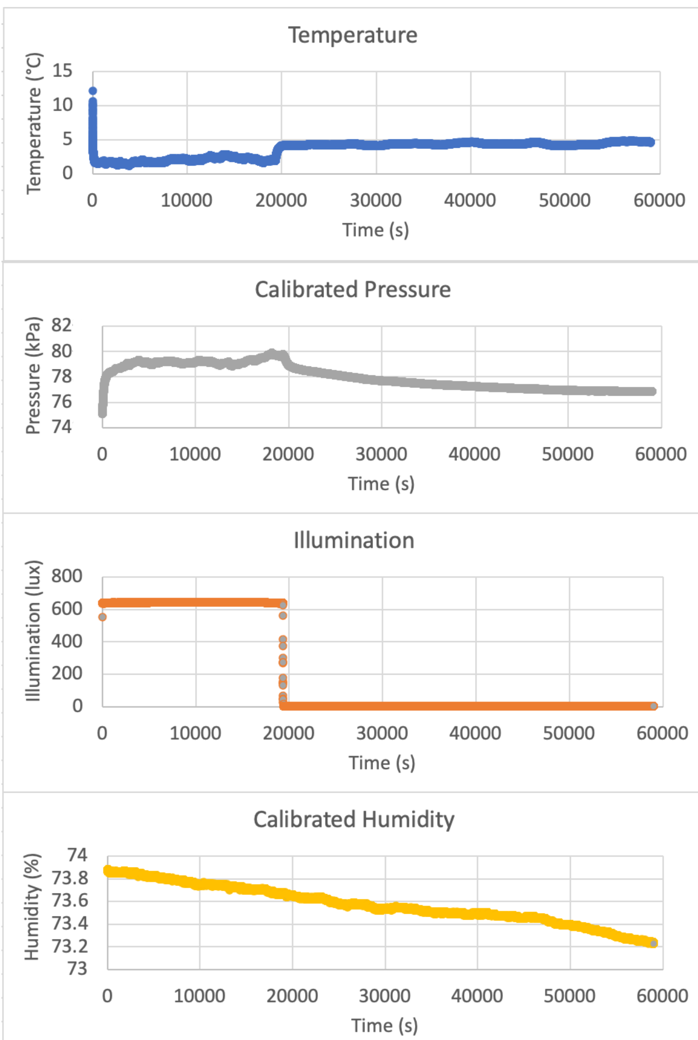

Figure 12: Calibrated environmental sensor data in graphical form from Site 1, Outcrop 1 over a period of 5 hours and 56 minutes, from top - temperature in degrees celcius, pressure in kPa, illumination in lux and humidity in percent humidity.

drone were used to provide an initial estimate of the camera location. Extrinsic and intrinsic camera properties together with the detected and matched features were then used to exactly determine the location of each photo. Once a point cloud was generated, the point cloud data was used to generate a 3D mesh of the field site or combined with image data to generate a 3D texture or orthomosaic. An example of this data for a field site is shown in Figure 11.

C. Environmental Sensor

The environmental sensor data was saved to a micro-SD card directly on the Arduino board as a .CSV file. Four data streams were collected – temperature (°C), humidity (%), pressure (kPa) and illuminance (lx) at 1 second intervals. The data was parsed for each site using illuminance to identify when the housing was opened or closed. The Arduino environmental sensor is factory calibrated and does not require user calibration[18]. Figure 12 shows a sample of the calibrated data in graphical form. This data will be incorporated into the VR environment following previous work on the Dopplemarsh project[19] using sensor nodes to visually represent the environmental data, Figure 13.

VII. Future Work

A. VR environment in Unity

With the processing complete, the data is now being combined in a single virtual environment in which the user can explore the three field sites. The drone data is being used as a base layer of depth and colour imagery of the site and the surrounding area. The Azure Kinect data is being overlain onto the drone imagery as higher resolution near-field depth and colour imagery for the 10 m x 10 m site. The background is being filled in using Google Earth imagery when available and pictures taken while in the field when not. This will be a representative far-field environment that will help the user with contextual cues but will not include depth data. The environmental sensor data will be included as a heat-map style node which can be turned on and off at the location where the data was collected (NE flag of the marked site), similar to the method used in Dopplemarsh[19], Figure 13. The field notes will also be accessible by the user in a pop-up

