DESIGN REPORT

SUMMER 2015

PARALLAX

# EMPOWERING ASTRONAUTS FOR GREATER AUTONOMY IN DEEP-SPACE EXPEDITIONS

Carnegie
Mellon
University

# EXECUTIVE SUMMARY

During regular missions aboard the International Space Station (ISS), NASA astronauts are tasked with conducting scientific experiments and performing a variety of maintenance operations. However, carrying out these operational tasks involves memory recall challenges due to the length of time that elapses between when astronauts receive training and when they execute tasks aboard the ISS. As NASA undertakes the next leap in a new era of human space exploration that extends beyond low-Earth orbit, an intelligent system that provides instructions can empower astronauts to autonomously execute procedures.

This project started with understanding the context in which astronauts work. We used this research to design a working prototype of an augmented reality headset that allows astronauts to get hands-free instructions for procedures.

After several design iterations, we developed an an intelligent, connected device that leverages various technologies to empower astronauts performing unfamiliar procedures while maximizing their mobility. We considered how to present information that allows users to stay focused on the task at hand and navigate the user interface (UI) while keeping both hands free. We also implemented features to aid the user with navigation and tool location. The integration of all of these features provides astronauts with increased autonomy by reducing the dependencies that they have using current methods for procedure execution.

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# PROBLEM CONTEXT: IMPROVED PROCEDURE EXECUTION

## INTERNATIONAL SPACE STATION

The International Space Station (ISS) is a habitable satellite used to conduct scientific experiments under conditions of zero gravity. Astronauts stationed there conduct and oversee these experiments, as well as repair and maintain internal equipment. Aboard the ISS, astronauts have access to an operator on the ground for clarification and for working around issues.

## 2030 MARS MISSION

NASA has outlined a roadmap to send engineers and scientists to Mars by the 2030s. When an astronaut tries to contact ground control while on a mission to Mars, it will take up to 40 minutes to get a response due to communication delays. To work more efficiently, astronauts on Mars may need to carry out procedures more autonomously.

## NOVICE USERS

Astronauts perform a wide variety of procedures in space, from repairing equipment when it is broken to conducting scientific experiments designed by researchers on Earth. Astronauts spend years on the ground training on different procedures that they will perform in space. It could be six months to two years from when an astronaut is training on a procedure until they execute that procedure in space.

We are tasked with envisioning how an astronaut might execute a procedure with no prior training or when they had been trained long ago and do not remember every instruction of the procedure.

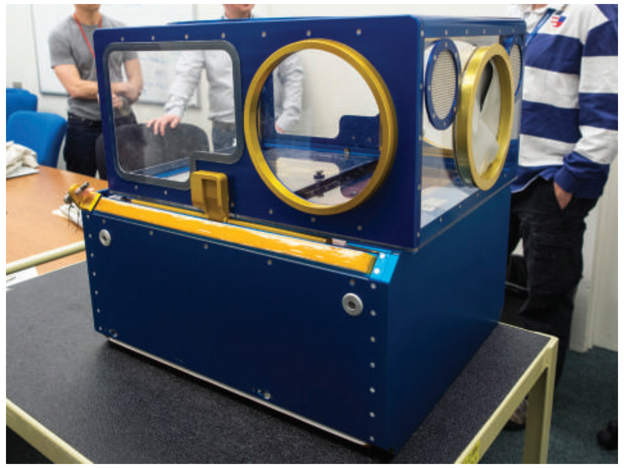
## OUR STRATEGY

We sought to understand the context in which astronauts perform procedures as novice users and develop a technically feasible solution that facilitates performing these tasks on the ISS and on future missions to Mars.

# RODENT HABITAT

## ISS EXPERIMENTS

The Rodent Habitat is used to house mice or rats on the ISS for long-term animal experiments in space. The experiments on rodents help to better understand the effects of microgravity on animals, how microgravity can potentially impact humans and fundamentals of biology and how to treat diseases.



*The Animal Access Unit (AAU) sits on top of the Rodent Habitat. The AAU has two gauntlets, which are used for containment, similar to gloves in a glove box. The access unit also has two socks that are used to transfer material into the AAU at the start of a procedure or out of the AAU at the end of the procedure.*

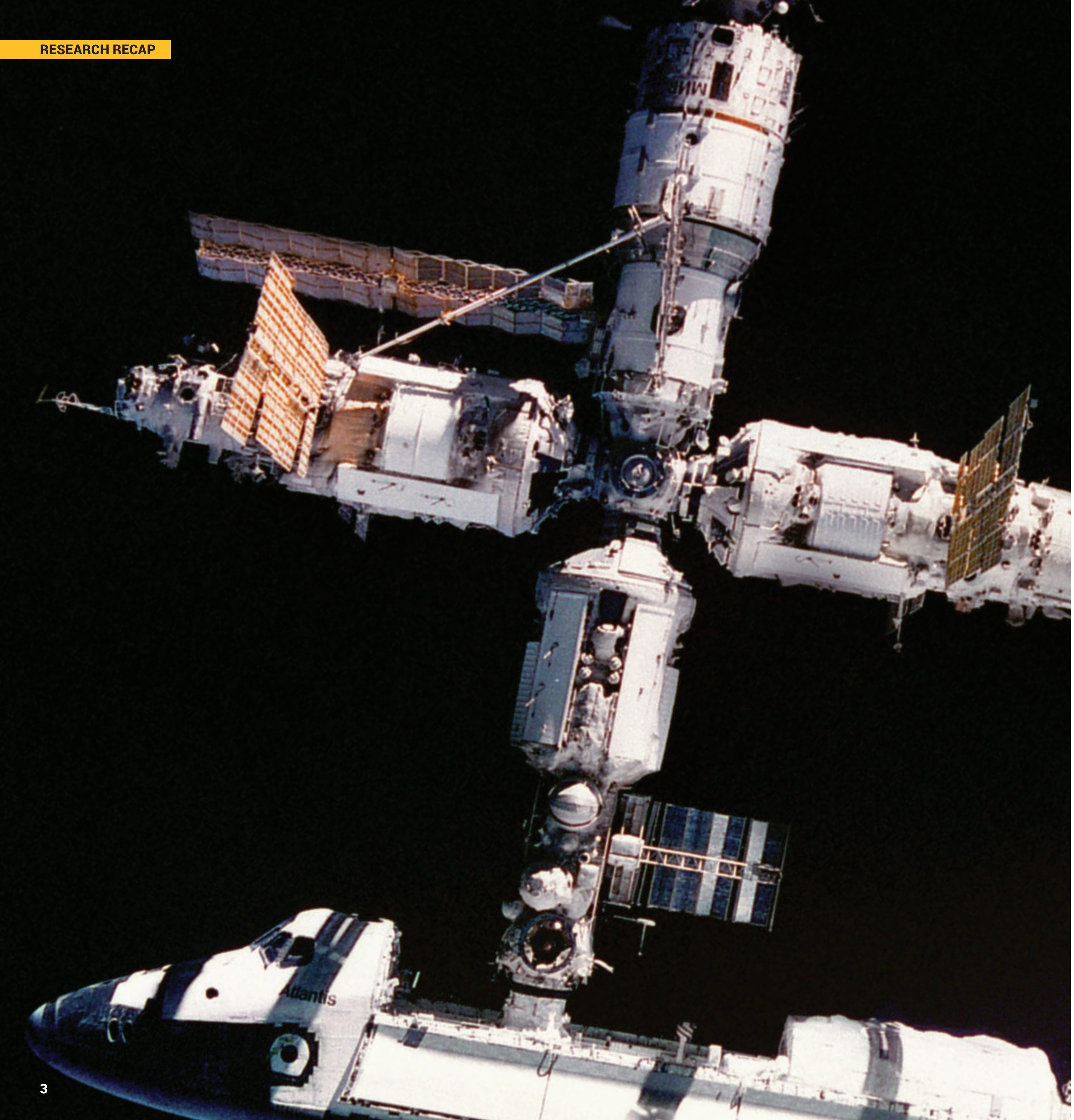
## EQUIPMENT

The Rodent Habitat has two sides for housing rodents, side A and side B. The two different sides in the same unit are so that the animals in the control version of the experiment are in one side and the animals in the experimental condition are in the other side.

Whenever the astronauts need to open the Rodent Habitat, they use the Animal Access Unit to provide a level of containment for the animals and animal byproducts. When the astronauts are cleaning out the Rodent Habitat or replacing water or food, they put mice into a Mouse Transfer Box temporarily. This ensures that the mice are not injured when the astronaut is working inside the Rodent Habitat. The Mouse Transfer Box is also used when the animals are transported outside the Rodent Habitat for things like x-rays to measure their changes in bone density.

## PROCEDURE

The prototype in this project was uses the “Rodent Habitat Restock” procedure, in which astronauts replace the food for the rodents.



# RESEARCH RECAP

Over the spring semester, the team conducted research to better understand the context in which an astronaut works, to review existing literature in relevant areas, and to understand applicable technology. For a full summary of this research, see the USB key.

The team performed contextual inquiries at the Arc Jet complex at the Ames Research Center and the Thermal Protection System Facility at Kennedy Space Center. Observing these processes allowed the team to observe two NASA procedures while they were being executed. Additionally, we performed research around nine domains whose conditions map closely to that of astronauts because access to current astronauts is extremely limited. Research in these analogous domains included two additional contextual inquiries, twenty interviews, and three experiential learning sessions in which we were able to perform the activities within the domain ourselves to give us hands-on knowledge of the experience.

In addition to understanding astronaut working conditions and procedure execution, we also engaged in research to inform our knowledge of current software and hardware technologies. In particular, we performed an in-depth review of several technology domains spanning augmented reality, computer vision, speech recognition, sensors, and wireless protocols. Gaining a deeper awareness of these technology areas influenced our prototype development in the context of our research findings.

# VALIDATED PRIOR FINDINGS

**Through our research, we validated the following findings that had already been discovered by NASA and past NASA MHCI project teams. Some of these will be used as design considerations for our solution.**

## FINDING TOOLS

Tools are sometimes difficult to locate without external assistance.

Tools are returned to places other than their expected storage location, leading to frustration when attempting to subsequently locate them.

Systems that can locate tools would be very helpful.

## MULTIPLE RESOURCES

Task completion often requires a back-and-forth process of referring to multiple resources.

## COORDINATION

Working in confined spaces often requires assistance to provide necessary tools and support.

## COMMUNICATION

Building relationships foster improved communication and work efficiency.

In addition to knowledge and skills, quality training also covers effective communication.

The need to share resources demands proper coordination to ensure their efficient usage.

## LOW RISK EXPOSURE TO TASK

Physically observing others perform tasks aids learning.

Simulating scenarios comprehensively can drastically reduce failure probability.

## AUTOMATION

Automatically tracking job completion improves efficiency.

## REDUNDANCY REASSURANCE

Having available back-up resources when needed provides confidence during task execution.

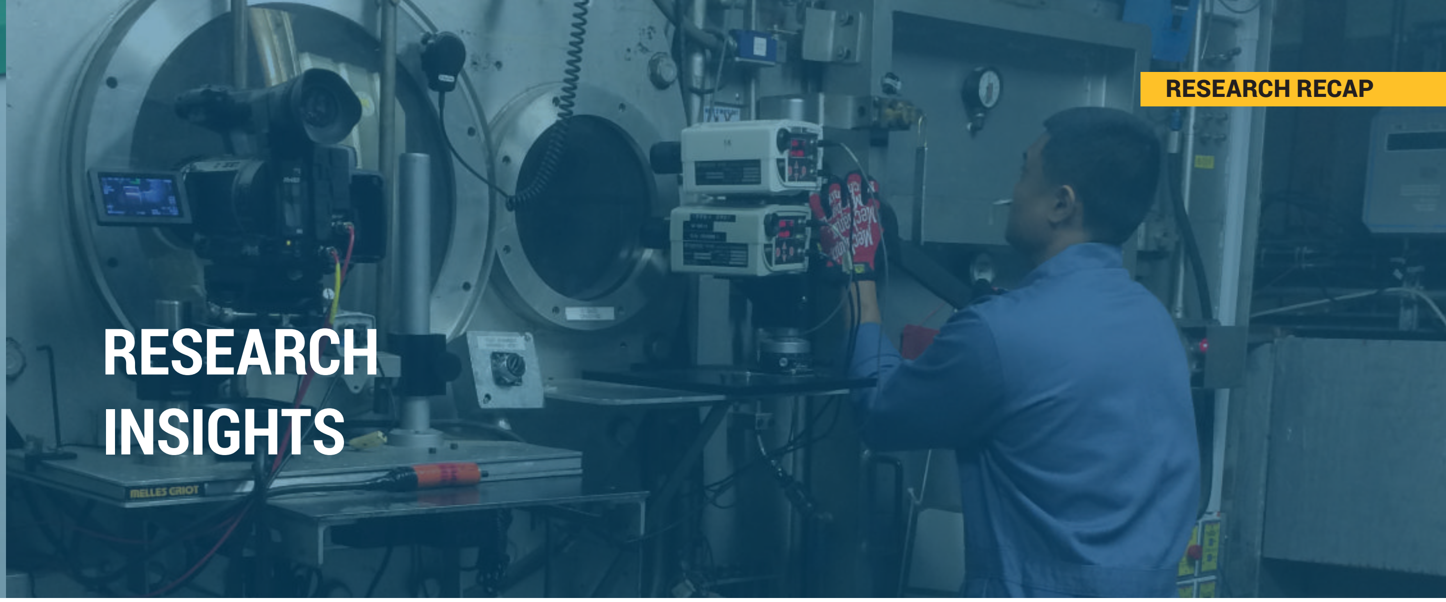
## HOLISTIC SITUATIONAL AWARENESS

Complications can be minimized by establishing a comprehensive picture of a particular situation.

