AUGUST 2, 2010 / FINAL REPORT

A Mobile Execution Tool for the Exploration of Planetary Surfaces

Carnegie Mellon

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EXECUTIVE SUMMARY

PROJECT BACKGROUND

Central to any human effort in space is the fluent and reliable execution of technical, operational, and scientific plans by astronauts. From current Shuttle and International Space Station missions to future planetary surface exploration efforts, unique planning challenges call for better tools that enable astronauts to execute complex tasks, often under shifting and unpredictable conditions.

To this end, our interdisciplinary team of five Carnegie Mellon Master of Human-Computer Interaction students, working with the Human-Computer Interaction Group at NASA Ames Research Center, has been tasked to design, develop, and evaluate a prototype assisting real-time execution of human space missions.

RESEARCH

To gain an informed understanding of planning and execution, we conducted extensive background and user research in human space missions and other domains with analogous planning challenges. Specifically, our research investigated the hallmarks of planning and execution commonly found across many disciplines, including real-time re-planning, unforeseen circumstances, remote communication, and authority tension. With these foci in mind, we conducted six Contextual Inquiries and three interviews involving 25 people in the domains of human space missions, surgical ward, and news broadcasting.

Our research reveals that inflexible plans often fail to accommodate real-time plan changes and unforeseen incidents, often resulting in large discrepancies between the plan and actual execution. In addition, our research indicates that a single representation of a plan does not accommodate the varying needs and usages across all roles utilizing the plan. These findings suggest the need for more flexible plans tailored to the unique needs of individual responsibilities.

DESIGN GUIDELINES

From our research findings we derived four guidelines to direct the design of a mobile execution tool for planetary surface missions. Our primary goal is to create a tool optimized for astronauts rather than planners. The following four design guidelines demonstrate different facets of this goal:

Delta between Plan and Execution

Timeline Optimized for Execution

Autonomy when Appropriate

Glanceable and Unobtrusive

For more information, see Background, pp. 11

FINAL DESIGN

Our final design, Lumina Mobile (LuMo), is a cuff-mounted tool that supports the execution of planned science and operation activities during planetary surface missions. The tool is designed to accommodate the unique needs of astronauts, who must often dynamically re-plan in the face of unforeseen circumstances from complex and time-constrained plans. LuMo allows astronauts to view an optimized version of the plan timeline, activities, procedures and execution notes, with timing information indicating how far ahead or behind schedule they are.

The prototype utilizes large physical buttons rather than alternative touch screen input to accommodate the physical constraints of heavy space suit gloves.

The final design of LuMo was inspired by our user research findings, informed by supplementary research on planetary surface missions and evaluated through two Operational Readiness Tests performed in preparation for Landing Day.

For a video demo, please visit:
www.hcii.cmu.edu/M-HCI/2010/NASA/demo

For more information, see Design, pp. 19

LuMo physical form

USER EVALUATION

To reproduce the user experience of a time-pressured execution environment to effectively test the usability of the interface, we evaluated our prototype across 12 user tests comprised of a planetary surface mission simulation. Specifically, nine unique participants used LuMo to complete mock geological science tasks, specified by a time-constrained plan, at several locations around the NASA Ames Research Center campus. The simulation sought to reproduce the physical constraints of the space suit, remote communication with ground support, and the need to dynamically re-plan to return to base camp on time.

In addition to user evaluation, we utilized several Human-Computer Interaction methods, including speed dating, needs validation, bodystorming, heuristic evaluation, and think-aloud protocol.

For more information, see Process, pp. 39

> *"Wow! This plan represents exactly how I think. Plus, it's simple and doesn't get in the way."*
>
> *Desert Research and Technology Studies (RATS) Geologist (7/22/2010)*

A scientist interacting with LuMo during a planetary surface mission simulation

EVALUATION & FUTURE RESEARCH

Across our 12 user tests, participants consistently improved in executing the plan as measured by our key metrics: execution errors and total time to completion. These results suggest that our iterative design process produced a well-vetted and usable tool. In addition, expert user feedback from an astronaut specializing in planetary surface missions confirmed that we achieved our core design goal of creating an optimized view of the plan for astronauts that supports the flexible and autonomous execution of planned activities.

Future research should investigate supporting components of the ecosystem surrounding a mobile execution device on planetary surfaces, including:

- The onboard plan viewer aboard the planetary surface vehicle
- Problems identified in plan-making workflow and tools at NASA
- Extravehicular activities aboard the International Space Station

For more information, see Conclusion, pp. 65

LuMo added into an artist rendering created for NASA by Pat Rawlings ©1995

BACKGROUND

RESEARCH SUMMARY

RESEARCH PROCESS

Our research investigated the hallmarks of planning and execution commonly found across many disciplines, including real-time re-planning, unforeseen circumstances, remote communication, and authority tension. To this end, we utilized Contextual Design methods to explore planning and execution not only within NASA, but also in work domains with planning challenges analogous to human space missions. Over eight weeks, we conducted six Contextual Inquiries and three Retrospective Interviews in the domains of human space missions, surgical ward, and news broadcasting.

In addition to our user research, we conducted a literature review surveying domains with similar planning workflows to human space missions. Finally, we analyzed several project management software packages, as well as other industry-specific planning tools, to research current methods and approaches of addressing challenges in planning and execution.

We conducted six Contextual Inquiries and three Retrospective Interviews in the domains of human space missions, surgical ward, and news broadcasting

A complex plan in human space missions spans over multiple monitors

PLANNING PROBLEMS

Our research findings consolidated into five central problems of human planning and execution:

1. **Inflexible plans** fail to capture the variable nature of execution.
2. The difficulties of communicating **experiential and *in situ* knowledge** result in uninformed plan making.
3. **Shift handoffs** within roles often involve poor information transfer, resulting in poor situational awareness and increased operating expense.
4. **Dependencies between highly siloed roles** ungracefully accommodate human error, which has cascading effects.
5. Any **single representation of the plan** fails to accommodate the varying needs and responsibilities across roles utilizing the plan.

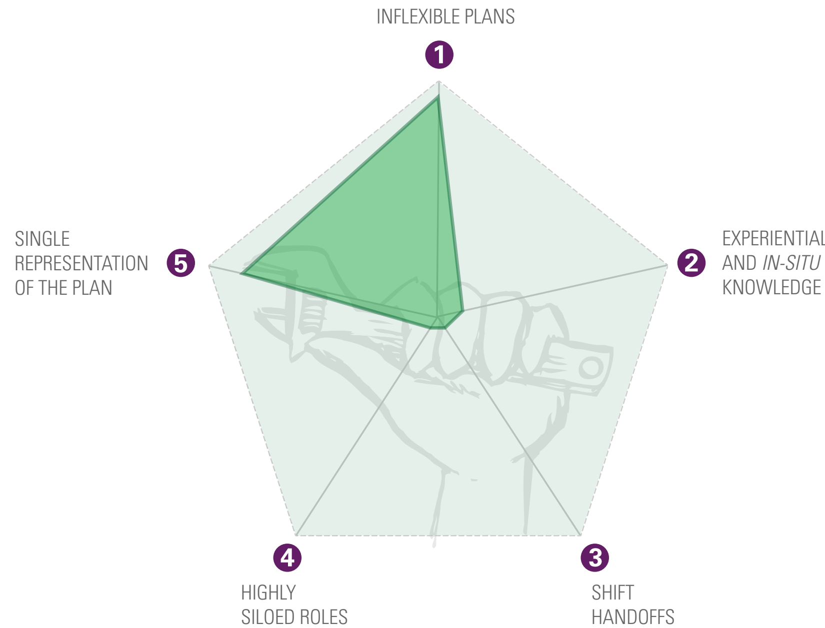
For more details about our user research and planning problems, please see our research report at: **www.hcii.cmu.edu/M-HCI/2010/NASA/solution/downloads**

BACKGROUND

PROJECT FOCUS

Although our research findings revealed many potential design opportunities, we chose to focus on a compelling user need exposed by planning problems one and five: the need for more flexible plans tailored to the unique needs of astronauts, who often dynamically re-plan in the face of unforeseen circumstances from complex and time-constrained plans.

To develop a tool specifically optimized for astronauts executing off the plan, we drew inspiration from NASA's Desert Research and Technology Studies (RATS) project, which investigates planetary surface operation concepts, including manned surface rovers and planetary science. Specifically, our design process and resulting prototype focused on supporting astronauts performing geological science on planetary surfaces.



Our project focus within the identified problem space

PROJECT PROBLEM SPACE

1 **Inflexible plans** fail to capture the variable nature of execution.

No matter how well vetted a plan is, static plans will never be able to fully anticipate how execution actually unfolds or dynamically respond to unforeseen circumstances. In addition, existing planning tools that focus on constraint modeling are not equipped to support the creation of flexible plans.

Consequently, inflexible plans often result in large discrepancies between the plan and the actual execution.