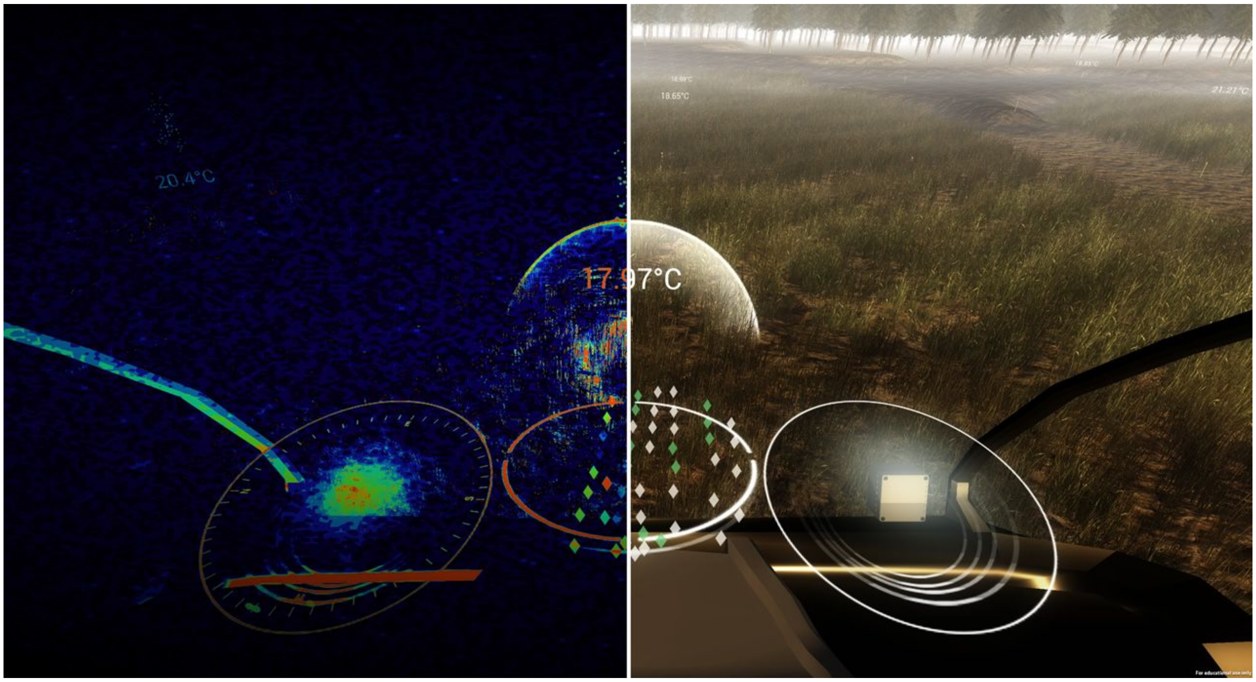

Figure 13: Virtual cockpit in the Dopplemarsh environment demonstrating node display of environmental data.

window format. At each location where notes or images were collected, there will be a location flag that will act as a toggle to open the image/note. Finally, two tools will be available to the user to aid in exploration: 1) a measuring tool that allows the user to select two points and the distance between them will be provided and 2) a highlighting tool, like a flashlight that brightens the area where the user is pointing; this can help to focus attention and provide a method of communicating specific areas of interest if a second user is present. A preliminary view of the virtual environment is shown in Figure 12 which shows the drone data for Site 2, the permafrost feature in Adventdalen.

B. Human subject testing

Using the VR environment developed from the Svalbard data, we will test the usefulness of VR as a tool for geological surface exploration of the Moon or a planet. The participants will explore each of the three sites using both the virtual environment on an Oculus Quest Pro and using the Desktop version of the environment (the same Unity application but used on a Desktop). For each site, the participant will be provided with a geology fact sheet ensuring that they are familiar with the terminology as well as the feature which they will need to identify. They will be given key elements which will define the geological feature and will require them to use all the datasets available to them to explore the site. For each feature, they will be provided with a potential alternative answer. They will be asked to provide feedback on their experience as well as being monitored during the testing. The main goal of the testing will be to assess if VR is the optimal tool for geological surface exploration using the following criteria:

- Identification of geological features of different scales
- Use of multi-scale data for near-field observation
- Comparison of VR to Desktop application

The following metrics will be used to assess workload, simulation experience, and tool capability:

- The NASA Task Load Index (NASA-TLX) a multi-dimensional tool to assess workload of a task[20,21]
- NASA Exploration Analog and Mission Development Rating Scales[22–24]
- Total time spent in simulation
- Time to identify main geological feature
- Number of points of interest (POI) identified
- Was the correct geological formation identified?
- Scale of identified POIs (<10cm, 10-50 cm, >1 m)
- Number of data sets used during observation
- Which data sets were used during observation (Azure, drone, environmental sensor, background images):

- Number of grid blocks explored
- Questions asked by user before observation
- Questions asked by user during observation
- Questions asked by user after observation

Figure 14: Preliminary virtual environment in Unity of Site 1, riverbed. Data was collected using the drone. Red box highlights the sensor node, white dashed lines to cones with hovering numbers show measurement tool capabilities.