Knowing “why” promotes work understanding.

Lack of context awareness can lead to complications and unexpected issues.

Lack of holistic context awareness between procedure authors and executors can often lead to disconnects.



# RESEARCH INSIGHTS

**Based on our research analysis, these four insights represent areas of discovery that are new to NASA and past NASA MHCI projects.**

## COORDINATION BETWEEN PLANNING AND EXECUTION CAN BE IMPROVED BY WORKER SUGGESTIONS.

We found disconnects between the work planner and the person executing the work. Some domains from our research have a feedback loop built into the process where a worker who notices issues can suggest improvements. These suggestions are evaluated and the best ones implemented. This has the dual benefit of improving processes while also allowing the workers to feel empowered that they are able to positively impact change.

## WORKERS TRACK STATUS WITHIN A PROCEDURE.

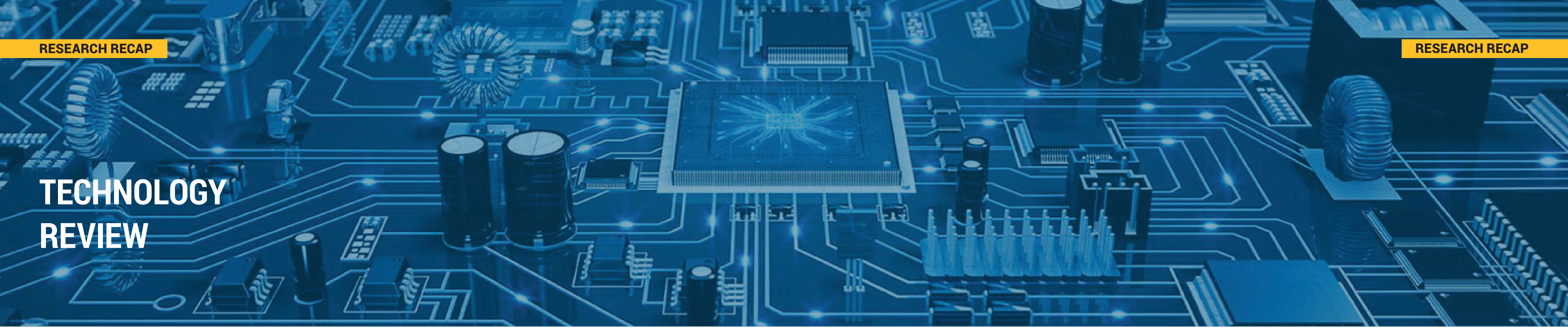
Astronauts follow long, multi-step procedures that often reference other books. They need to be able to keep track of not only where they are in a procedure, but also the important, actionable parts. They sometimes use physical objects like post-it notes to maintain their cognitive orientation within the procedure.

## SPATIAL REFERENCES HELP GUIDE WORKERS THROUGH A PROCEDURE.

In some domains, cues in the environment or within the interface of a tool help workers navigate a physical area during a procedure. In other domains, hand positions and gestures give physical cues for how to perform a task.

## ADJUSTING INSTRUCTIONS FOR A USER CAN IMPROVE UNDERSTANDING.

The amount of detail necessary for a user to follow in a given task varies by a particular person’s experience and role. A beginner typically requires detailed information to ensure proper task execution, but with greater experience and increased knowledge, however, the need for finer levels of detail typically decreases.



# TECHNOLOGY REVIEW

**Reviewing the insights from our research led us to evaluate various types of technology and determine how we could implement them in our prototype development.**

## AUGMENTED REALITY DISPLAYS

A head-mounted augmented reality (AR) display, which can insert virtual objects into the real world around users wearing the device, uses transparent lenses so that users can continue to view the physical environment around them. Combined with sensors such as accelerometers, gyroscopes, and infrared cameras, AR display devices can also compensate for head movement and adjust the orientation of virtual objects accordingly. Increased computing power and miniaturization has led to a recent influx of AR display device offerings, many of which we reviewed from a technical capability and usability perspective. We were also able to experience some of these devices in-person at a recent augmented reality conference. Most of these AR display devices were not available for direct purchase, however, leading us to construct our own solution.

## COMPUTER VISION

Our research indicated the importance of providing spatial awareness to the user. One way to achieve this awareness is to use computer vision to optically recognize various objects in a user's surroundings and determine which direction the user is facing. The system can then guide the user to turn in a particular direction to find a particular tool.

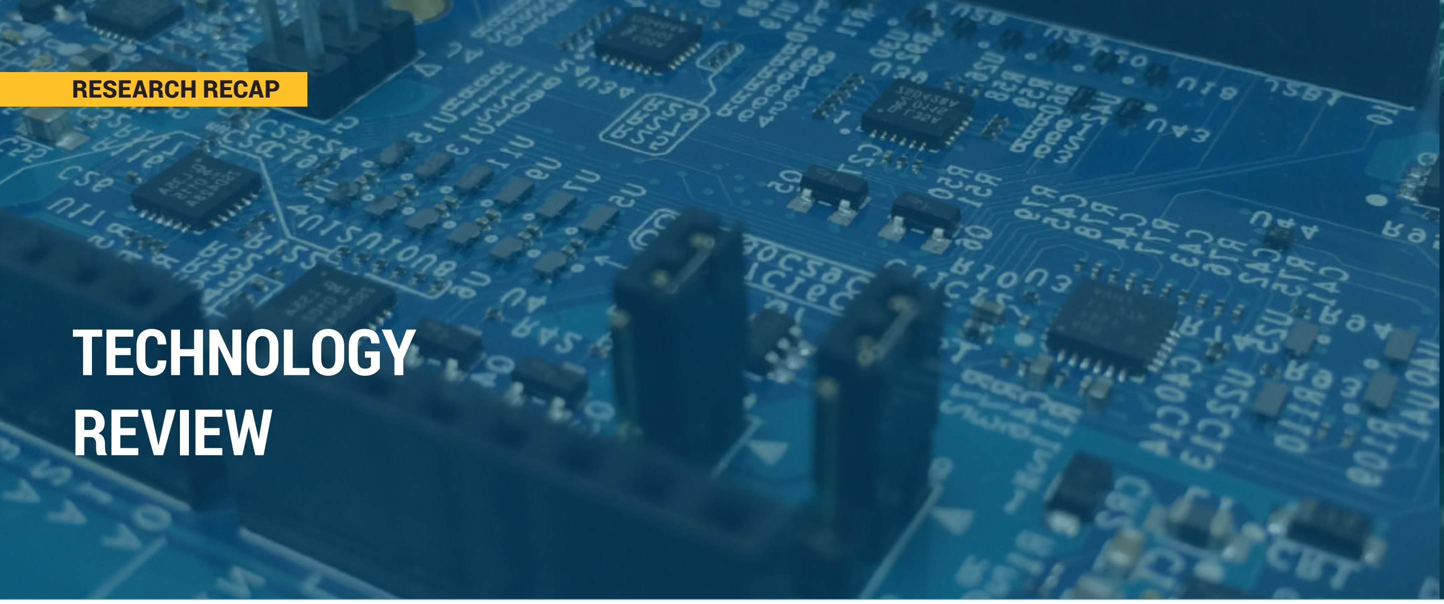
OpenCV is a cross-platform software library that includes several hundred computer vision algorithms and enables the detection of predefined objects. By using a webcam and computer vision in our system, we would be able to enable our system to scan, recognize, and remember the location of objects in a user's environment to provide information on a user's orientation relative to these objects.

Computer vision can also detect facial expression and eye gaze. This information allows a system to determine a user's stress and attention level, which can help to improve procedures and user interfaces accordingly.

**Our research findings provided strong justification for leveraging augmented reality and computer vision collectively in our solution. We examined what types of capabilities currently exist and, based on ongoing research in these areas, learned what potential features we can expect to see within the next decade. The table below summarizes these capabilities.**

## ADVANCES IN AUGMENTED REALITY AND COMPUTER VISION

| CAPABILITY | NOW | APPROACHING *1 to 5 yrs* | FUTURE *5+ yrs* |
|---|---|---|---|
| **Projecting Overlays** | Multiple head-mounted displays | Additional augmented reality displays with increased capabilities | Holograms / glass-less AR |
| **Detecting Stress** | Visual toolkits | Research into using cheap cameras and existing sensors | |
| **Tracking Attention** | Eye gaze | Pupil, eyelid, and eye pigment detection | |
| **Understanding Sentiment** | Facial expression recognition | Robust facial expression recognition | |
| **Object Detection / Recognition** | Visual toolkits | Robust recognition | Wide scope recognition |
| **Heads-Up Instructions** | Display instruction slides and advance with voice | Visual and audio instructional guidance using computer vision | |

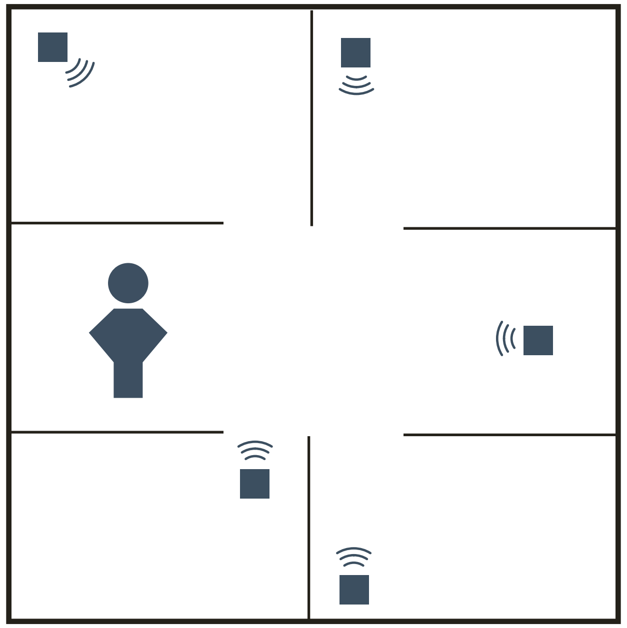


# TECHNOLOGY REVIEW

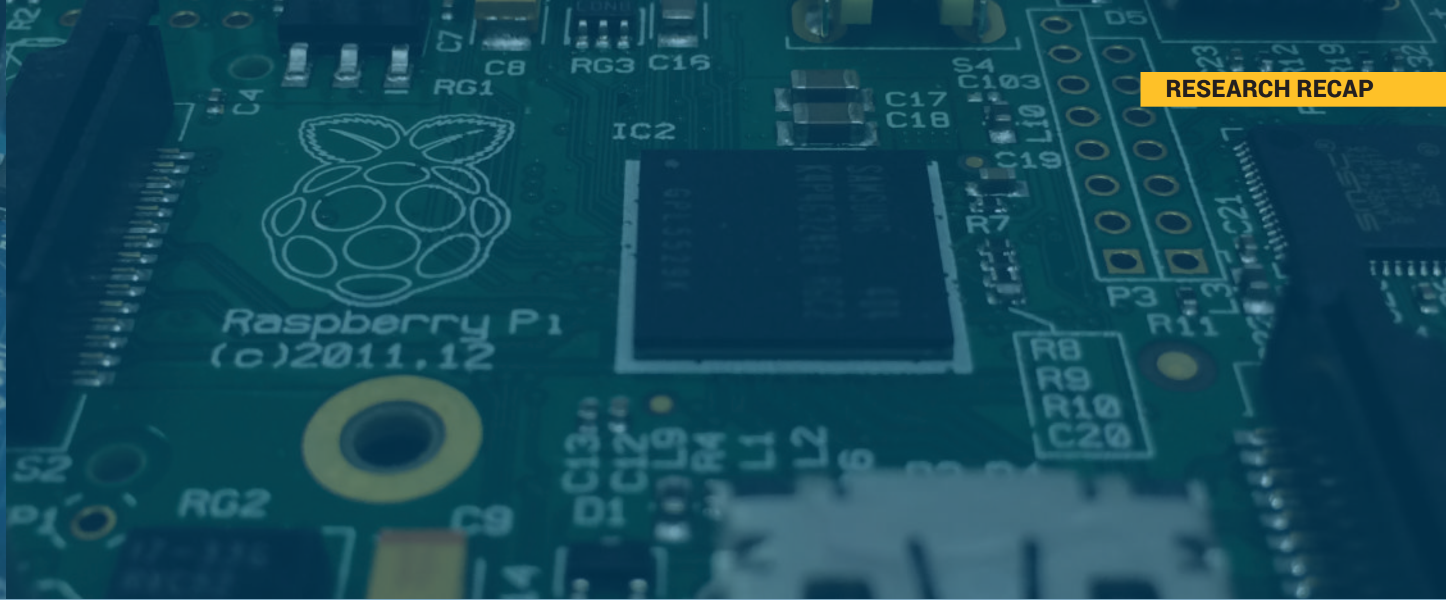
## BLUETOOTH

Spatial awareness can also be realized by using Bluetooth technology. Bluetooth is a wireless technology standard that operates in the 2.4 GHz frequency band and enables short-range connectivity between devices. Bluetooth Low Energy (LE), also known as Bluetooth Smart, is an extension of Bluetooth version 4.0 that delivers significantly reduced power consumption over previous versions of Bluetooth, allowing many small devices to be networked together, supporting Internet of Things.