> *"The plan is just a suggestion."*
>
> *Former Astronaut (3/1/2010)*

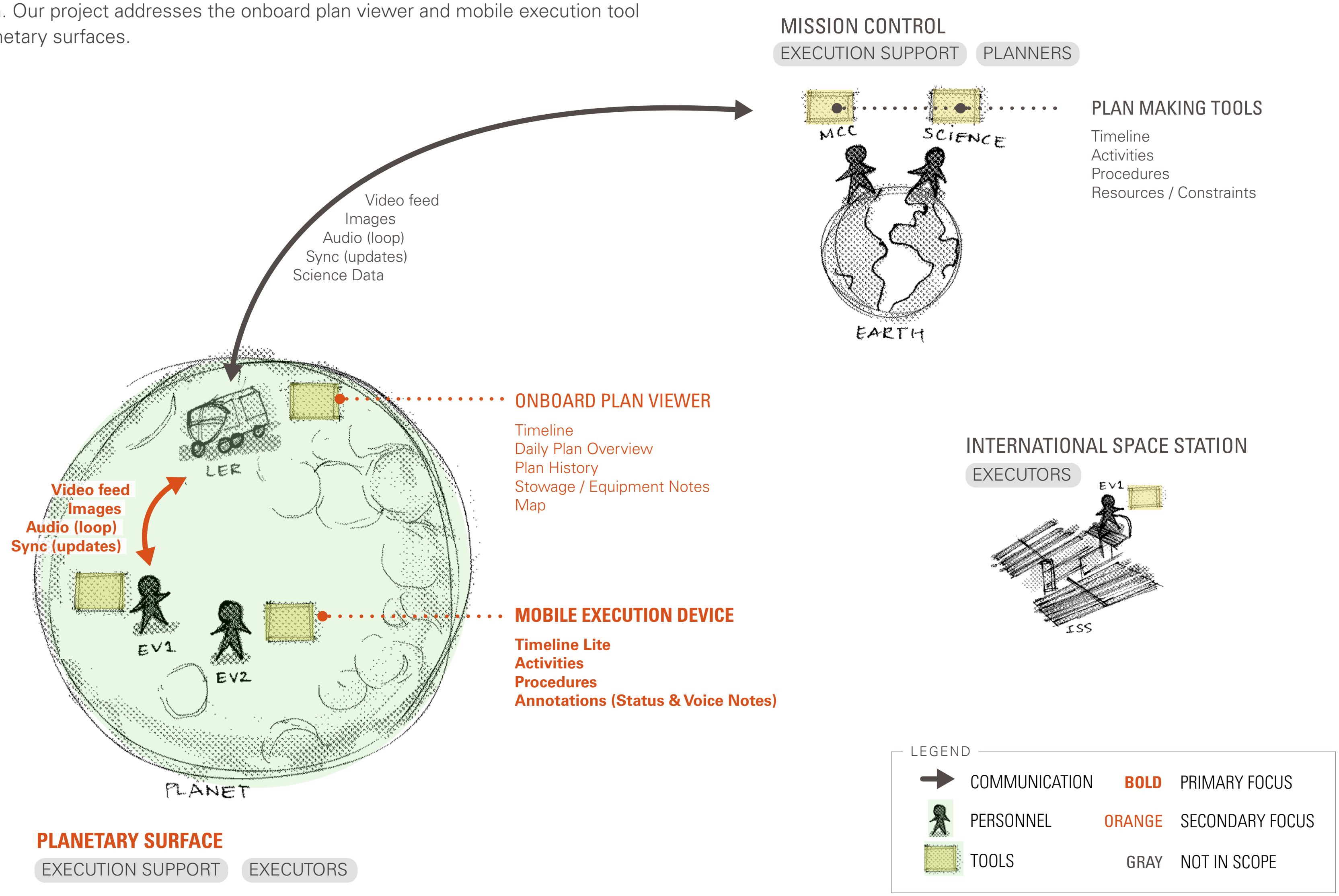
5 **Single representation of the plan** fails to accommodate the varying needs and responsibilities across roles utilizing the plan.

Primarily intended as a communication device, the plan is an abstract representation of an intended future. However, as the plan is created, refined, reviewed, and executed, it is utilized by many different roles, each with a different set of goals requiring different types of information.

Often one representation of the plan will accommodate all roles broadly, but fail to deeply serve the unique needs of any one role.

PROJECT SCOPE

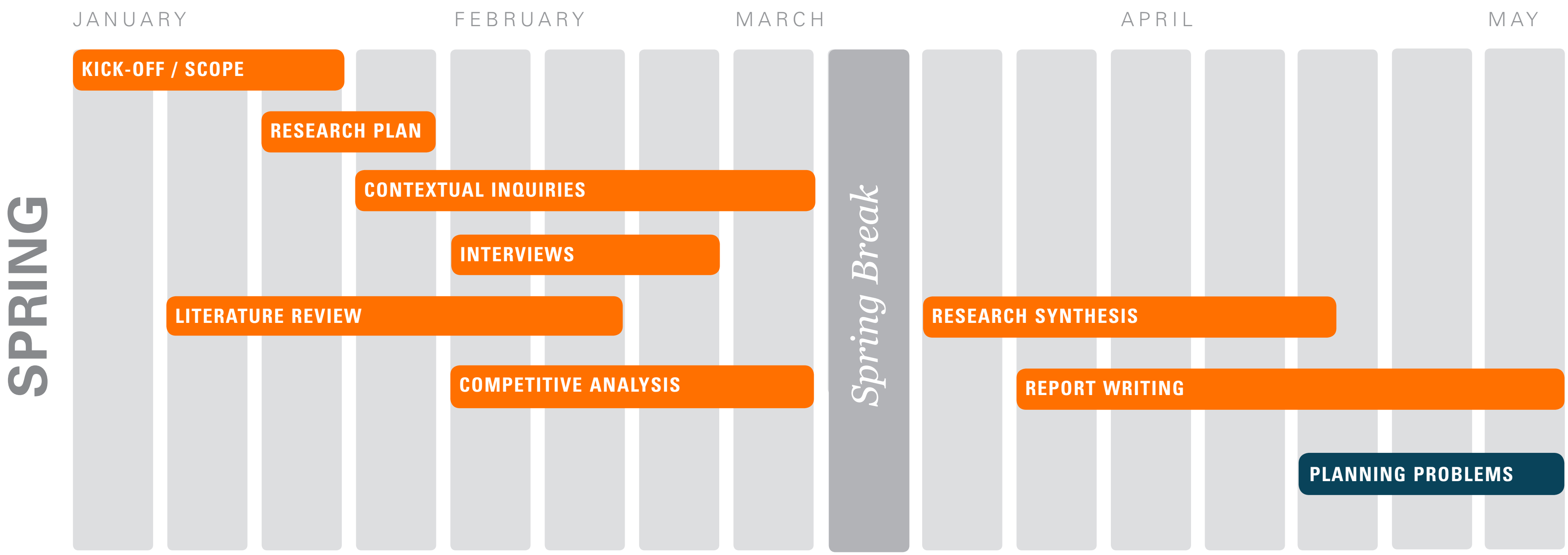
The following diagram illustrates how a mobile execution tool integrates into the ecosystem of existing tools at Mission Control and the International Space Station. Our project addresses the onboard plan viewer and mobile execution tool on planetary surfaces.



SCHEDULE: RESEARCH

The research phase produced many design opportunities

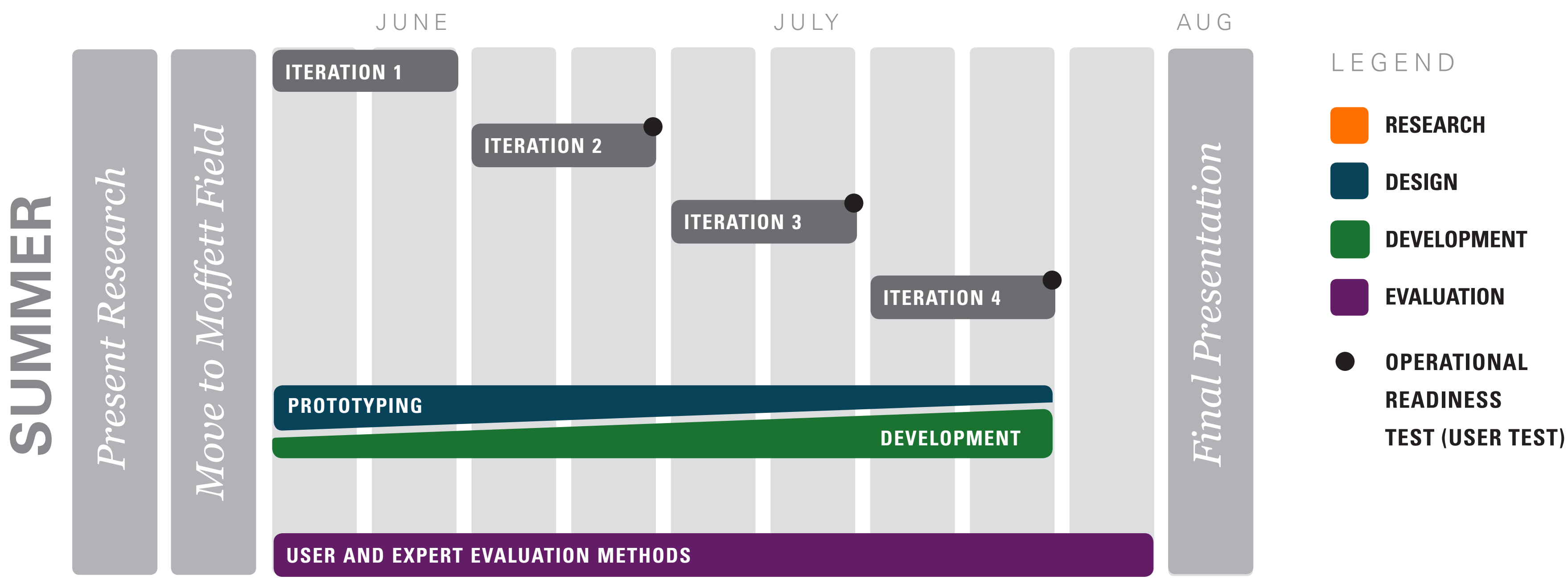
We spent half of the spring semester researching the domain of human space missions, conducting Contextual Inquiries, Retrospective Interviews, Literature Reviews, and a Competitive Analysis. We synthesized the research data in the second half of the semester to derive five central planning problems.