VIII. Conclusion

Field work for a geologist is critically important for building the story of the environment and understanding how each component fits in. Being physically present gives us an innate understanding of a feature simply by being able to see the distant geology, understand the size of the feature compared to our own physical size and get a sense of how the two connect. Virtual reality has the potential to provide scientists with a substitute for field work on the Lunar and planetary surfaces. While we can never replace in-person exploration, this technology could supplement it, giving a broader range of scientists the opportunity to analyse these environments, and by providing a safe alternative to explore regions of interest that cannot or should not be accessed by humans, and an environment in which to train for the in-person missions. But we must first understand the limitations of the current technology and determine if we are able to inform the senses with enough accuracy to make this substitution. Using Svalbard as an analog for a Martian environment, we are building a virtual platform to test this.

Collecting data in Svalbard presents challenges that can inform future expeditions both on Earth and in space working in remote locations with extreme environmental conditions. Some of the lessons learned from this expedition included:

- Data transfers should be completed daily in case of loss of electronics capabilities
- Use devices to enable hands-free work, for example a laptop carrier would provide freedom to control other hardware during traverses
- Minimize use of touchscreens and key-stroke inputs – using a tablet application for field notes allows the combination of various data inputs (images, annotation, GPS, voice recordings, compass, etc.), but needs to ensure that it can be used in extreme temperatures. Consideration should also be given for using tablet pens with minimal finger mobility.
- Scouting missions should be used to assess the region where data will be collected prior to site selection. Without scouting, it was not possible to assess the ground stability, small-scale features and points of

interest using only satellite data. The first day of the expedition was spent visiting multiple sites to select the prime locations for data collection. The application to the Svalbard government required modification after this first day to accommodate changes.

- Having our expedition leader be familiar with the field area and the resources available there was invaluable during the mission. Because she was already integrated into the community, she was able to provide us with a last-minute generator rental, electronics components, footwear needed to ford a river, and vehicle extraction aid. This is particularly important when exploring sites that have minimal access to resources and/or small communities that share their resources informally.
- Finally, the team itself was composed of five researchers each working on their own unique projects, but each member supported the work of others, bringing different skills to the group. It was important to quickly feel comfortable asking for help and volunteering aid – this was accomplished in our group through communal meals.

VR is a technology with great potential to enhance scientific exploration and enable better human-robotic exploration. OnSight, NASA's VR software for Mars, is a perfect demonstration of the capabilities this technology may provide. Here we are exploring more accessible avenues to develop VR as an exploration tool while focusing on the usefulness of the cost-efficient methodology developed in Svalbard. Space start-ups, industry partners, and the Commercial Lunar Payload Services are all contributing to making space more accessible. Using low-cost technologies in partnership with these services furthers this accessibility opening the scientific exploration of data collected in space to a broader range of researchers. Given the challenges associated with exploring craters and lava tubes, regions of interest for in-situ resource utilization, enabling exploration through VR could allow for safer methods for astronauts to both train for upcoming missions, such as the Artemis missions, and for robotic data collection to supplement astronaut exploration in challenging areas. The RESOURCE team, in collaboration with NASA Ames and the MIT Space Exploration Initiative are currently preparing to send a modified Azure Kinect to the Lunar south pole on a Lunar Outpost rover as part of a Commercial Lunar Payload Services mission to demonstrate the viability of this technology[25]. While current rovers may not be capable of exploring deep craters and lava tubes in permanently shadowed regions, we have demonstrated that with alternative methods of locomotion, like on a quad-ped rover[13], this will become a viable option. Additionally, the drone work done here demonstrates capabilities for Mars surface exploration with tools like Ingenuity (NASA Mars drone). In testing these low-cost solutions for VR development, we hope to enable future data collection on multiple platforms, expanding our exploration capabilities.

We plan to continue not only this work in the assessment of the VR platform for Lunar and planetary surface exploration, but also to understand how this can be leveraged to explore our own world's fragile environments without over-burdening these remote spaces. Increasing their accessibility will allow more science and a better chance of learning how to protect our own planet.

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References

[1]Caravaca, G. *et al.* 3D Digital Outcrop Model Reconstruction of the Kimberley Outcrop (Gale Crater, Mars) and It's Integration Into Virtual Reality for Simulated Geological Analysis. *Planet. Space Sci.* **182**, (2019).