A Bluetooth beacon is a small object that broadcasts a unique wireless signal signature. Bluetooth LE devices function as beacon readers. By reading the strength of a beacon's Bluetooth signal, beacon readers can approximate a beacon's proximity without requiring line-of-sight. Placing multiple Bluetooth beacon readers on a room's walls can help enable more precise beacon location through trilateration.



*Bluetooth beacons, each of which broadcasts a unique wireless signal signature, can be embedded within tools located throughout a physical space. As a user wearing a beacon reader navigates through the space, a beacon's broadcasted signal strength can indicate the associated tool's proximity relative to the user's position.*



## HAPTIC FEEDBACK

A system can use haptic feedback to create a physical sensation to a user in response to a particular action. Haptics are commonly driven by electronics that control a vibrating motor or a linear actuator.  Haptic feedback can enhance on-screen activity by allowing a user, for example, to feel resistance during the press of a virtual button or to physically sense vibrations of an event in a video game. Haptics can also improve work performance by using subtle vibrations to convey tactile information while allowing a user to remain focused on the current task. As an alternative or supplement to audio or visual feedback, haptics can also serve to draw a user's attention, provide motivation, or to provide reassuring confirmation.

Haptic feedback differs from simple vibration alerts in that the former uses more advanced vibration patterns that are controlled by microcontrollers and haptic driver chips. Where vibration alerts are a simple form of feedback to indicate an event, haptic feedback can provide more granular information based on context. Consider a situation, for example, where a user is looking for a tool; as he approaches the tool's location, a system can issue a fixed vibration alert. Haptic feedback can greatly enhance this feedback for the user by varying the vibration force or the frequency at which the vibration occurs based on the user's proximity to the tool.

## SPEECH RECOGNITION

In a computing system, speech recognition is accomplished by first sampling the air vibrations that are created when a user speaks into a connected microphone and converting these vibrations into a digital signal. Next, the system breaks this signal down into the fundamental blocks of language known as phonemes. It then examines these phonemes in context, compares them to an extensive library of words, and then returns the most probable written text of the spoken data.

Advances in computing power over the last few decades have led to relatively quick and accurate speech recognition, and many application programming interfaces (APIs) are now available that allow software developers to provide native speech recognition support. Speech recognition has useful applications in situations where a keyboard for input is not practical, such as in-car systems. Since we designed our wearable prototype to be a hands-free device, we believed that having our system accept speech input to allow the user to navigate through the user interface would be appropriate.

# DESIGN PROCESS

**After presenting our research and technology reviews to NASA, we held a visioning session where we determined a concrete direction for the project: leveraging connected devices to improve procedure execution.**

**With this vision in mind, we designed and tested three low fidelity prototypes, one medium fidelity prototype, and one high fidelity prototype. For the low fidelity prototype, we had our participants perform a cooking procedure. For all later prototypes, the participants followed a NASA procedure related to the Rodent Habitat experiment that astronauts use on the ISS.**

**The final design of our system is a head-mounted augmented reality display, with features supporting cues for verbal commands, cognitive orientation, and spatial navigation.**

# VISIONS

## FROM RESEARCH TO DESIGN

For our visioning session, our team got together with our clients and other HCI professionals at NASA Ames and brainstormed different ideas based on the four insights from our research. Afterwards, we met with our clients to discuss the merits and drawbacks of the top four ideas that emerged from the visioning session:

- Leveraging connected devices to improve procedure execution
- Enabling more direct feedback from actual astronauts to procedure writers
- Investigating a more detailed progress bar that is responsive to deviations and errors
- Using information granularity to individualize procedures

Each idea involved different aspects of our insights. The first idea included aspects of both spatial navigation and cognitive orientation through the use of sensors and information from the environment. The second highlighted our insight about implementing worker suggestions. The third idea isolated one particular support for cognitive orientation, the progress bar, that can become increasingly more complicated with more complex NASA procedures. The fourth idea emphasized our last insight on adjusting instructions.

*At the visioning session, we divided into two groups and used props to help brainstorm ideas.*

*One group used props to act out gathering objects to construct a new space station.*

*One group member served as an instructional display that followed the main worker around the room to help minimize disruptions from the procedure.*

*The second group used foam blocks to brainstorm how improvements could be made to spatial navigation instructions during a construction procedure.*

## FINAL VISION FOR THE PROJECT

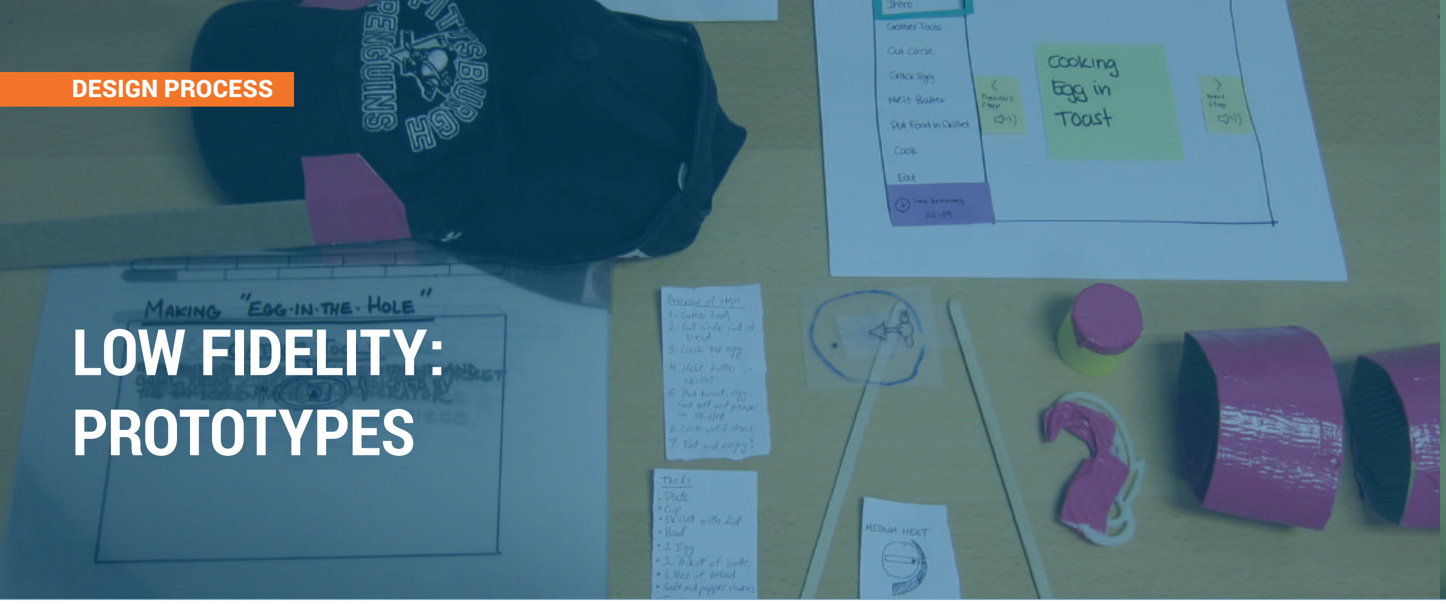
We decided that the third and fourth ideas warrant more exploration and research than we would be able to complete within the remaining three months of our project. Therefore, we reserved those concepts for future MHCI projects.

To decide between the first and second ideas we returned to the initial prompt that was given to us by our client. NASA wanted our project to focus on the novice experience and to serve as an exciting demonstration of what future work with NASA could look like. We believed that our first idea was the most exciting and the best addition to the novice experience for astronauts.

Moving forward with our first vision, we identified two specific elements related to our research findings that we wanted to investigate further:

Leveraging connected devices to improve procedure execution

- Using sensors on users and tools to give real-time directions in relation to the user's current orientation
- Exploring other methods for improving spatial navigation and cognitive orientation



# LOW FIDELITY: PROTOTYPES

## STARTING BROADLY

To begin our design process, we started broadly and looked at three different physical forms and various methods of spatial navigation and cognitive orientation while participants performed a simple but unfamiliar cooking procedure. Due to the hands-on nature of the tasks that astronauts perform, the prototypes were designed to stay out of the way and take verbal commands (except for the tablet prototype which took both touch input and verbal commands). Each prototype was tested with two new users with an even mix of male and female participants as well as advanced and novice cooks.

## AUGMENTED REALITY

**Spatial Navigation**

Arrows overlaid on the environment

**Cognitive Orientation**

Step-based progress bar and a preview of the final product

## WEARABLES WITH AUDIO

**Spatial Navigation**

Top-down compass

**Cognitive Orientation**

Optional overview, tools list, and time estimate report

## TABLET

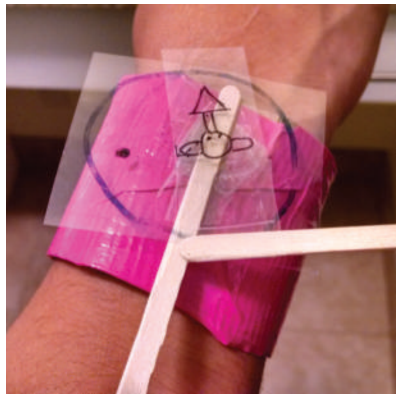
**Spatial Navigation**

Annotated photos of tool storage locations

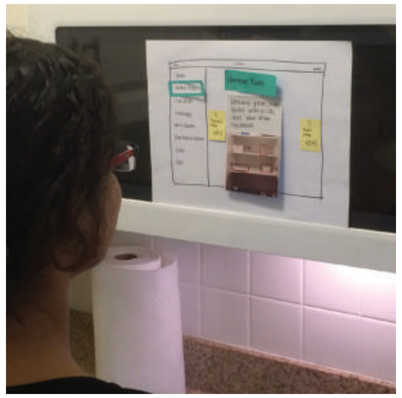
**Cognitive Orientation**

Visual cues for commands and an overview on all screens

*The augmented reality prototype was created by mounting transparencies with instructions on a hat.*



*The wearables prototype had two wristbands with visual displays and an earpiece for hearing instructions.*



*The tablet prototype was created using paper, post-it notes, and photos of the locations of different tools.*

# LOW FIDELITY: USABILITY TAKEAWAYS

## PHYSICAL FORM

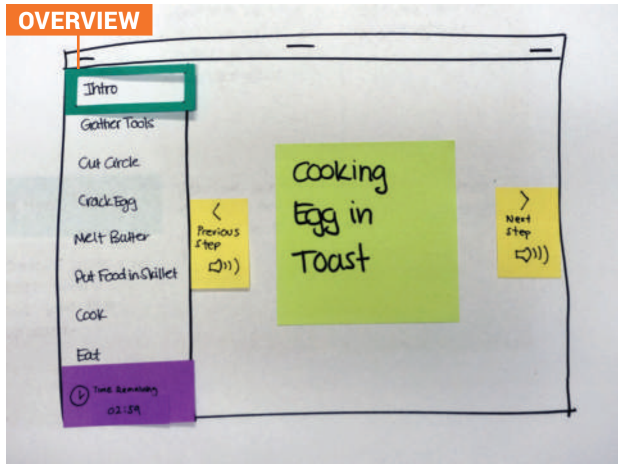
Through usability testing, we determined that the augmented reality form was the most appropriate for astronaut context since it enables hands-free control that travels with the user while still allowing for visual elements and easy scannability. More specifically, a visual interface can also provide visual affordances for verbal commands to help lower the stress on the user's working memory.