SCHEDULE: DESIGN

We structured the design phase around four iterative cycles of user testing and refinement

Over the summer semester at the NASA Ames Research Center, we completed four major iterations of design. We created low-fidelity sketches, medium-fidelity wireframes, and high-fidelity prototypes to create our design of a cuff-mounted execution tool for planetary surface missions.

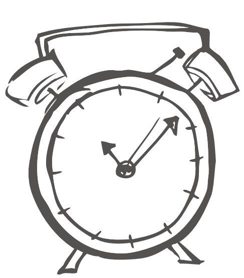


DESIGN GUIDELINES

From our research findings, we derived four guidelines to direct the design of a mobile execution tool of planetary surface missions. Our primary goal was to create a tool optimized for astronauts rather than planners. The following four design guidelines demonstrate different facets of this goal.

> *"The challenge becomes assimilating the large set of information that one plan represents and presenting the tasks to the end-user as efficiently as possible."*
>
> *NASA Project Problem Description*

FOUR DESIGN GUIDELINES

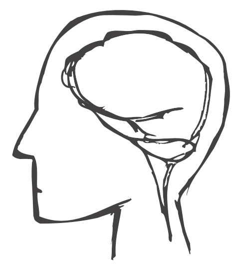


Delta between Plan and Execution

Due to unforeseen circumstances, execution may be ahead or behind schedule. The delta is the difference between the ideal planned state and the current reality of execution. [1]

Timeline Optimized for Execution

Astronauts and planners have very different goals when viewing the timeline. A timeline optimized for execution displays planned activities in a way that matches an astronaut's unique workflow. [2]



Autonomy when Appropriate

Though many activities are constrained by sequence or time, several are not. Autonomy allows astronauts to execute activities as appropriate to the environment of execution. [1]

Glanceable and Unobtrusive

An execution device should support, rather than burden the astronaut's workflow. It should be helpful when needed but not require additional or unnecessary interaction. [3]

[1] Derived from Problem #1: Inflexible Plans

[2] Derived from Problem #2: Single Representation of the Plan

[3] Derived from May 12th, 2010 Interview with Desert RATS Crew Member

DESIGN

SUMMARY: LUMINA MOBILE

Our final design, Lumina Mobile (LuMo), is a cuff-mounted tool that supports the execution of planned science and operation activities during planetary surface missions. LuMo allows astronauts to view an optimized version of the plan timeline, activities, procedures and execution notes, with timing information indicating how far ahead or behind schedule they are.

The prototype utilizes large physical buttons rather than alternative touch screen input to accommodate the physical constraints of heavy space suit gloves. Planned activities are grouped by the core components of planetary surface missions: traversals and stations. Each Activity List displays all activities associated with the currently selected Plan Segment. Time insensitive activities can be completed in any order within the total time allocated for the Plan Segment. Procedures and Execution Notes detailing the steps required to complete an activity are integrated into the timeline to support the astronaut's workflow.

The following design section details a typical scenario of use and describes the core components and features of the tool.

For a video demo, please visit:
www.hcii.cmu.edu/M-HCI/2010/NASA/demo

PERSONA

Tim Saunders
(38 years old)

Summary
Tim is a Geologist Astronaut on his first space mission and has trained extensively for his mission to the moon. He is intimately familiar with all the processes and tools involved (including LuMo) and has tirelessly practiced every procedure. He has studied the plan and objectives of the mission, and understands how each station fits into the overall purpose of the mission.

Background
Stanford Ph.D in Planetary Geology
Extensive analogue experience on earth

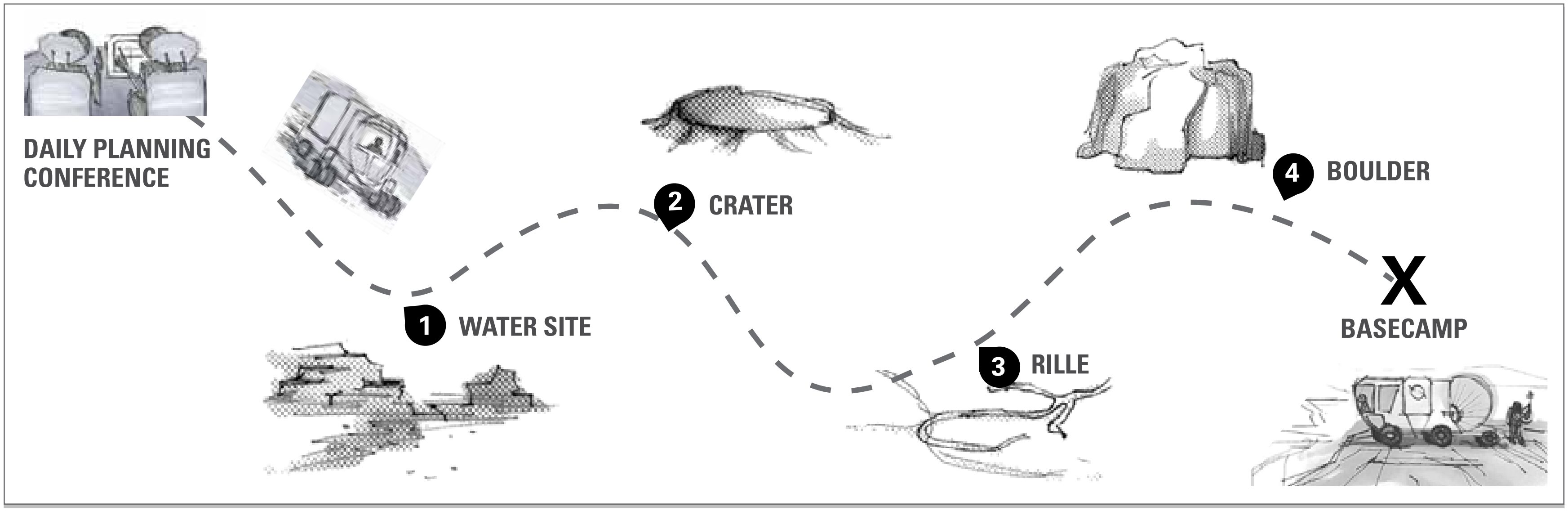
Responsibilities
Take photos and collect rock samples
Communicate with Sci-Ops & Mission Control
Collaborate with partner in the field

Life Goals
Advance space exploration
Promote planetary science at NASA

Experience Goals
To feel confident while completing tasks
To not burden or complicate his workflow

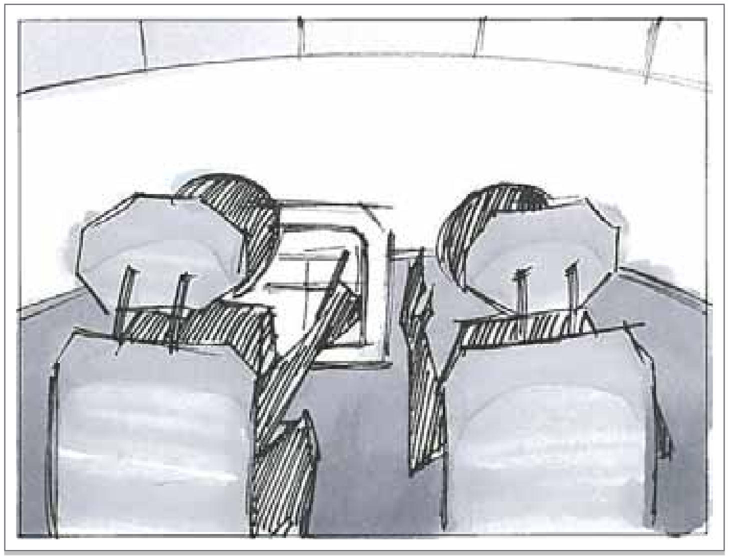
End Goals
Execute as best as he can to the plan
Wants to work ahead & know time left in the plan

SCENARIO: MISSION DAY 5 OVERVIEW



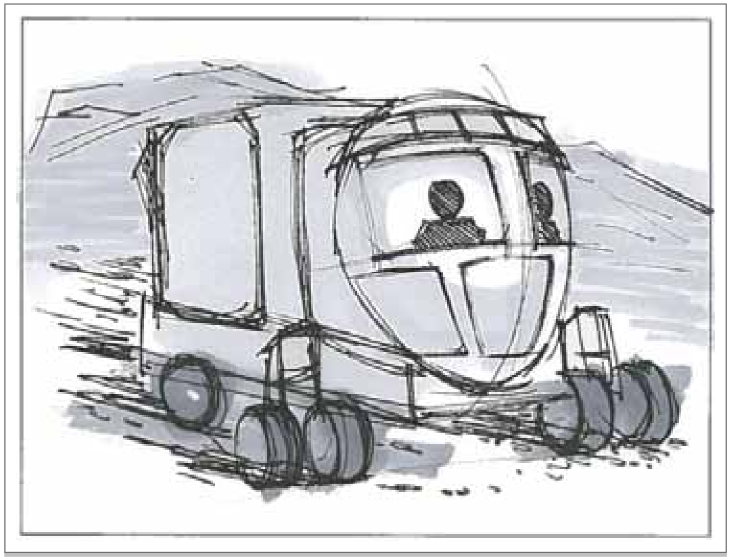
Tim is a Geologist Astronaut. **Bernard** is an Operations Astronaut. The crew's objective is to **collect a soil sample from a possible water site**. Their work day on the moon is about 8 hours, and it is extremely important that they return to basecamp on time. In this time, the crew **traverses** (drives in the space exploration vehicle) to four **stations** (locations of interest).