[2] NASA. *NASA's Plan for Sustained Lunar Exploration and Development*. (2020).

[3]Garcia, A. D., Schlueter, J. & Paddock, E. Training astronauts using hardware-in-the-loop simulations and virtual reality. *AIAA Scitech 2020 Forum* **1 PartF**, 1–13 (2020).

[4]Lim, D. S. S. *et al.* The BASALT Research Program: Designing and Developing Mission Elements in Support of Human Scientific Exploration of Mars. *Astrobiology* **19**, (2019).

[5]Institute, N. P. Norsk Polarinstitutt. *Research*.

[6]Pewe, T. L., Rowan, D. E., Pewe, R. H. & Stuckenrath, R. *Glacial and periglacial geology of northwest Blomesletta peninsula, Spitsbergen,Svalbard. Norsk Polarinstitutt Skrifter* vol. 177 (1982).

[7]Liestøl, O. Pingos, springs, and permafrost in Spitsbergen. *Nor. Polarinstitutt Arb.* 7–29 (1977).

[8]Burr, D. M., Tanaka, K. L. & Yoshikawa, K. Pingos on Earth and Mars. *Planet. Space Sci.* **57**, 541–555 (2009).

[9]Hauber, E. *et al.* No TitleLandscape evolution in Martian mid-latitude regions: insights from analogous periglacial landforms in Svalbard. *Geol. Soc. London, Spec. Publ.* **356**, 111–131 (2011).

[10]Osinski, G. R. & Soare, R. J. Circular structures in Utopia Planitia, Mars: Impact V. Periglacial origin and implications for assessing ground-ice content. *Lunar Planet. Sci. Conf. XXXVIII* 1609 (2007).

[11]Burr, D. M., Soare, R. J., Wan Bun Tseung, J. M. & Emery, J. P. Young (late Amazonian), near-surface, ground ice features near the equator, Athabasca Valles, Mars. *Icarus* **178**, 56–73 (2005).

[12]Sevestre, H., Benn, D. I., Hulton, N. R. J. & Bælum, K. Thermal structure of Svalbard glaciers and implications for thermal switch models of glacier surging. *J. Geophys. Res. Earth Surf.* **120**, (2015).

[13]Forsey-Smerek, F. *et al.* Assessment of Depth Acquisition Methods for Virtual Reality Mission Operations Support Tools. in *IEEE Aerospace Conference Proceedings* (2022).

[14]Open3D. www.open3d.org.

[15]Choi, S., Zhou, Q. Y. & Koltun, V. Robust reconstruction of indoor scenes. in *IEEE Conference on Computer Vision and Pattern Recognition* 5556–5565 (2015).

[16]Park, J., Zhou, Q. Y. & Koltun, V. Colored point cloud registration revisited. in *IEEE Conference on Computer Vision and Pattern Recognition* 143–152 (2017).

[17]Osinski, G. R. *et al.* The CanMars Mars Sample Return Analogue Mission. *Planet. Space Sci.* **166**, 110–130 (2019).

[18]Garcia, J. Reading Temperature & Humidity on Nano 33 BLE Sense. *Arduino DOCS* https://docs.arduino.cc/tutorials/nano-33-ble-sense/humidity-and-temperature-sensor (2023).

[19]Haddad, D. D. *et al.* Resynthesizing reality: Driving vivid virtual environments from sensor networks. in *ACM SIGGRAPH* (2017).

[20]Hart, S. G. & Staveland, L. E. Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. *Adv. Psychol.* 139–183 (52AD).

[21]NASA Task Load Index (TLX) iOS.

[22]Lim, D. S. S. *et al.* The BASALT Research Program: Designing and Developing Mission Elements in Support of Human Scientific Exploration of Mars. *Astrobiology* **19**, 245–259 (2019).

[23]Beaton, K. H. *et al.* Using Science-Driven Analog Research to Investigate Extravehicular Activity Science Operations Concepts and Capabilities for Human Planetary Exploration. *Astrobiology* **19**, 300–320 (2019).

[24]Beaton, K. H. *et al.* Mission enhancing capabilities for science-driven exploration extravehicular activity derived from the NASA BASALT research program. *Planet. Space Sci.* **193**, 105003 (2020).

[25]Jha, V., Garrett, M., White, B., Shimada, J., Cook, A., Colaprete, A., Heldmann, J., Dave, A., Paige, C., Ward, F. and Auffinger, S., 2022, December. Ruggedizing a Commercial Depth Camera for Novel Lunar Exploration. In *AGU Fall Meeting Abstracts* **2022**, P55E-1617 (2022).