## SPATIAL NAVIGATION

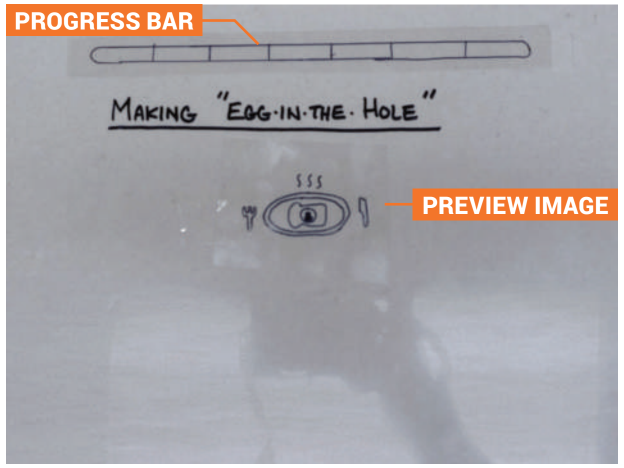
The real-time, responsive arrows were the most effective method for spatial navigation, but we had difficulties communicating the difference between forward and up as well as backward and down.

## COGNITIVE ORIENTATION

We received positive feedback on both the overview and preview image. However, we found that users needed a way to jump between sections of the procedure easily and that they expected that the progress bar would symbolize information about estimated effort required for each step.



*During testing of the tablet prototype, one of our users tried to touch different sections of the overview text to jump between sections.*



*The augmented reality prototype included an evenly-divided progress bar and a preview image that helped users interpret the final goal of the procedure.*

# MEDIUM FIDELITY: PROTOTYPE

## GETTING MORE SPECIFIC

In the medium fidelity prototype, we honed in on implementing a heads-up display prototype for an actual NASA procedure for restocking food in the Rodent Habitat experiment. We tested our implementations of the user interface, spatial navigation, and cognitive orientation with five users from NASA (mission planners, developers, and user experience designers), all of whom were unfamiliar with this procedure.

## RODENT HABITAT RESTOCK

Here is a high-level summary of the steps in the procedure, which was used for the medium and high fidelity prototypes and usability testing.

**Operational Setup**

Retrieve supplies

Attach Animal Access Unit to Rodent Habitat

**Animal Removal**

Put all mice in the Mouse Transfer Box

**Habitat Foodbar Removal**

Remove old Foodbar

Put in new Foodbar

**Animal Replacement**

Return mice to Rodent Habitat

Dispose of garbage

**Restow Equipment**

Return the Animal Access Unit

*For this project, the team constructed a cardboard mock-up of the Rodent Habitat in approximately the same dimensions as the real Rodent Habitat. This mock-up of the Rodent Habitat was used in the usability testing for the medium fidelity and high fidelity prototypes, as well as for demos of the final solution.*

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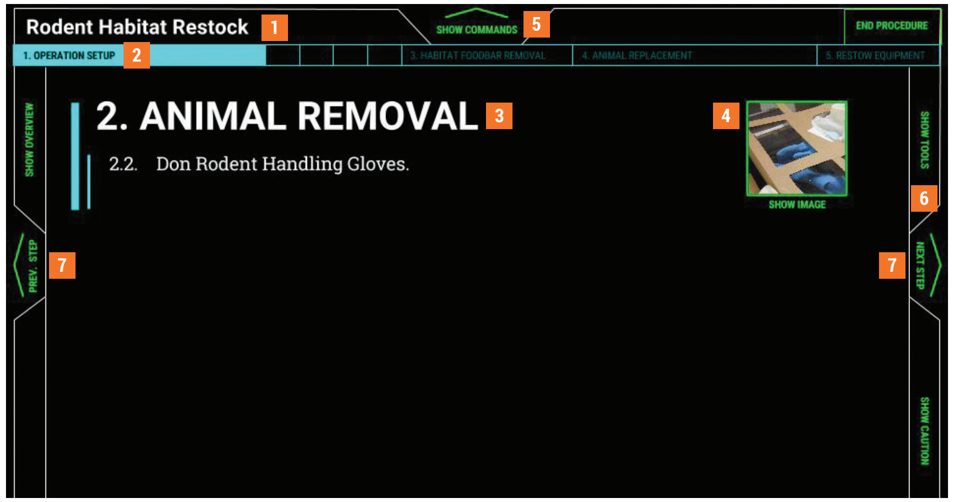
# MEDIUM FIDELITY: USER INTERFACE

## DETAILED VIEW OF USER INTERFACE

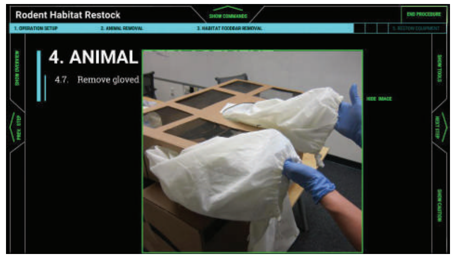


Rodent Habitat Restock

2. ANIMAL REMOVAL

2.2. Don Rodent Handling Gloves.

### 4 IMAGE

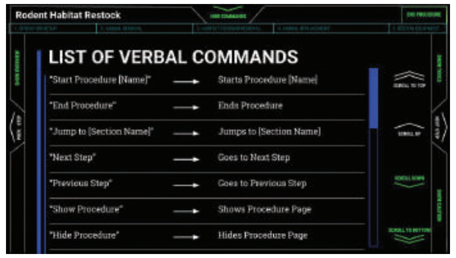


Rodent Habitat Restock

4. ANIMAL

4.7. Remove gloved

### 5 LIST OF COMMANDS



Rodent Habitat Restock

LIST OF VERBAL COMMANDS

"Start Procedure [Name]" → Starts Procedure [Name]

"End Procedure" → Ends Procedure

"Jump to [Section Name]" → Jumps to [Section Name]

"Next Step" → Goes to Next Step

"Previous Step" → Goes to Previous Step

"Show Procedure" → Shows Procedure Page

"Hide Procedure" → Hides Procedure Page

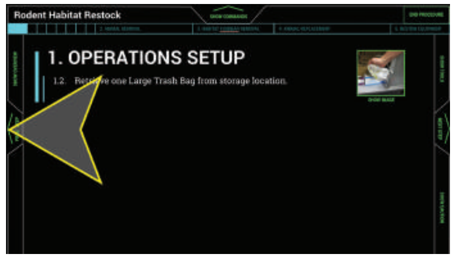
### 6 LIST OF TOOLS

Rodent Habitat Restock

TOOLS

- Access Unit
- Habitat Foodbar
- Large Trash Bag (one)
- Gauntlet (two)
- Sock (two)
- Mouse Transfer Box
- Nitrile Gloves (two pairs)
- Rodent Handling Gloves (one pair)
- Small Trash Bag (one)
- Ziplock Bag (two)
- Flashlight (use as needed)

### 8 TOOL FINDING



Rodent Habitat Restock

1. OPERATIONS SETUP

1.2. Retrieve one Large Trash Bag from storage location.

### 1 PROCEDURE TITLE

### 2 PROGRESS BAR

The system displays an effort-based progress bar with section titles and steps of current section.

### 3 PROCEDURE

The current section title and step are displayed in prominent text.

### 4 IMAGE

Each procedure step includes an associated photo that can be enlarged using the "Show Image" command.

### 5 LIST OF COMMANDS

Valid speech commands are shown in green text. To reduce stress on user memory, issuing the command "Show Commands" displays all available verbal commands.

### 6 LIST OF TOOLS

The "Show Tools" command displays all required tools for a given procedure, as well as associated images that can be enlarged for more detail.

### 7 STEP NAVIGATION

"Previous Step" and "Next Step" commands allow the user to navigate through each step of the procedure.

### 8 TOOL FINDING

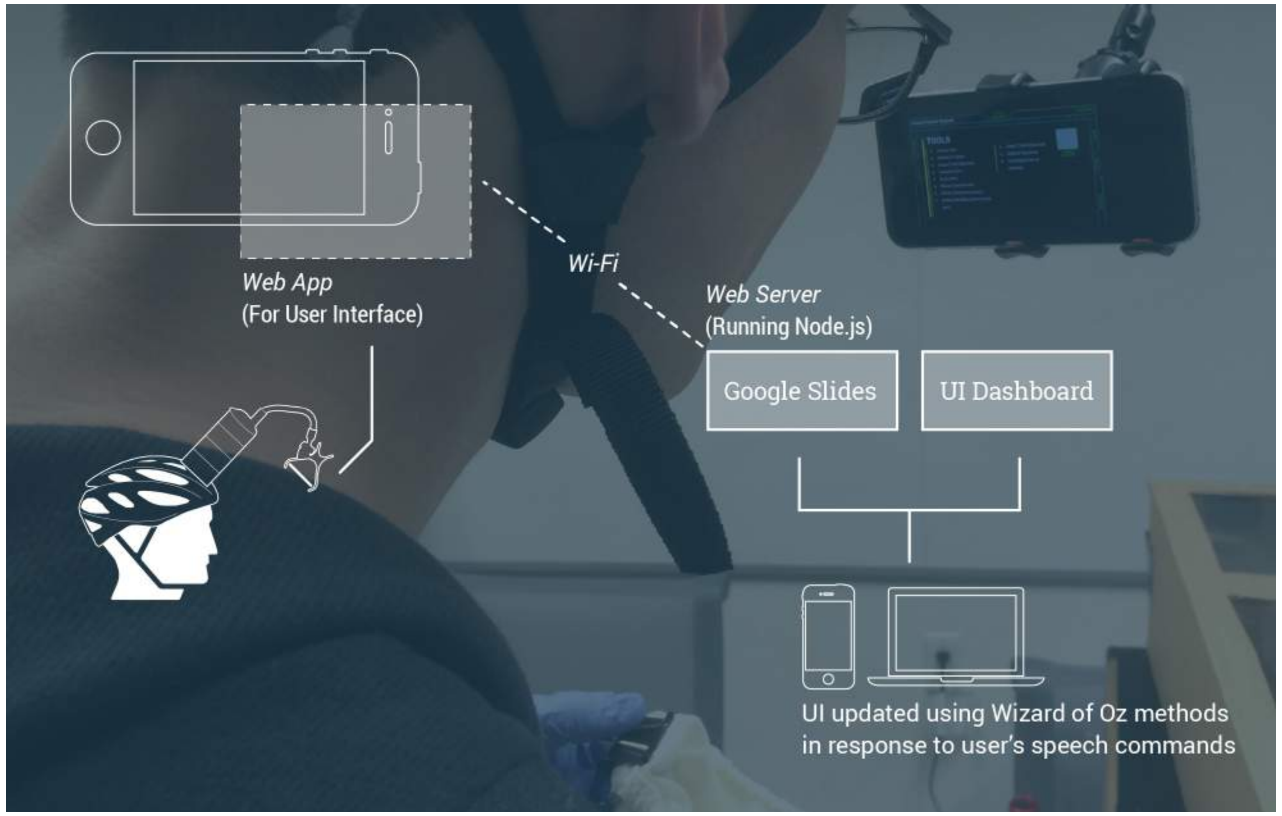
Guidance arrows provided by the system help the user to locate required tools.

# MEDIUM FIDELITY: IMPLEMENTATION

## PHYSICAL FORM

Our prototype was a simulation of augmented reality in the form of a cell phone attached to a helmet, serving as a heads-up display. The phone was mounted on a bike helmet so that the participant was able to see it within the top of his vision.

## TECHNOLOGY



*The procedure was stored in Google Slides and presented to the user through a web application. Navigation through the procedure and the display of directional arrows were controlled through a "wizard-of-oz" dashboard.*

# MEDIUM FIDELITY: USABILITY TAKEAWAYS

## USER INTERFACE

The participants were able to recognize that the green text in the interface corresponded to available verbal commands and use them throughout the procedure. However, the font was a little small for some participants to read comfortably.

We had an extremely positive response to the addition of supplemental images, which helped the participants clarify the text instructions. However, to reduce workflow interruptions, the images should appear larger next to the text instead of needing to ask for enlarged images for each step.

## COGNITIVE ORIENTATION

Participants did not find the overview and progress bar helpful in completing the task. We determined that the progress bar was mainly used to see when a user was almost done with the task and that the current level of detail in the progress bar was confusing, hard to see, and unnecessary. The overview screen - a list of the high-level sections within the procedure - did not have enough information for the users.