SCENARIO: CREW PREPARES FOR THE MISSION DAY



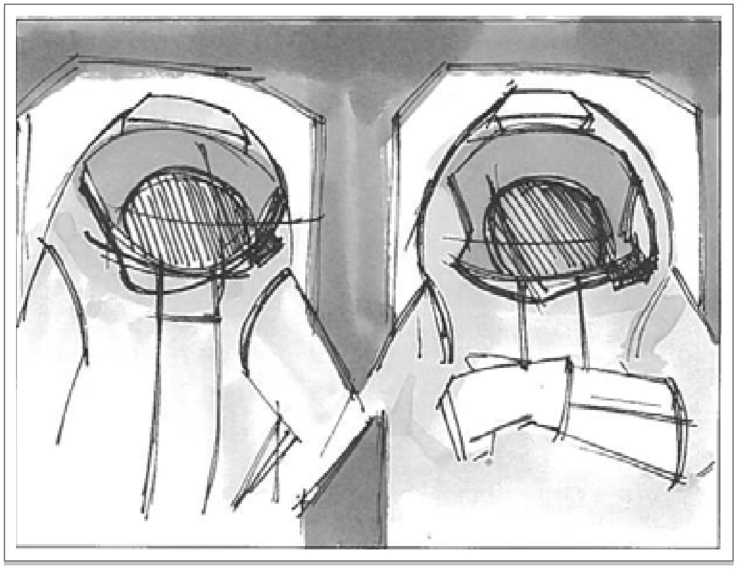
At the beginning of the day, Tim and Bernard participate in a Daily Planning Conference to review the day's plan, answer any open questions, and discuss any necessary revisions.

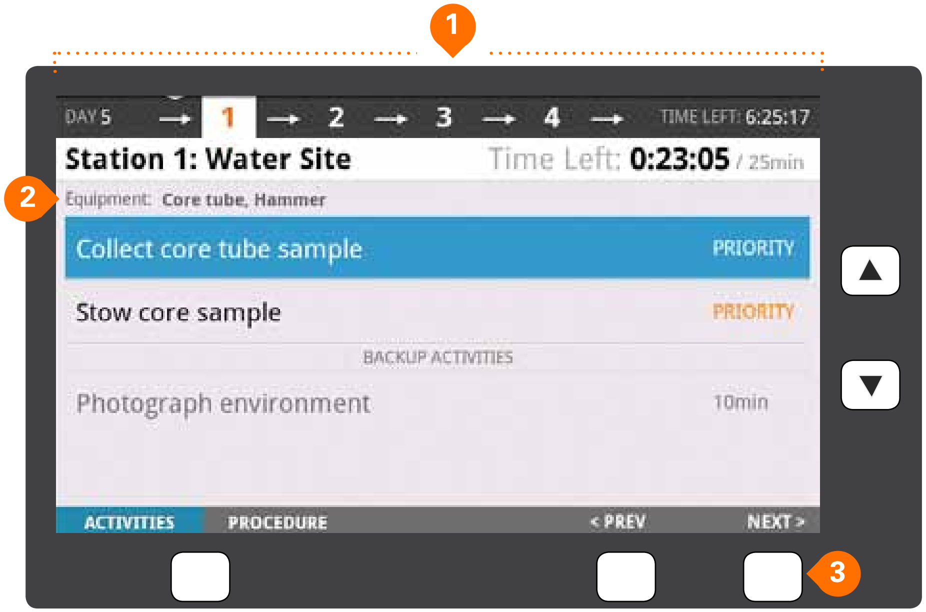
The data from the previous mission day revealed the possibility of hydrogen in the soil. Hydrogen suggests the presence of lunar water and would represent a sizable scientific discovery. As such, ground decides to add a trip back to the possible water site to the beginning of the day's plan and makes collecting the soil samples a high priority for the day. Ground uploads the revised plan and Tim and Bernard are ready to begin the day's mission.



The crew traverses to this first station. As planned, they make observations about the environment during the drive. They also stop to take a picture from the vehicle.

SCENARIO: CREW REVIEWS THE PLAN DURING EGRESS





1 **Segment Navigator** 2 **Equipment List** 3 **Next Button**

While they wait during egress (exiting the vehicle), they review the plan on LuMo. Tim reviews the list of scheduled activities for this station and the procedure for collecting samples. He has practiced these procedures hundreds of times, but likes to review before performing the EVA.

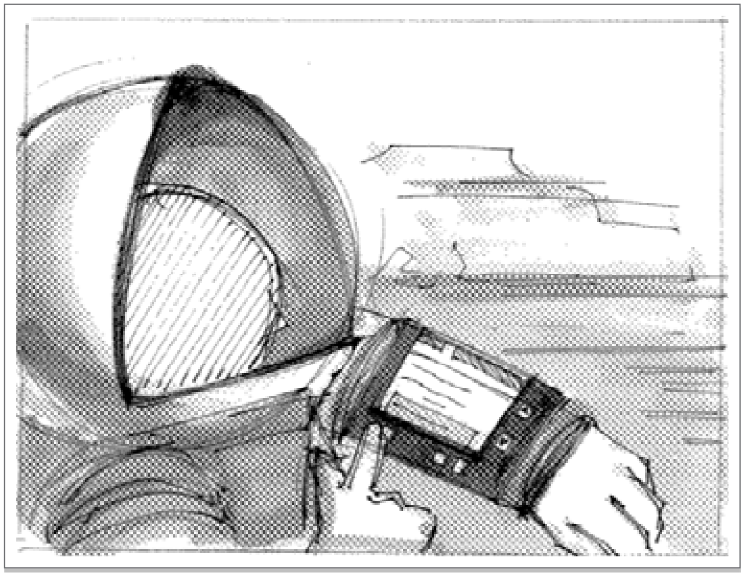
He uses the Segment Navigator and Next Button to navigate to Station 1 and reviews the scheduled list of activities. Tim then reviews the Equipment List and makes a mental note about which equipment he should collect before walking to the site.

SCENARIO: TIM CHECKS TIME LEFT AT STATION 1

As Tim completes the list of activities in the field, he uses LuMo to check his progress periodically. Tim and his partner, Bernard, work together for the first activity. Bernard uses the drill to loosen the sediment so that Tim can collect a sample. While stowing the sample, he glances at the device. The color of the text in Station Time Left is still black, so he knows he is on track.

4 **Station Time Left**

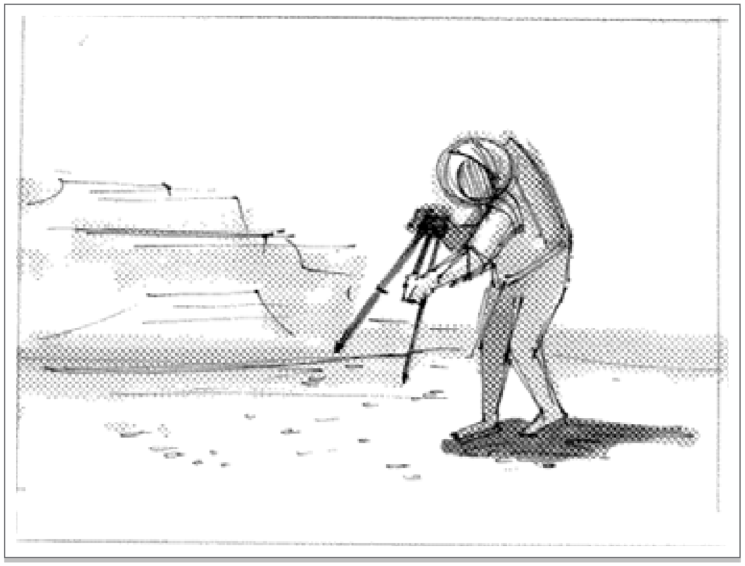
SCENARIO: EXTRA TIME AT STATION 1 (WATER SITE)

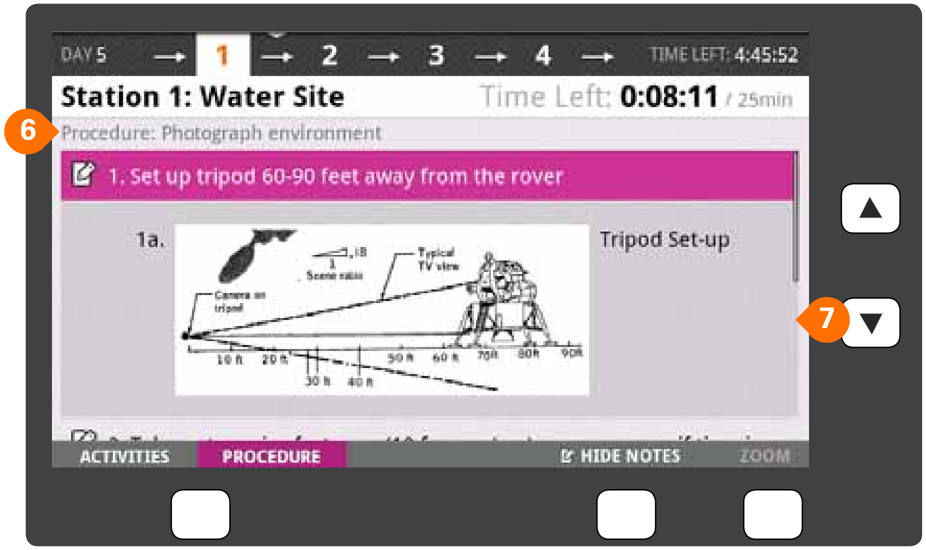


Tim finishes the planned activities early and looks at the list of Backup Activities that he might be able to complete opportunistically with the extra time. He views the procedure for "Photograph Environment". Photographing takes about 10 minutes and since Tim has a little over 13 minutes left, he decides to execute the backup activity before moving on to the next station. Having taken many photographs before, Tim remembers that a tripod is needed for this activity. He tells his partner that he's going back to the vehicle to retrieve the tripod.