## SPATIAL NAVIGATION

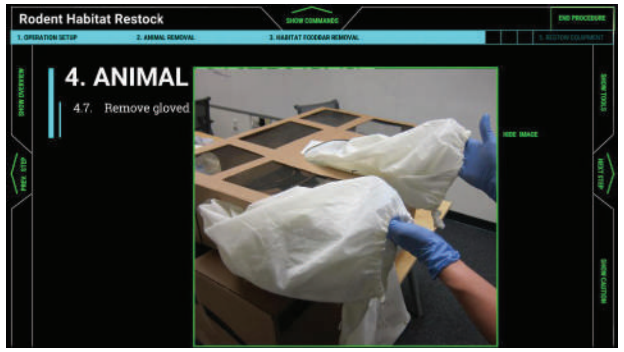
Participants used directional arrows to successfully find tools during the procedure. However, participants did mention that more granularity in the angles of the displayed directional arrows would be helpful and that they did not know the purpose of the arrows initially.

Rodent Habitat Restock

4. ANIMAL REPLACEMENT

4.7. Remove gloved hands from Gauntlets.

*The small image thumbnail was not always clear enough to draw conclusions from at a glance.*



Rodent Habitat Restock

4. ANIMAL

4.7. Remove gloved

*The enlarged image option showed more details, but covered the text of the instruction.*

# HIGH FIDELITY: PROTOTYPE

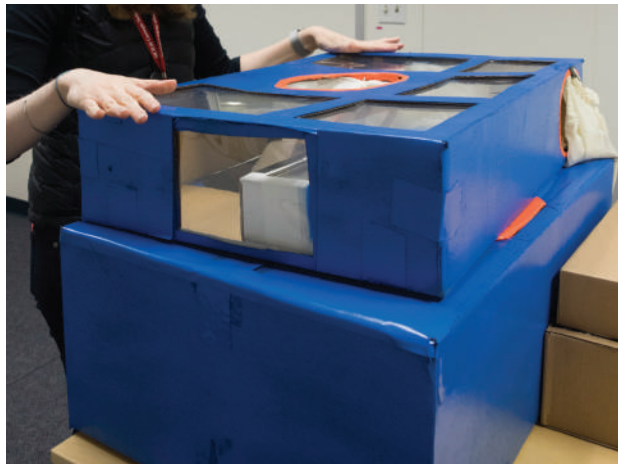
## IMPROVING THE DESIGN

In our high fidelity prototype, we focused on improving the physical hardware, technology usage, and user interface as we moved the system to a more realistic augmented reality interface with a simplified user interface. We continued to use the NASA Rodent Habitat Restock procedure and the cardboard equipment mock-ups that we made for the medium fidelity prototype study, but we reinforced the cardboard for more long-term use and colored the boxes for a more professional appearance. The prototype was tested with six NASA users who work as human systems engineers, quality assurance, user experience, and interaction designers.

## PHYSICAL FORM

For this prototype, we upgraded from a bicycle helmet to a much sturdier construction helmet that adjusts to fit most head sizes. Instead of using a heads-up display like our medium fidelity prototype, we created a mock-up of augmented reality by reflecting the display of an iPad mini onto a pane of glass mounted to the helmet in front of the participant. Since the helmet became front-heavy with the addition of the iPad mini and glass pane, we added a weight to the back of the helmet for balance. The participant also wore a headset for audio output and speech input, a Windows phone for speech recognition in her pocket, and a Raspberry Pi with an external battery on a lanyard around her neck.

*The new physical prototype has multiple pieces to incorporate all of the technology required for the prototype.*

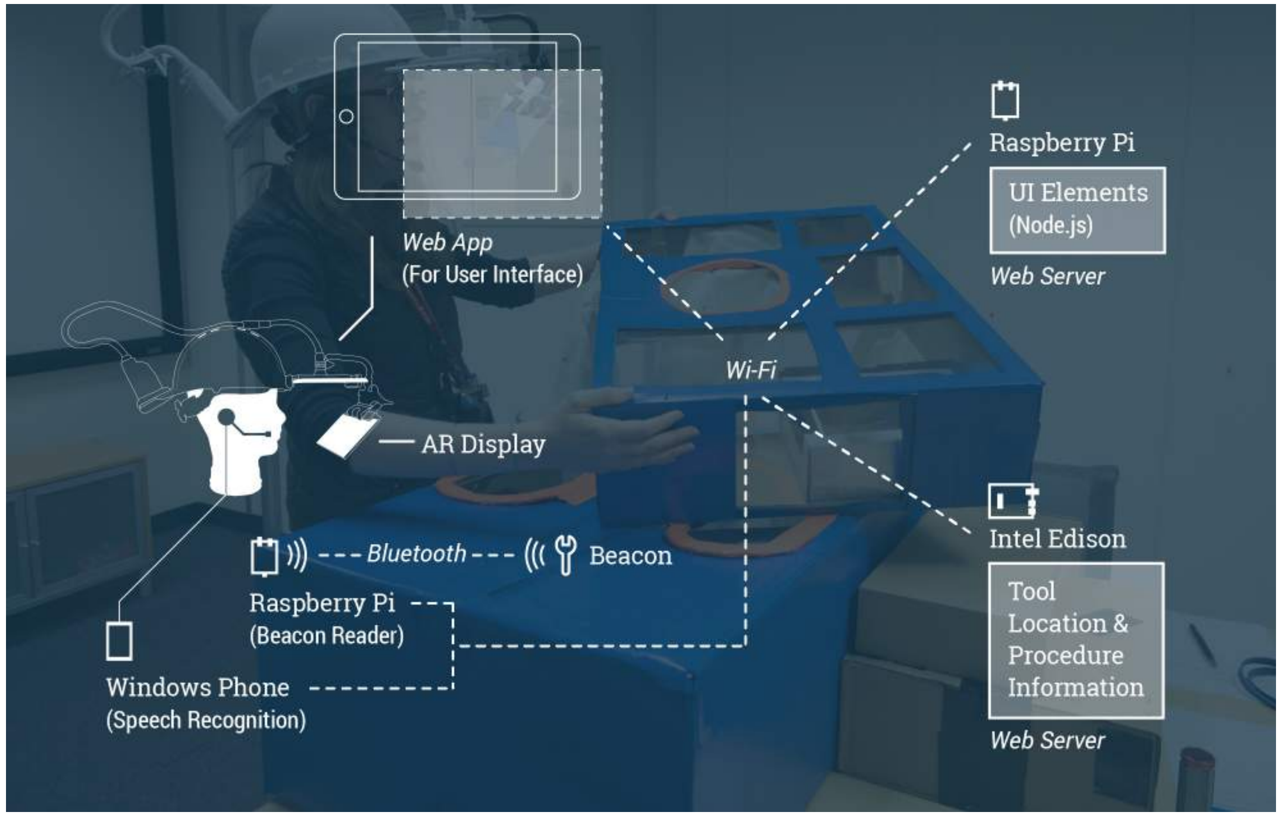


*The Rodent Habitat equipment was colored blue and orange to better match the colors of the real equipment.*

# HIGH FIDELITY: IMPLEMENTATION

## TECHNOLOGY

The procedure runs on an Intel Edison, which maintains the user's current progress. An iPad mini connects to another Raspberry Pi to display a web application containing the Heads Up Display visuals. The participant speaks verbal commands into a microphone attached to a Windows Phone device, which then recognizes and sends them to the Edison to control the state of the procedure. Lastly, although arrows to direct movement in a space were still controlled by the experimenter, we used a Raspberry Pi to determine a user's proximity to tools by automatically measuring the wireless signal strength of Bluetooth beacons located near them.

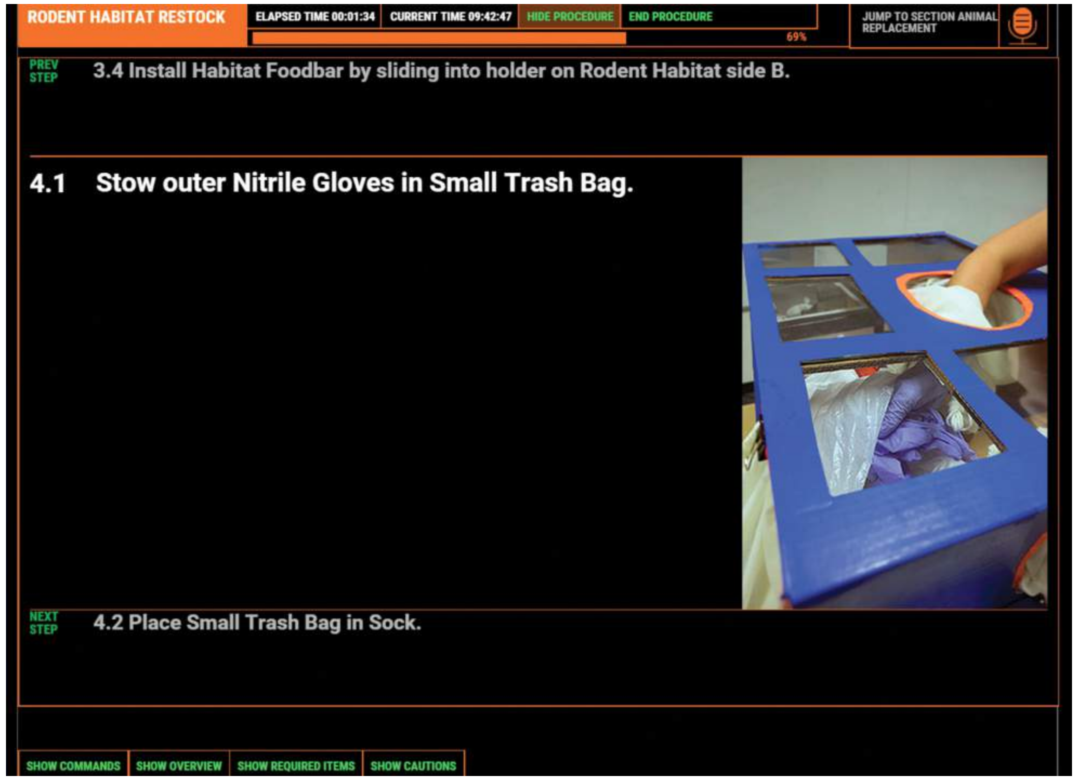


*The prototype incorporates speech recognition for UI navigation, Bluetooth beacons to help the user locate tools, and web servers to deliver procedure information and tool location onto the user's AR display.*

# HIGH FIDELITY: USER INTERFACE

## DETAILED VIEW OF USER INTERFACE

For the updated interface, we changed the frame coloring from grey to orange for better visibility on a transparent interface in the ISS, which has a palette of mostly whites and blues. In response to our findings from the our usability studies, we used a larger font size, added text labels to new guidance arrow artwork, increased information granularity to help identify precise location of tool within one meter, enlarged images for every step, simplified the progress bar, and added a label to identify the current step in the overview. In addition, we moved less relevant command cues to the bottom of the interface to reduce clutter and created a more streamlined interface. To support the new speech recognition feature, we added both audio and visual feedback to help users understand the state of the system during use.



RODENT HABITAT RESTOCK

ELAPSED TIME 00:01:34

CURRENT TIME 09:42:47

PREV STEP 3.4 Install Habitat Foodbar by sliding into holder on Rodent Habitat side B.

4.1 Stow outer Nitrile Gloves in Small Trash Bag.

NEXT STEP 4.2 Place Small Trash Bag in Sock.

*The dimensions of the interface were altered to fit the larger screen size of the iPad mini.*

# HIGH FIDELITY: USABILITY TAKEAWAYS

## USER INTERFACE

The larger images that we used had enough detail to help participants perform a step without having a negative impact on the text. We also observed that participants had some difficulty viewing the next step and previous step previews, but they used the previews to clarify the current instruction and perform related tasks together, saving time.

## SPATIAL NAVIGATION

All participants found the arrows helpful, but would have done better with more granular angles for the walking directions.

## COGNITIVE ORIENTATION

Most participants noticed the progress bar, but did not use it very often. The remaining participants who did not notice it mentioned that they wished they had used that functionality.

1.1 Retrieve one Habitat Foodbar from Laboratory Freezer.

NEXT STEP 1.2 Retrieve one Large Trash Bag from storage location.

*The arrows for walking directions were similar to those in the medium-fidelity prototype in terms of granularity levels.*

## VERBAL COMMANDS

In post-study questioning, participants verified that they found the verbal commands to be natural. The one exception was the last voice command used, “Confirm End Procedure.” This command was designed to not feel as natural so that people would not accidentally end a procedure, so this result was not unexpected.

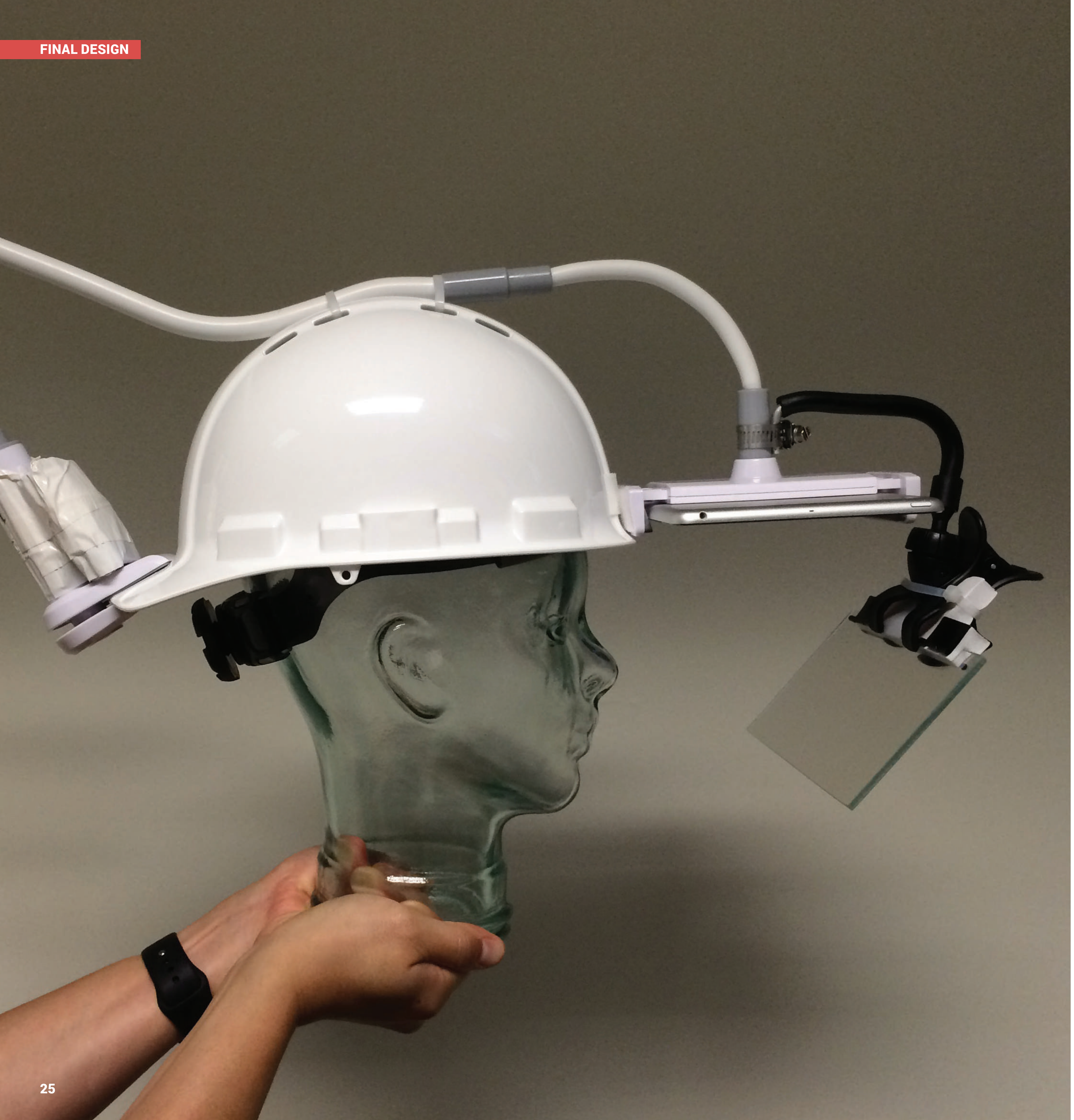
## SPEECH RECOGNITION FEEDBACK

We did not receive much feedback regarding the visual feedback for speech recognition, but we did get very clear results regarding the audio feedback. Positive audio feedback was understood and acted on correctly. However, the other audio signal which indicated that the speech recognition system was listening to the participant’s speech and was not detecting a valid voice command was annoying and distracting to participants.

1.1 Retrieve one Habitat Foodbar from Laboratory Freezer.

NEXT STEP 1.2 Retrieve one Large Trash Bag from storage location.

*However, the arrows changed to a more granular visual in close proximity to tools.*

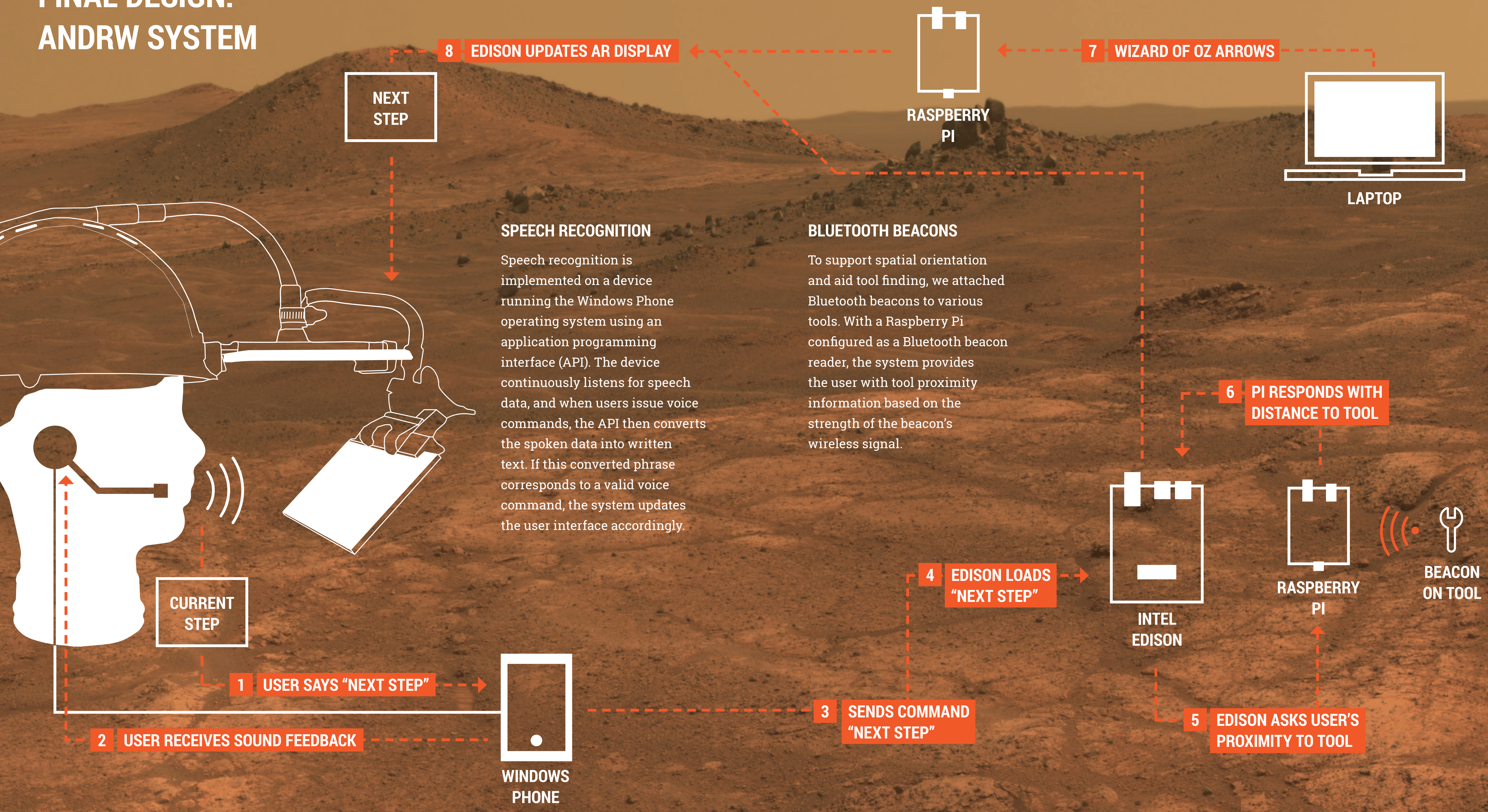


# FINAL DESIGN:
# ANDRW 3000

ANDRW 3000 (AugmeNteD Reality Wearable, whose name is a nod to the founders of Carnegie Mellon University) is the culmination of prototype and usability testing of prior design iterations. We made several refinements to the high fidelity prototype. We provided greater room for viewing adjustments by using a clamp for the arm holding the AR display glass, and we improved weight distribution of the helmet for stability. We also used a thinner battery pack for the Bluetooth beacon reader, which reduces weight. Tweaking the sensitivity of Bluetooth beacon range detection provides a faster system reaction time when the user approaches tools with embedded beacons. Adjustments to the speech recognition feature eliminated audio feedback for unrecognized instructions, instead replacing it with a more subtle visual indicator. Other system-wide improvements fixed various bugs and improved overall reliability.

ANDRW is an intelligent, connected device that leverages various technologies to empower astronauts performing unfamiliar procedures while maximizing their mobility. By overlaying written and visual procedure information over their real world field of view, ANDRW allows users to stay focused on the task at hand. A carefully designed AR user interface supports intuitive use and clear legibility against various background colors and textures. ANDRW's speech recognition feature accepts verbal commands to navigate the user interface while both hands are free to perform work. The system also aids the user by automatically providing guidance to tool locations, reducing the time spent looking for misplaced tools. Additionally, by natively storing multiple procedures and contingencies, ANDRW enables greater autonomy by quickly providing critical information that astronauts would otherwise have to request from ground support.

# FINAL DESIGN: ANDRW SYSTEM



## SPEECH RECOGNITION

Speech recognition is implemented on a device running the Windows Phone operating system using an application programming interface (API). The device continuously listens for speech data, and when users issue voice commands, the API then converts the spoken data into written text. If this converted phrase corresponds to a valid voice command, the system updates the user interface accordingly.

## BLUETOOTH BEACONS

To support spatial orientation and aid tool finding, we attached Bluetooth beacons to various tools. With a Raspberry Pi configured as a Bluetooth beacon reader, the system provides the user with tool proximity information based on the strength of the beacon's wireless signal.

# FINAL DESIGN: WEARABLES

**HELMET**
Fits varying head sizes

**BALANCING WEIGHT**
Provides overall stability

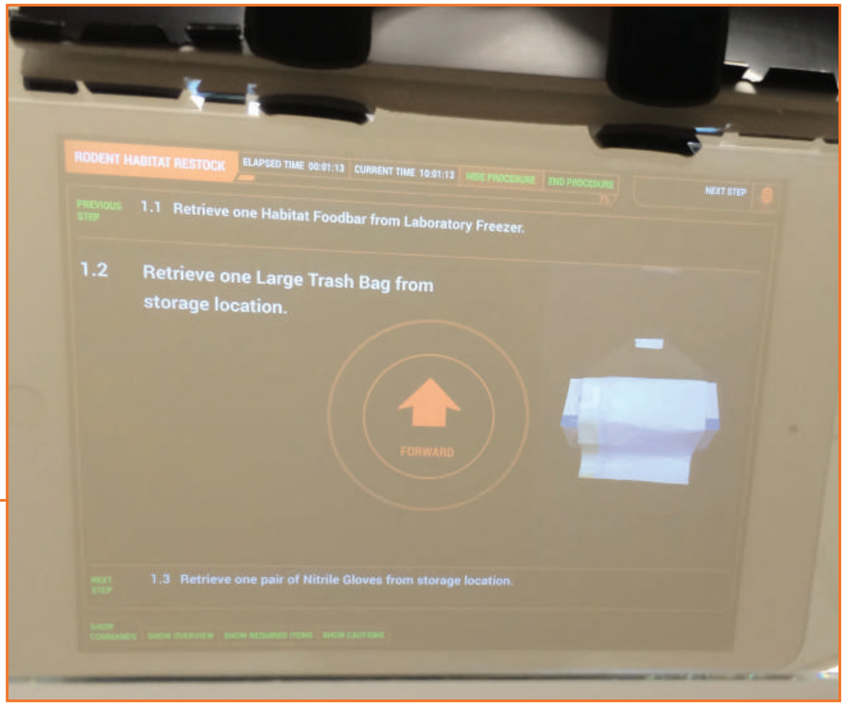
**HEADSET**
Enables voice control and sound feedback