5 **Backup Activities**

SCENARIO: EXECUTION NOTE ASSISTS TRIPOD SETUP

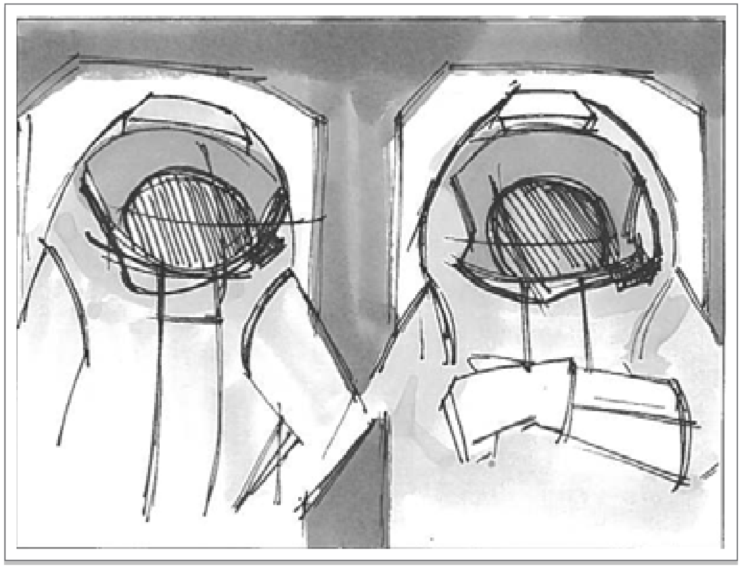




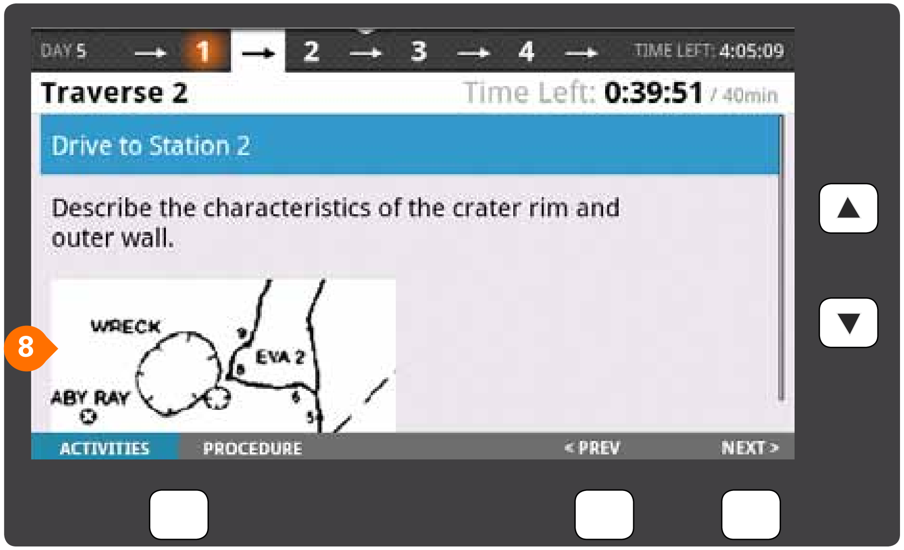
6 Procedure Viewer 7 Execution Note

The type of photograph the plan calls for is very specific. Since Tim cannot recall the exact specifications from the top of his head, he opens the Procedure Viewer to see the list of steps required to complete the activity. He views the Execution Note which tells him how to set up the tripod. The note informs him of the approximate angle and distance required to take the picture.

SCENARIO: REVIEWS TRAVERSE DURING INGRESS

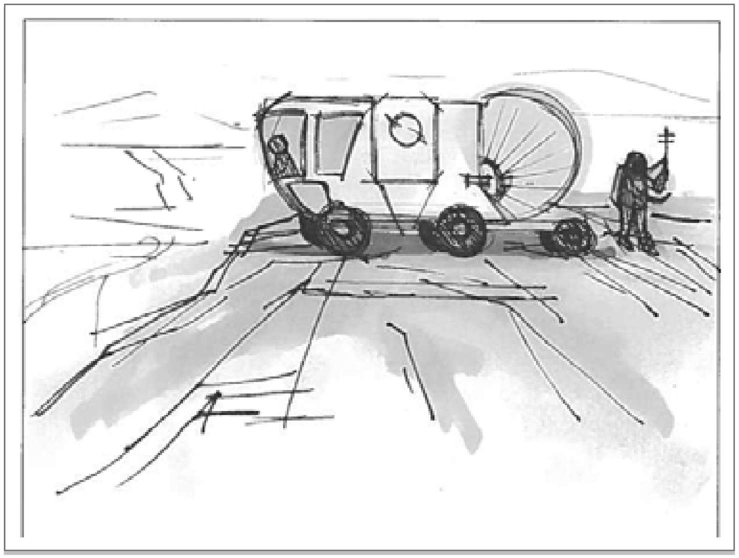


Tim informs his partner that he completed all activities. The two head back to the vehicle, stow equipment, then ingress (re-enter the vehicle). During ingress, Tim and Bernard chat about the activities they just performed. Tim then takes the opportunity to look ahead at the next traverse. He takes a look at both the driving directions and the Traversal Map.

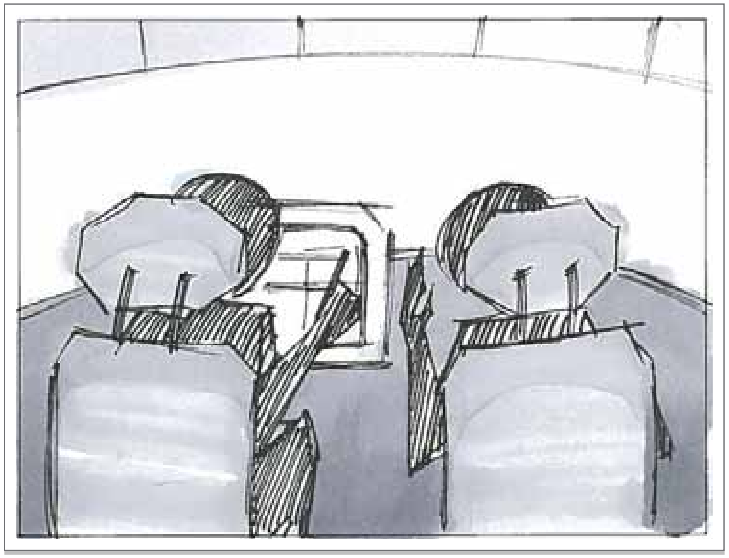


8 **Traversal Map**

SCENARIO: CREW RETURNS TO BASECAMP



Tim and Bernard return safely to basecamp on time.



At basecamp, Tim and Bernard perform daily maintenance and describe their findings from the day and send geological data to Ground for further analysis.

HARDWARE

LuMo is designed to integrate into the cuff of a space suit. A 4.8 inch high-contrast color screen displays the plan while five physical LED buttons provide all input controls. We designed and implemented the LuMo hardware.

For more detail about hardware, see Appendix D, pp. 139

CUFF MOUNTED

The cuff positioning provides the most accessible location for an interactive tool considering the physical limitations of a space suit and the requirement to not consume the visual or audio modalities within the space helmet.

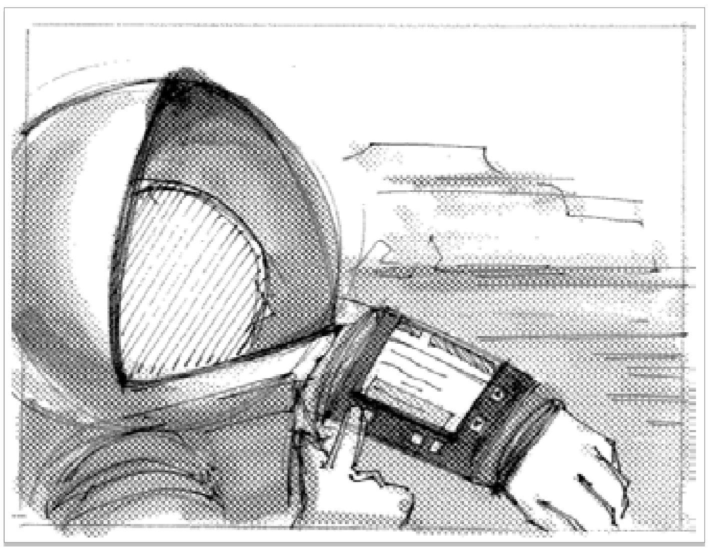
LED BUTTONS

The necessity of large cumbersome gloves suggests that large and easily depressible buttons are the most appropriate form of input. LED buttons, in addition, provide visual feedback of button presses. Frequent communication with ground excludes alternative audio forms of input.

DISPLAY

A display with color, large text and high contrast facilitates readability and glanceability in varying atmospheric conditions.

Restricted mobility in a space suit and uncertain gravitational conditions eliminates gestural modes of input and output or contextual display orientations that may require accelerometers, gyroscopes, or free range of motion. Additionally, the landscape orientation is best suited to accommodate the textual information frequently found in the plan.

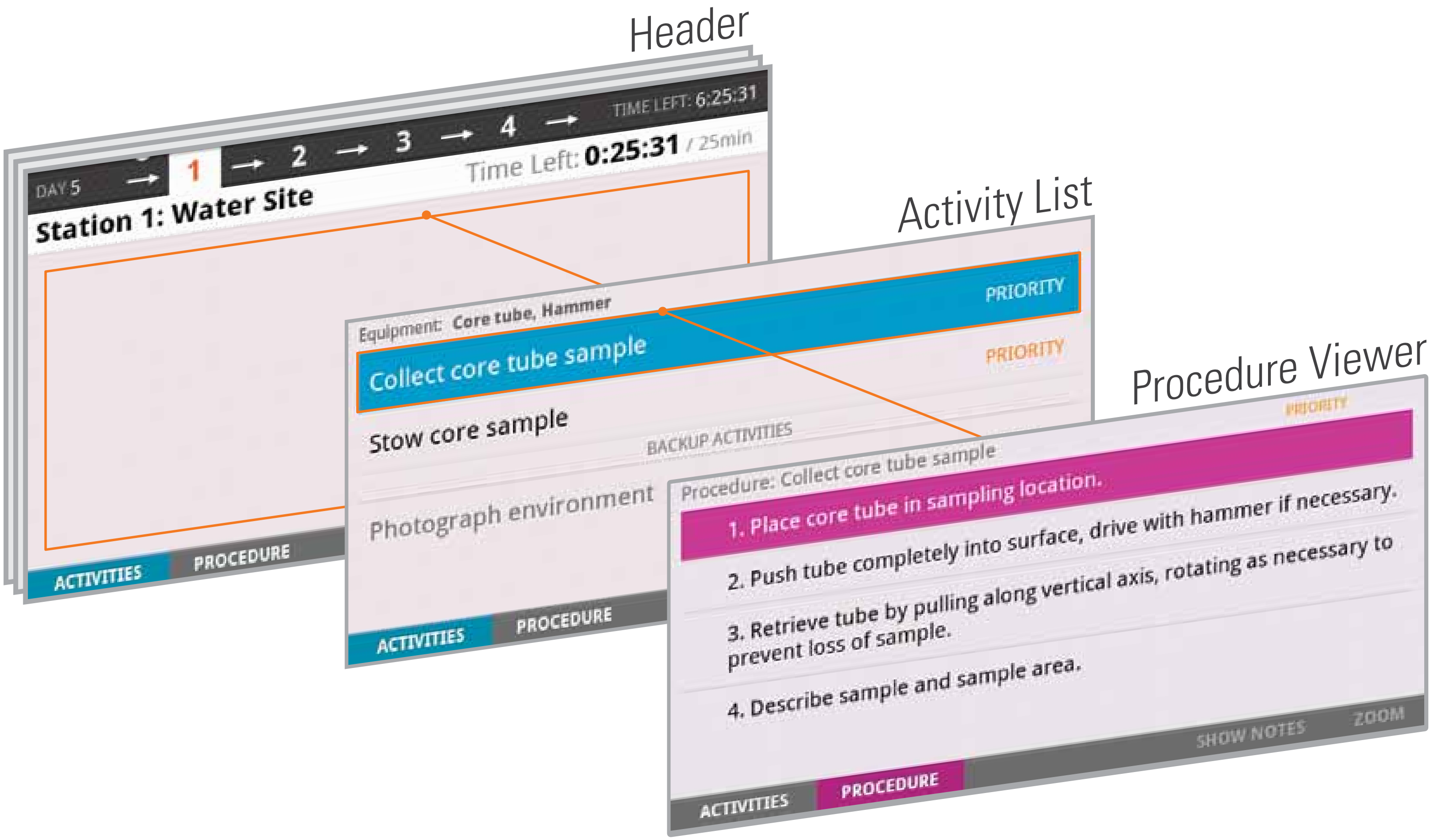


The envisioned cuff-mounted display on a space suit

The current LuMo prototype

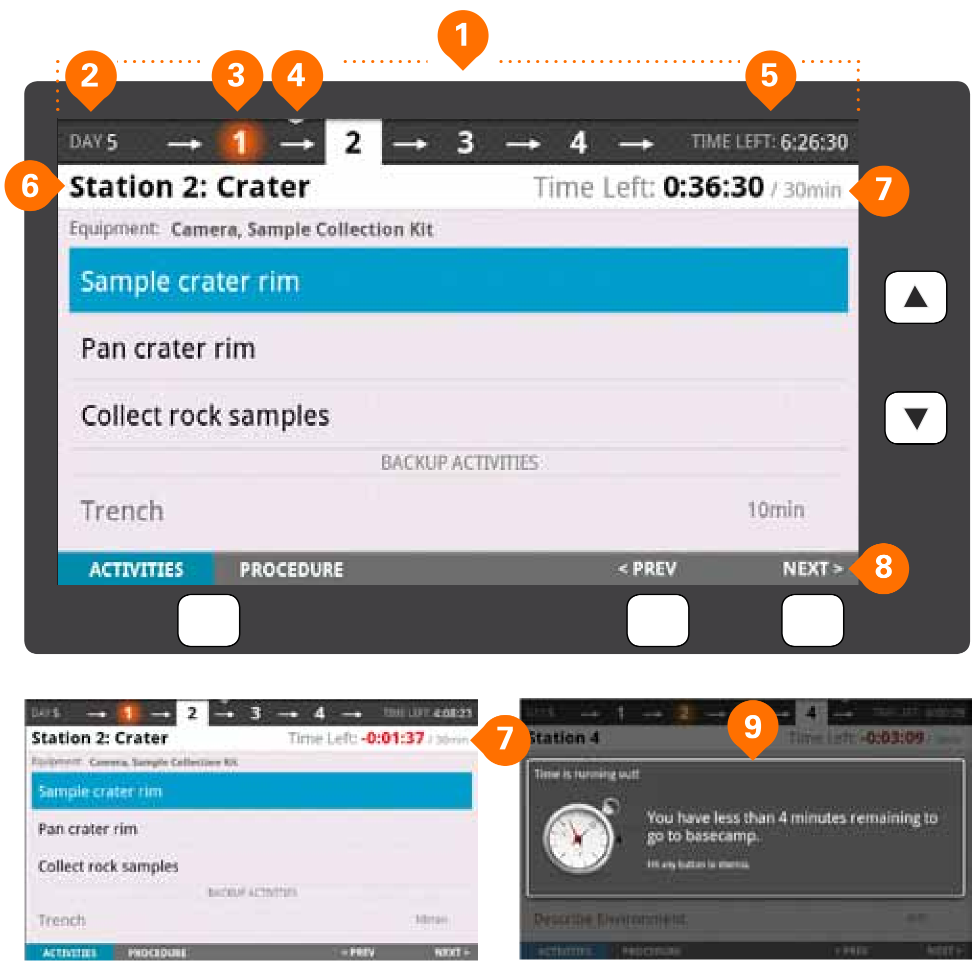
INFORMATION MODEL

The information model of LuMo is organized around three hierarchical categories. The Header contains a set of Plan Segments that are composed of stations and traversals. Plan Segments denote the top level groupings of the plan, with each containing an Activity List. Each activity in an Activity List has an associated Procedure Viewer. Details of each component of the LuMo information model are discussed in the following design section.



HEADER

The purpose of the Header is to indicate where in a multi-step plan the user is currently viewing and keeps users informed about how far they have progressed in the plan. The Plan Navigator displays a row of Plan Segments representing the current mission day's plan. Plan Segments are either a Stations or Traversals, as indicated by an arrow or number, respectively. The currently selected Plan Segment is displayed as a tab, with the station or traversal title presented in the Segment Information Bar. The Header represents the top level navigation for the interface and contains two crucial pieces of time: Mission and Station Time Left.



1 Plan Navigator

Arrow icons indicate traversals and numbers indicate stations. The currently viewed Plan Segment is displayed as a tab.

2 Mission Day

The current Mission Day is displayed within a multi-day mission plan.

3 Priority Indicator

Stations highlighted by an orange outline contain activities prioritized by planners.

4 Marcus-Bains Notch

The notch icon indicates which Plan Segment executors should be completing based on time elapsed.

5 Mission Time Left

The amount of time left to complete all of the activities in a mission day.

6 Segment Name

The Segment Info Bar indicates which segment of the plan timeline is selected.

7 Segment Time Left

The amount of time left at the selected plan segment is displayed alongside the segment's allocated time. Time left turns negative if the executor is 'over' the time allocated.

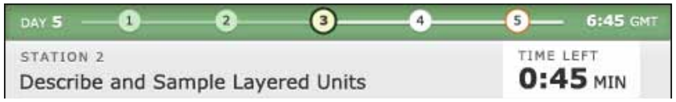
8 Prev / Next Segment

Segments of the plan are selected through the 'PREV' and 'NEXT' labeled buttons.

9 Time's Up Notifier

When Mission Time Left is under a predefined amount, a modal notification displays a message urging astronauts to return to base camp.