**TABLET MOUNT**
Secures iPad mini

**IPAD MINI**
Displays UI elements

**GLASS MOUNT**
Fastens teleprompter glass

**TELEPROMPTER GLASS**
Reflects UI from iPad mini to user



1.1 Retrieve one Habitat Foodbar from Laboratory Freezer.

1.2 Retrieve one Large Trash Bag from storage location.

1.3 Retrieve one pair of Nitrile Gloves from storage location.

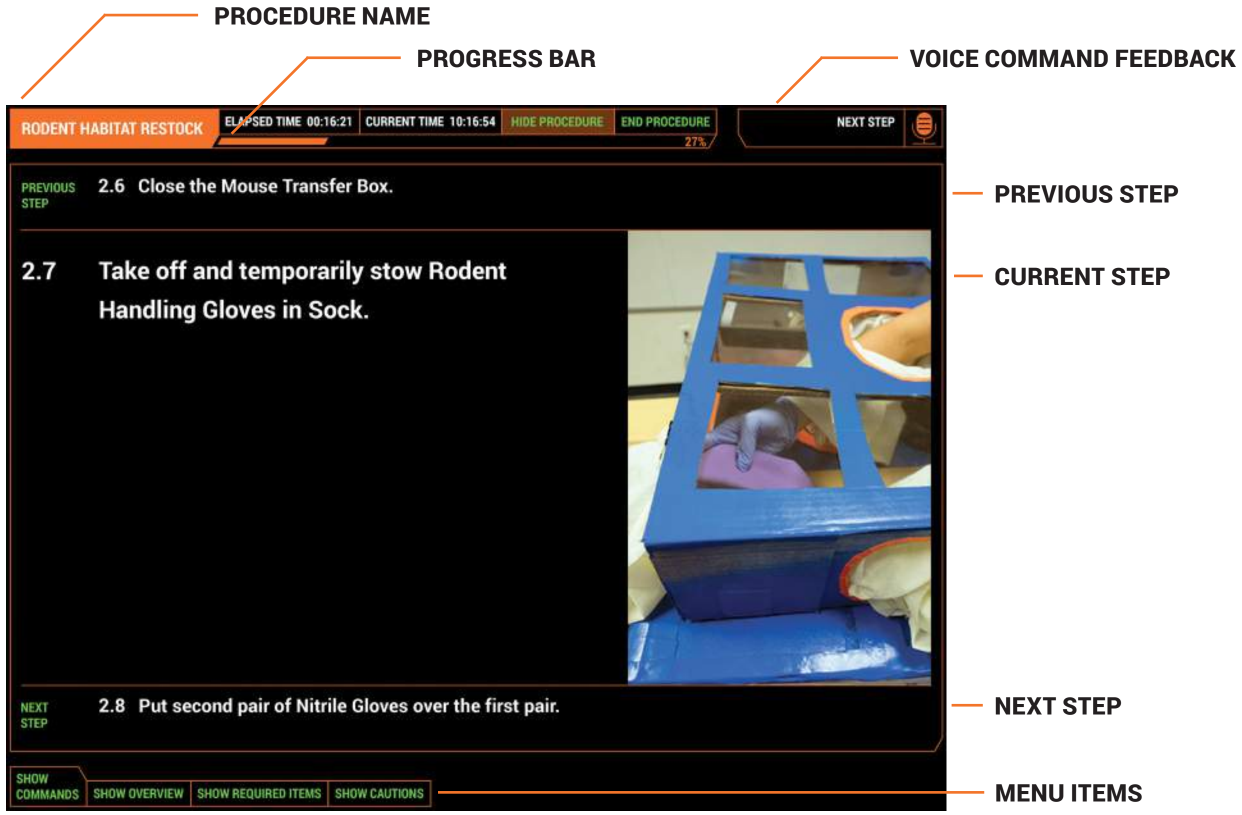
**WINDOWS PHONE**
Performs speech recognition for audio commands

**PORTABLE BATTERY**
Supplies power to Raspberry Pi

**RASPBERRY PI**
Aids tool finding by detecting Bluetooth beacons

# FINAL DESIGN: USER INTERFACE

The user interface was designed for the screen size of the iPad mini. We chose black for the background color of the interface, because black does not reflect as much on teleprompter glass, creating a more transparent interface. On top of the black background, we used high contrast colors to stand out from the background. We used a thicker sans-serif font to increase legibility on the teleprompter glass as well.



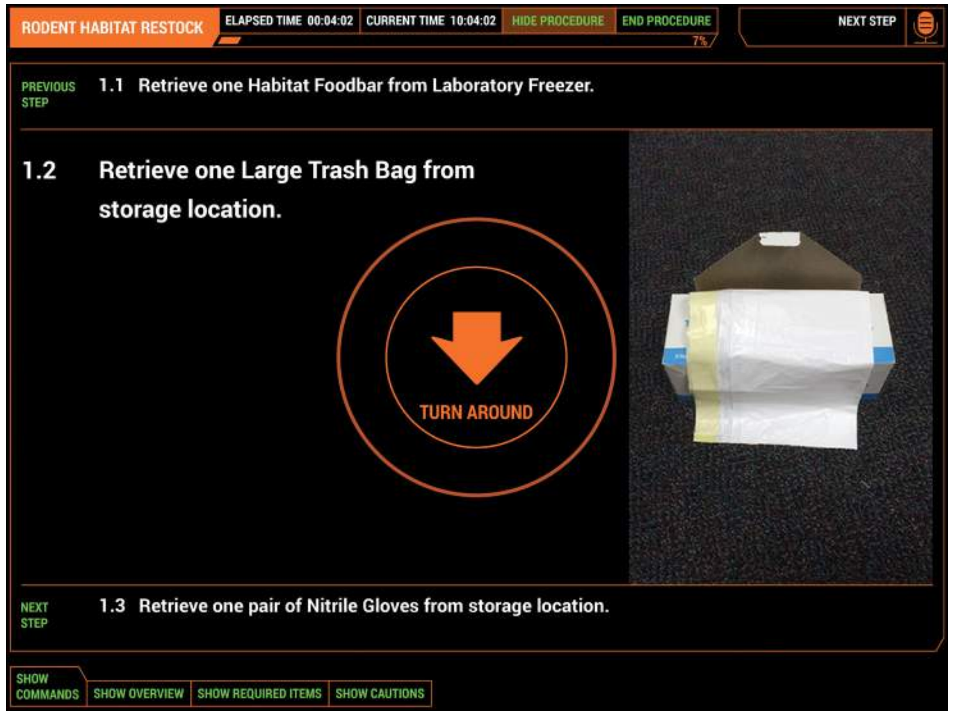
2.6 Close the Mouse Transfer Box.

2.7 Take off and temporarily stow Rodent Handling Gloves in Sock.

2.8 Put second pair of Nitrile Gloves over the first pair.

## MAIN PROCEDURE

The current step in the procedure is displayed in the middle of the screen along with a descriptive image. The screen also shows the previous step above the current step and the next step below the current step in order to give the user context for where they are within the procedure. Text listed in green is an available verbal command.



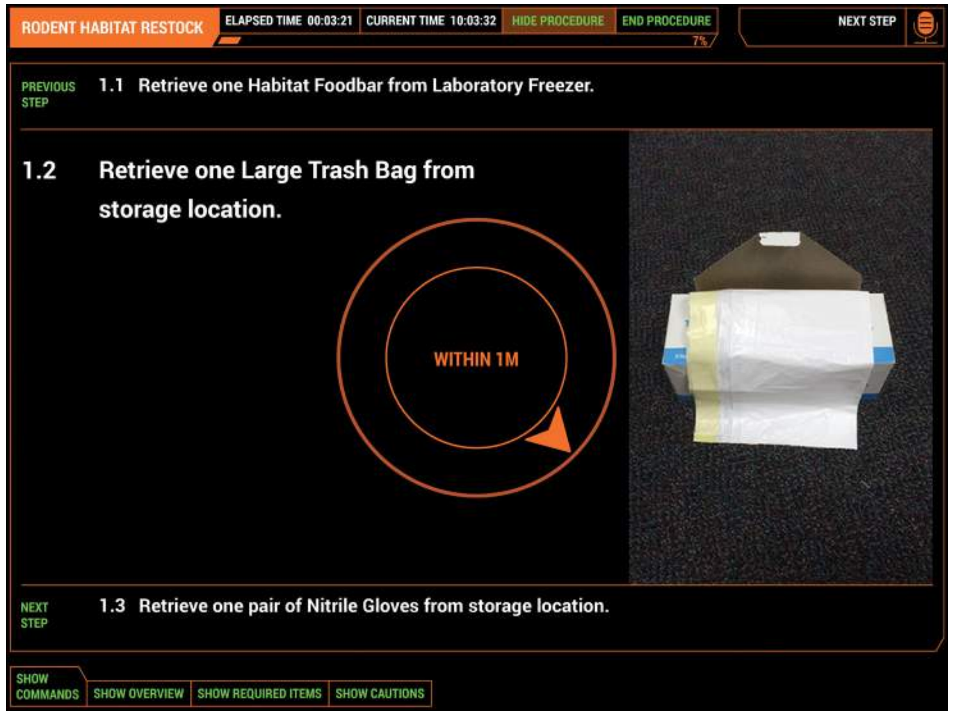
1.1 Retrieve one Habitat Foodbar from Laboratory Freezer.

1.2 Retrieve one Large Trash Bag from storage location.

1.3 Retrieve one pair of Nitrile Gloves from storage location.

## TOOL FINDING ARROWS

When the current step in a procedure involves tool finding, navigation arrows are displayed to guide users to the location of the tool.



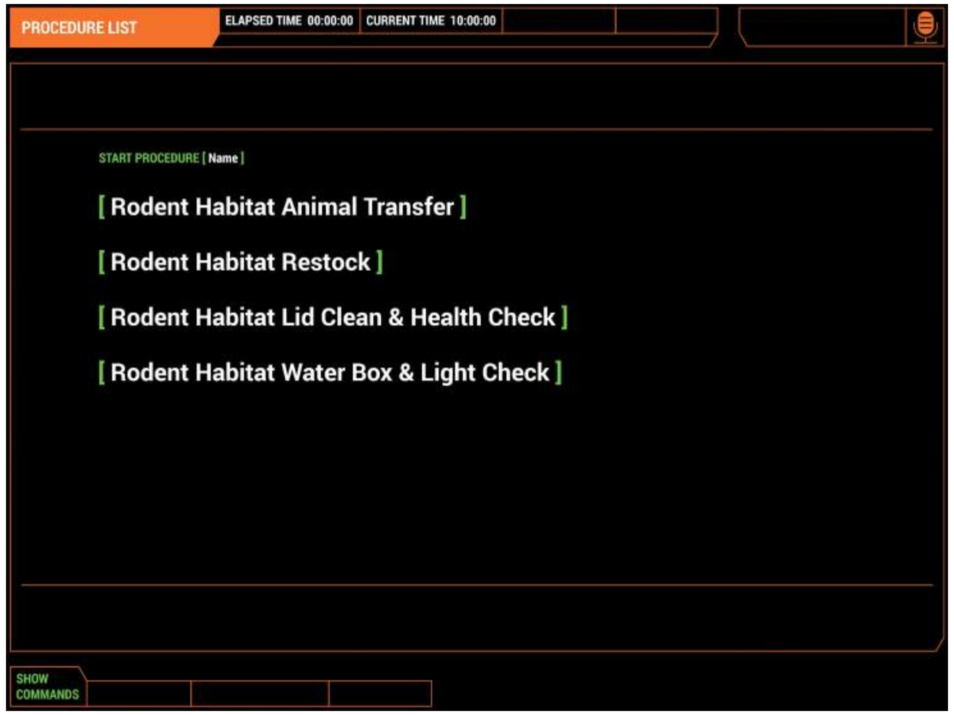
1.1 Retrieve one Habitat Foodbar from Laboratory Freezer.

1.2 Retrieve one Large Trash Bag from storage location.

1.3 Retrieve one pair of Nitrile Gloves from storage location.

## CLOSE PROXIMITY ARROWS

When the user is in close proximity to the tool, the arrow information becomes more detailed and a distance reading appears in the middle of the circle.



PROCEDURE LIST
ELAPSED TIME 00:00:00
CURRENT TIME 10:00:00

START PROCEDURE [ Name ]

[ Rodent Habitat Animal Transfer ]

[ Rodent Habitat Restock ]

[ Rodent Habitat Lid Clean & Health Check ]

[ Rodent Habitat Water Box & Light Check ]

SHOW COMMANDS

## PROCEDURE LIST

The start screen is a list of all available procedures. Commands that are not applicable to this screen are hidden.

RODENT HABITAT RESTOCK
ELAPSED TIME 00:05:40
CURRENT TIME 10:05:40
SHOW PROCEDURE
END PROCEDURE
9%
SHOW OVERVIEW

PROCEDURE OVERVIEW

JUMP TO [ Section Name ]

1. Operations Setup CURRENT STEP 3/7
2. Animal Removal
3. Habitat Foodbar Removal
4. Animal Replacement
5. Restow Equipment

SHOW COMMANDS
HIDE OVERVIEW
SHOW REQUIRED ITEMS
SHOW CAUTIONS

## PROCEDURE OVERVIEW

Procedure Overview is available anytime during the procedure for the user to oversee the sections of the whole procedure. Current section and step number are highlighted and give users ability to jump through sections with the verbal command visible on the top right corner.