FIRST ITERATION



The header displays the discrepancy between the plan and actual execution

The first iteration of the Header aimed to provide a high-level overview of the mission day's plan in an intuitive horizontal timeline, and display which Plan Segment is currently viewed in context of the day's mission. In addition, we designed the Header to prominently display the discrepancy between the plan and actual execution through the Station Time Left display and the current GMT time.

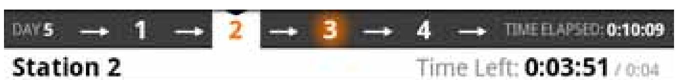
SECOND ITERATION

Refinements in the second iteration included increasing the contrast with a darker background color and text size in the Plan Navigator. In addition, we introduced simpler iconography to distinguish between traversal and station Plan Segments. Lastly, we updated the Station Time Left feature to include additional timing information, including the allocated time for the plan segment and a seconds count.

"Could you let me know when there is 5 seconds until 1 minute left?"

User Test, ORT1 (6/18/2010)

THIRD ITERATION



"I looked at the future activities during ingress."

User Test, Landing Day (7/22/2010)

The third iteration clarified prioritized stations with an updated visual design (orange highlights) and increased text size across the board. We updated Time information to give the executor a better sense of the Delta between the plan and execution, with the Marcus-Bains Notch (indicating where the user should be in the plan given the time elapsed) and Mission Time Left in place of GMT time.

FINAL ITERATION

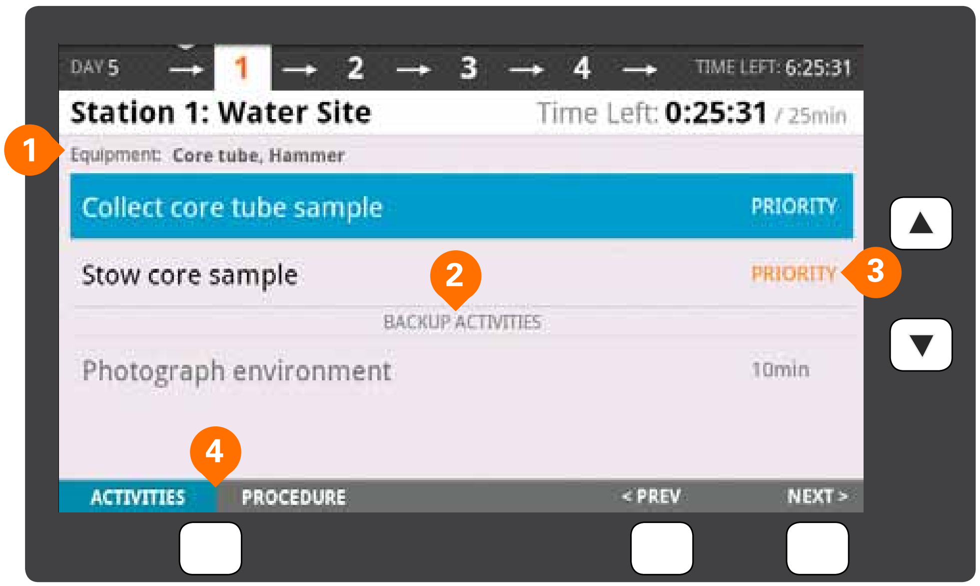
100% of users completed the entire plan on time

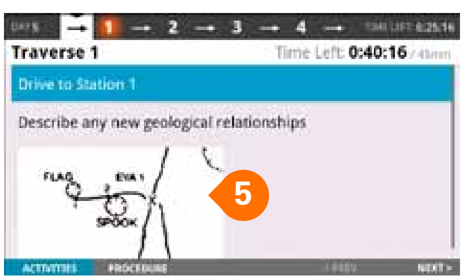
Compared to 33% in the previous iteration

Our final iteration included small refinements to timing information. Mission Time Left counts down from the total mission day allocated time to 0, as suggested by our user evaluation findings. Additionally, we updated time format to be consistent across both Mission and Station Time Left.

ACTIVITY LIST

The Activity List displays all activities associated with the currently selected Plan Segment. Planned activities are not individually time constrained and can be completed out of order, however all must be completed within the total time allocated for the selected plan segment. Backup Activities are not factored into the time allocated for the Plan Segment and are completed opportunistically as time allows. Content that flows below the fold of the display is accessible with the side up and down buttons.





1 Equipment List

This feature displays the requisite equipment for the currently selected plan segment.

2 BackUp Activities

Time insensitive activities that are not factored into the time allocated for a station are displayed under the 'BACKUP' label. The time allocated for Backup Activities are specified inline with the activity name.

3 Priority Indicator

A 'PRIORITY' label indicate Science or operation activities prioritized by planners

4 Activity List Label

The Activity List Label indicates the Activity List is currently displayed.

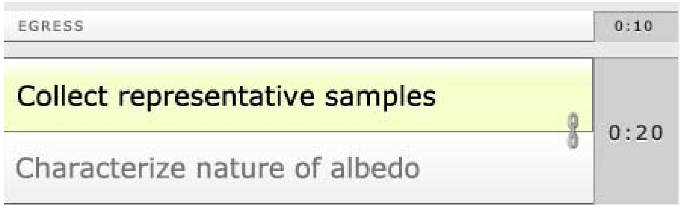
5 Traversal Maps

Pictorial maps of a traversal are displayed in the activity list for traversal plan segments.

6 Discrete Selection

The current selection is displayed with a blue highlight and discretely scrolled with the up and down side buttons.

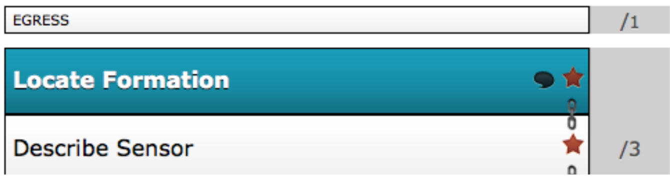
FIRST ITERATION



The first design of the Activity List efficiently used screen real estate to promote large and easy to view activity names. Activities were not individually time constrained, which allow astronauts to perform activities when appropriate. Instead, activity groups have an allocated time. The repeated activities of Egress and Ingress received less vertical space to provide more room for the planned activities of the current segment.

> *Activities are not individually time constrained, providing a more flexible plan*

SECOND ITERATION



> *"One of the biggest problems is the sun and lack of contrast"*
>
> *User Test, ORT 1 (6/18/2010)*

In the second iteration we introduced new functionality, including Activity Flagging and Priority with new iconography. The Activity Priority Indicator conveyed the relative importance of each activity so that astronauts can make appropriate decisions in cases of dynamic re-planning. What is more, we introduced a stronger contrast with darker text highlight colors and clarified the time format for activities.

THIRD ITERATION

After the second iteration, we moved Ingress and Egress activities into traverse Plan Segments, which removed the need for allocated activity group times (see Appendix C). We combined Activity Flagging and Voice Note functionalities into one feature because they served similar purposes, which reduced iconographic clutter. Finally, we clarified the activity Priority Indicator with a text label and increased the overall font sizes for glanceability.

> *"I want to know total time for each segment without having to add..."*
>
> *User Test, ORT 1 (6/18/2010)*

FINAL ITERATION

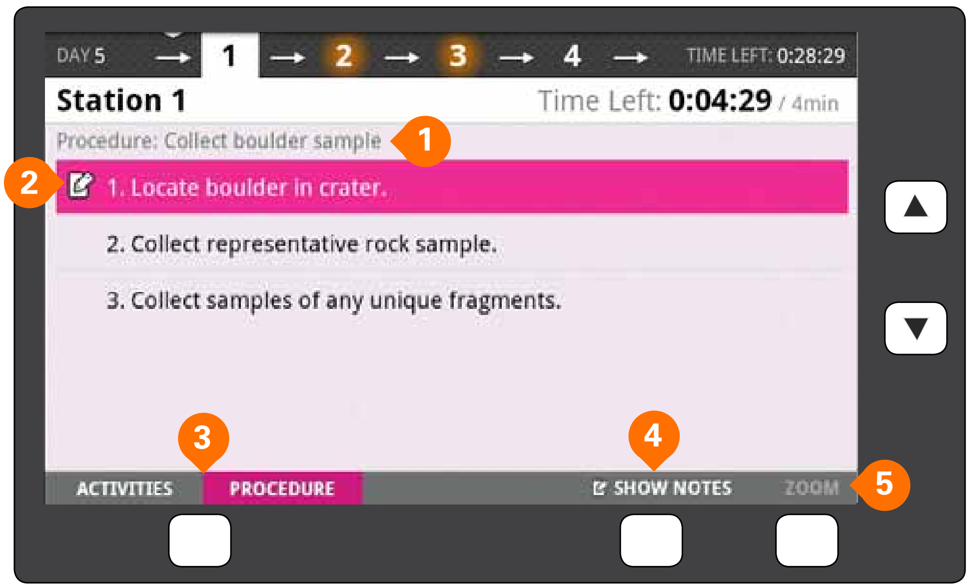
> *"I like being able to see everything I needed [in the equipment list]."*
>
> *User Test, Landing Day (7/22/2010)*

We added an Equipment List to our final iteration, detailing which equipment is required for the currently selected Plan Segment. We removed Voice Notes following feedback from user tests and expert user interviews. We flattened the visual design of selections by removing the bevel, which previously caused users to touch the screen. Finally, we optimized screen real estate using white space adjustments.