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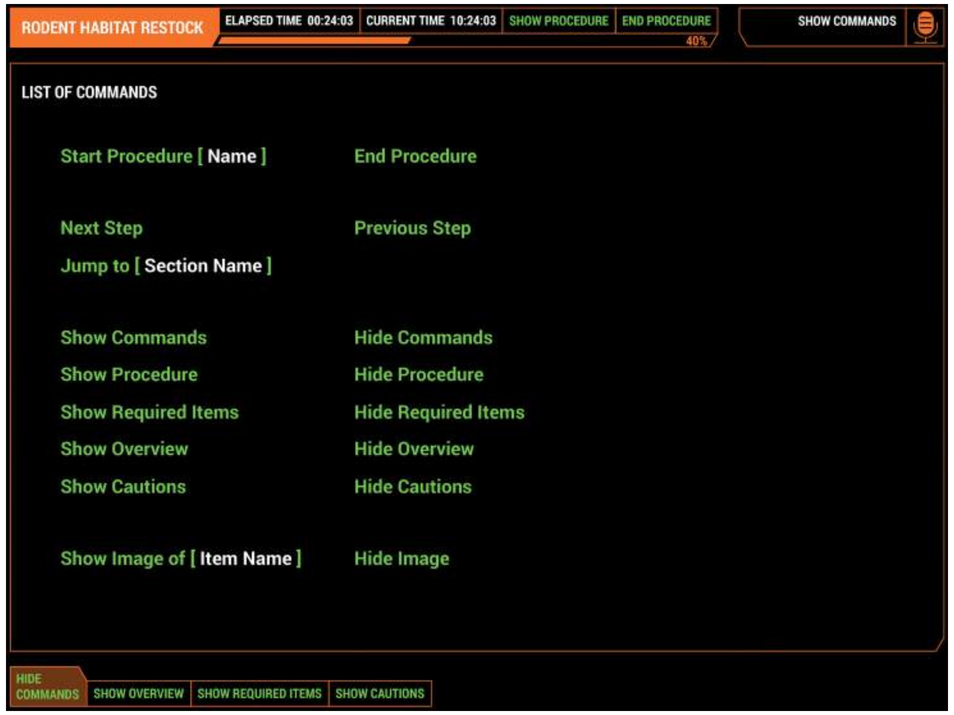
## LIST OF COMMANDS

When the system is running, a user can access the list of all verbal commands from any system state. Throughout the system, verbal command cues are highlighted in green. This removes the need to memorize each of the commands.



RODENT HABITAT RESTOCK
ELAPSED TIME 00:24:03
CURRENT TIME 10:24:03
SHOW PROCEDURE
END PROCEDURE
40%
SHOW COMMANDS

LIST OF COMMANDS

Start Procedure [ Name ]
End Procedure

Next Step
Previous Step
Jump to [ Section Name ]

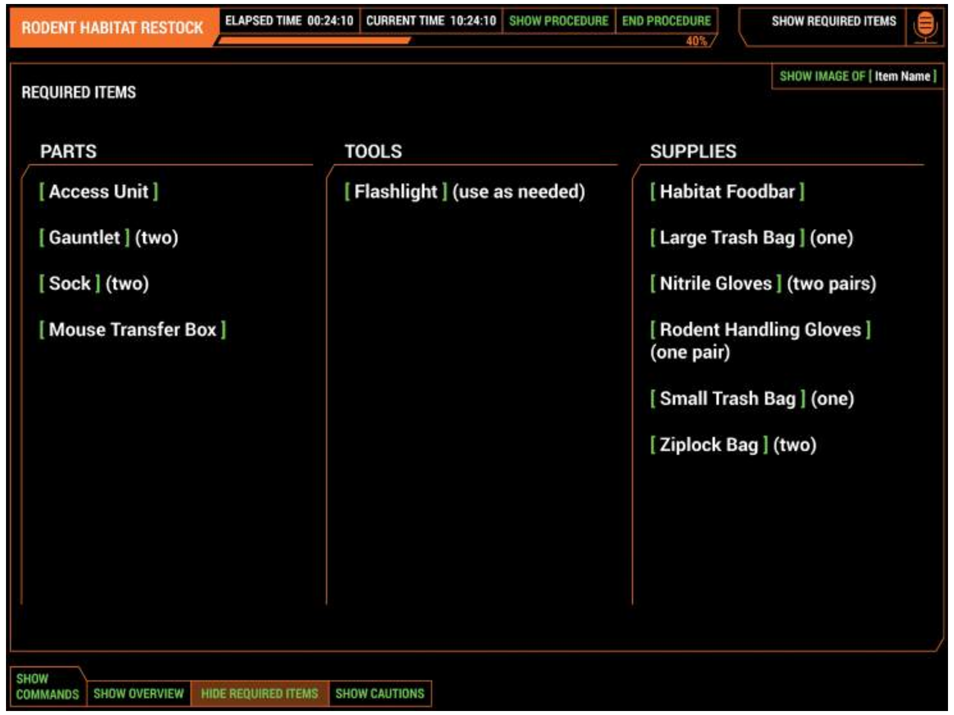
Show Commands
Hide Commands
Show Procedure
Hide Procedure
Show Required Items
Hide Required Items
Show Overview
Hide Overview
Show Cautions
Hide Cautions

Show Image of [ Item Name ]
Hide Image

HIDE COMMANDS
SHOW OVERVIEW
SHOW REQUIRED ITEMS
SHOW CAUTIONS

## REQUIRED ITEMS

The Required Items list is available at any time during a procedure. Users can use voice commands to show images of the various items.



RODENT HABITAT RESTOCK
ELAPSED TIME 00:24:10
CURRENT TIME 10:24:10
SHOW PROCEDURE
END PROCEDURE
40%
SHOW REQUIRED ITEMS

REQUIRED ITEMS

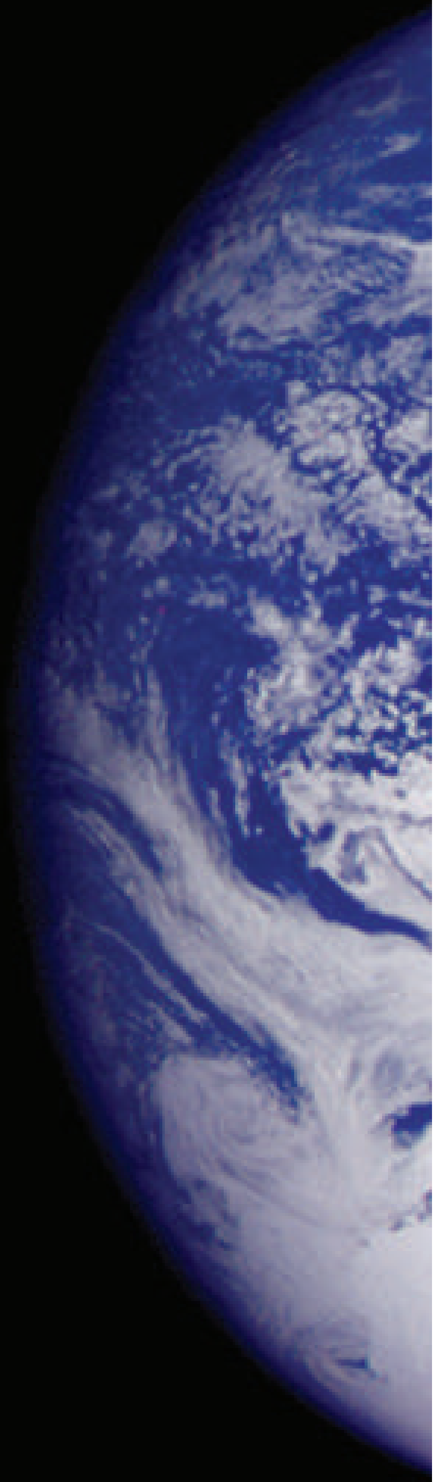
SHOW IMAGE OF [ Item Name ]

PARTS
[ Access Unit ]
[ Gauntlet ] (two)
[ Sock ] (two)
[ Mouse Transfer Box ]

TOOLS
[ Flashlight ] (use as needed)

SUPPLIES
[ Habitat Foodbar ]
[ Large Trash Bag ] (one)
[ Nitrile Gloves ] (two pairs)
[ Rodent Handling Gloves ] (one pair)
[ Small Trash Bag ] (one)
[ Ziplock Bag ] (two)

SHOW COMMANDS
SHOW OVERVIEW
HIDE REQUIRED ITEMS
SHOW CAUTIONS



# NEXT STEPS

**Our working prototype demonstrates how an intelligent system can improve procedure execution for astronauts. It was developed over three months with the constraints of technology today, and thus, there is much room for improvement.**

## FUTURE EXTENSIONS

### Object Recognition

While our system tracked the proximity of the user to tools, object recognition and detection could further point out tools and other relevant items. It would allow the system to visually highlight in the view the targets that were mentioned in the procedure.

### Integrated Speech Recognition

In our prototype, a smartphone processed human speech and sent recognized commands to the system A more integrated speech recognition system would allow for more natural language input.

## EMERGING TECHNOLOGY

### Tool Sensing

Right now, stable readings of distance through wireless technology, such as beacon, are limited to a single meter range. Our prototype could not properly locate tools beyond that range, but over time this technology will improve to judge proximity over longer distances.

### Context Aware Guidance

Our prototype relies on human assessment over the completion of a step. The user has to manually tell the system to move to the next step or to a previous step. As computer vision becomes more robust, the system could judge the completeness of a step and automatically advance to the next step. Such a system could also warn or alert the user of improper action or tool usage.

# FUTURE RESEARCH

**During the course of our spring semester, we envisioned various ideas that may help improve the experience for astronauts working through procedures. We implemented only a few of them in order to still deliver an inspirational prototype within a short timeframe.**

## FEEDBACK FOR PROCEDURES

We were interested in capturing an astronaut's performance during a procedure as an indicator of potential procedural improvement. Such performance could be captured through emotion sensing and stress detection, as well as through tracking both the time spent executing steps and the astronaut's level of engagement. A feedback system might even allow the astronaut to take a visual snapshot of the target view and record a verbal note for post-procedure follow-up.

## COMPLEX PROGRESS INDICATION

Not all astronauts read through a set of instructions linearly. The more advanced ones may skip steps or run through a batch of them at once. Furthermore, an astronaut may run into issues that may force a revisit of an earlier step. In all these deviations in the natural flow of a procedure, tracking the astronaut's absolute work progress becomes difficult. Secondary progress bars might be one way to model these jumps from a main progress flow.

## MODULATING INFORMATION GRANULARITY

Novice astronauts may require more detailed information than their expert counterparts. An astronaut might not need to see every step of a procedure due to prior experience or may just need additional detail for a particular step. Being able to switch between levels of detail and annotate steps may help personalize a procedure to an astronaut's information needs. Tailoring a procedure to an astronaut can further satisfy her individual needs.

# CREDITS

Our team would like to thank our faculty advisors, Jason Hong and Skip Shelly and our clients, Matt Sharpe and Kristle McCracken. Their help was integral to the success of this project.

We would also like to thank the 17 participants from our three rounds of usability testing. Their participation helped us to refine and improve our prototype.

Additionally, we would like to thank the team from the Rodent Habitat who helped us to understand Rodent Habitat research and provided us with the procedure that we used in our prototype and for usability testing. They were also generous in allowing us to photograph and video record the Rodent Habitat hardware. No rodents were harmed in this project.

# ACKNOWLEDGEMENTS

## OUR FACULTY ADVISORS

**Jason Hong**
Associate Professor
HCII at Carnegie Mellon Univ.

**Skip Shelly**
Strategist
Summa Technologies

## OUR CLIENTS

**Matt Sharpe**
NASA Ames HCI Group

**Kristle McCracken**
NASA Ames HCI Group

## PHOTO CREDITS

All space and astronaut images courtesy of NASA

Printed circuit board image courtesy of excelelectronicsinc.com, pages 7-8

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2 Presentations
3 Prototypes and Usability Tests
4 Technology
5 Visions
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# TEAM PARALLAX

**An interdisciplinary team of five master's students at Carnegie Mellon University's Human-Computer Interaction Institute.**

**VIVEK PAI**
*PROJECT LEAD*

**RON KIM**
*TECHNOLOGY LEAD*

**AMALYA HENDERSON**
*UX DESIGN LEAD*

**HOLLY BROSNAHAN**
*UX RESEARCH LEAD*

**HYUNSOO ANDREW PARK**
*VISUAL DESIGN LEAD*