DESIGN

PROCEDURE VIEWER

The Procedure Viewer displays an ordered list of steps required to complete the associated activity. Some procedures have accompanying Execution Notes, providing supplemental information such as equipment schematics, science images, cautions or other information intended to support execution. Execution Notes are displayed inline with the procedure step list and are collapsed by default. Content that flows below the fold of the application is accessed with the side scroll buttons.



1 Activity Info Bar

Provides context by displaying the associated activity for the procedure list.

2 Execution Notes Indicator

An Execution Note icon indicates that a given procedure step has an associated execution note.

3 Procedure Viewer Label

Indicates the Procedure Viewer is currently displayed by highlighting the procedure label.

4 Show / Hide Notes

The Show / Hide Notes button toggles the visibility of all execution notes for a given procedure list.

5 Image Magnifier

The 'Zoom' button enlarges the image of a selected Execution Note in a modal overlay.

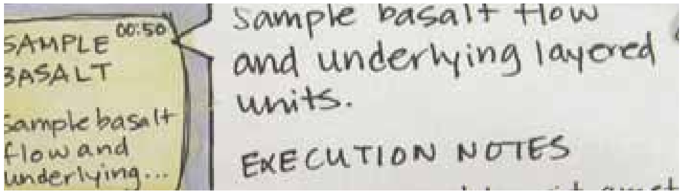
6 Execution Notes

Displays supplementary execution information within the context of an associated procedure step. Execution Notes include equipment schematics, science images, cautions or other information intended to support execution.

7 Scrollbar

Indicates the scroll position of the procedure list and presence of content below the fold.

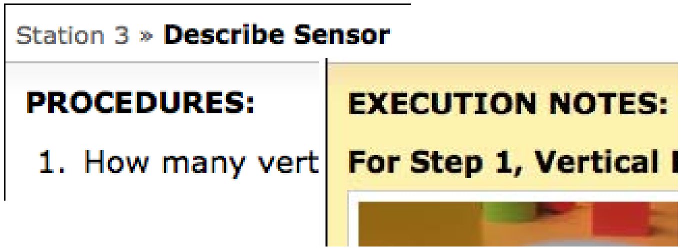
FIRST ITERATION



The first iteration displayed the associated procedure on-demand to accommodate the expert executor who may selectively access this information when needed. Also, the concept paired supplemental information with a procedure, such as execution notes, equipment lists, warnings and cautions, and personal notes.

> *"A checklist helps for when you might get distracted"*
> *Desert RATS Crew Member (5/12/2010)*

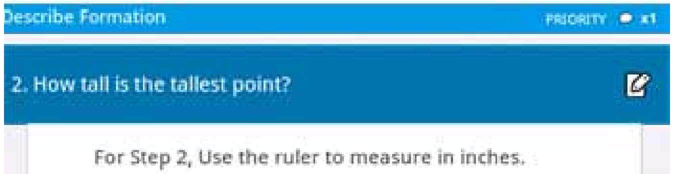
SECOND ITERATION



The second iteration displayed the Procedure Viewer and Execution Notes in two separate screens (see Appendix B). User testing suggested that separate screens divorced each Execution Note from the qualified procedure step and occluded much of the Procedure Viewer, requiring additional input to return to previous screens.

> *"I'm not sure which [execution notes] refers to which procedure."*
> *User Test, ORT1 (6/18/2010)*

THIRD ITERATION



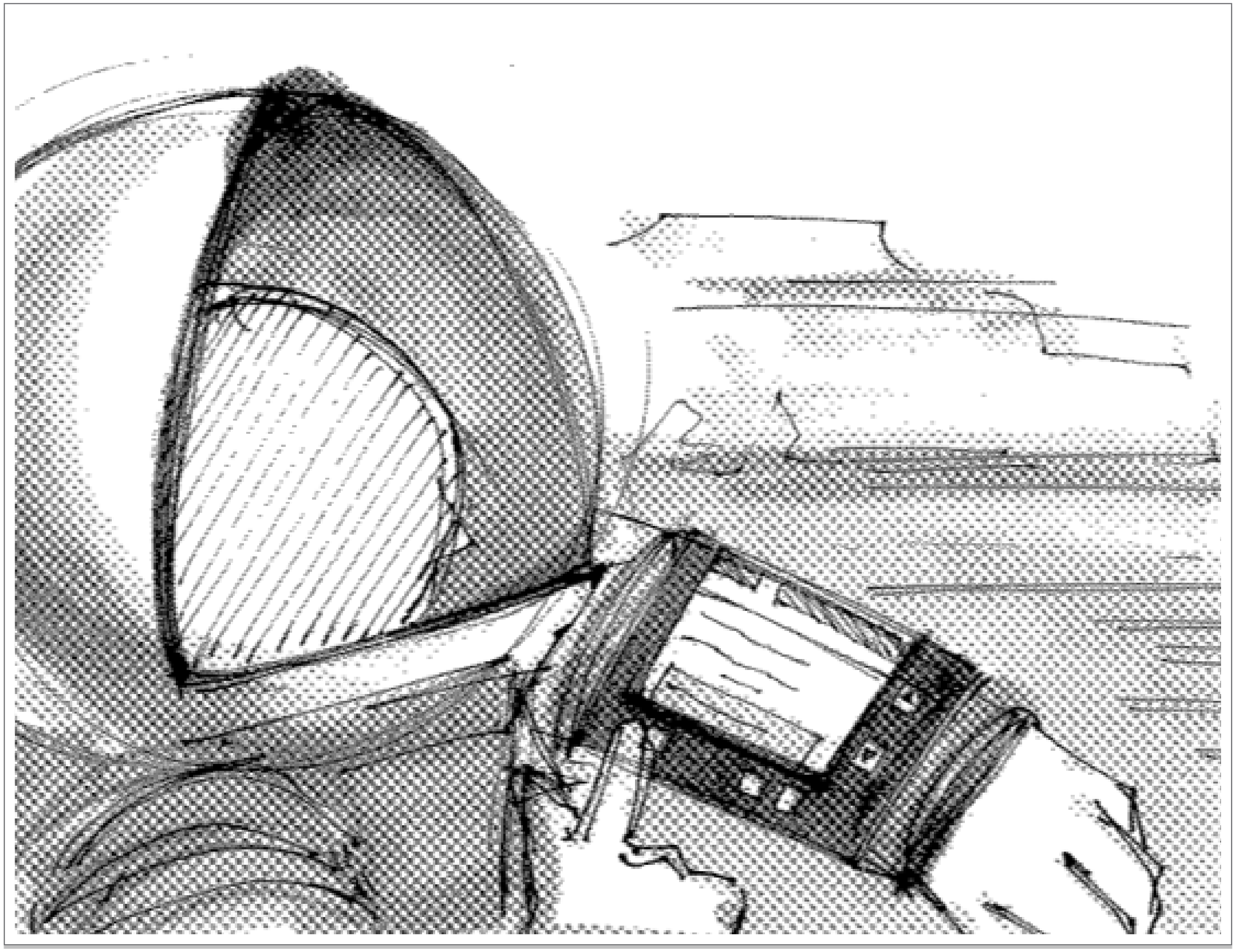
> *Execution Notes are there when you want them and hidden when you don't*

To resolve the issues discussed in the previous iteration, we redesigned Execution Notes to appear inline with the procedure step. Execution Notes are collapsed by default and not visible to optimize the plan for execution, providing ancillary information on demand. The Show / Hide Notes button toggles the display of all execution notes for the selected activity. Lastly, an execution note icon indicates an associated note.

FINAL ITERATION

Our final iteration introduced a clear visual signal (purple highlight) to distinguish the Activity List from the Procedure Viewer. We numbered and darkened Execution Notes to help link them with the associated procedure step. Finally, we redesigned the Procedure List to enhance scannability. For example, we moved the Execution Notes Indicator to the left of the procedure step text.

> *"The new display of procedures was much clearer this time around."*
> *User Test, Landing Day (7/22/2010)*



PROCESS

SUMMARY: DESIGN PROCESS

We developed our prototype across four complete iterations. While the four iterations were not identical, user testing and design refinement were common across all. Early iterations focused more exploratory methods like domain research and brainstorming, while later iterations relied heavily on refinement methods like Think Alouds and Operational Readiness Tests. As rapid prototyping methods like sketching and wireframing tapered off, software and hardware development ramped up.

FIRST ITERATION

- DOMAIN RESEARCH
- DESIGN GUIDELINES
- PERSONA & SCENARIO
- BRAINSTORM 50 TIMELINE IDEAS
- TEAM & CLIENT EVALUATION
- 4 CONCEPT SKETCHES
- SPEED DATING
- LOW-FI (SKETCHES)
- HI-FI (SCREEN MOCK-UPS)
- HTML DEVELOPMENT
- PEER EVALUATION

SECOND ITERATION

- DOMAIN RESEARCH
- PROJECT SCOPE
- PERSONA & SCENARIO
- BRAINSTORM & BODYSTORM
- TEAM & CLIENT EVALUATION
- INFORMATION ARCHITECTURE
- LOW-FI (SKETCHES)
- MID-FI (WIREFRAMES)
- HI-FI (SCREEN MOCK-UPS)
- HTML DEVELOPMENT
- HEURISTIC EVALUATION
- OPERATIONAL READINESS TEST

THIRD ITERATION

- MID-FI (WIREFRAMES)
- THINK-ALOUD
- DEVICE RESEARCH
- HI-FI (SCREEN MOCK-UPS)
- ANDROID DEVELOPMENT
- WEARABLE DEVELOPMENT
- OPERATIONAL READINESS TEST

FINAL ITERATION

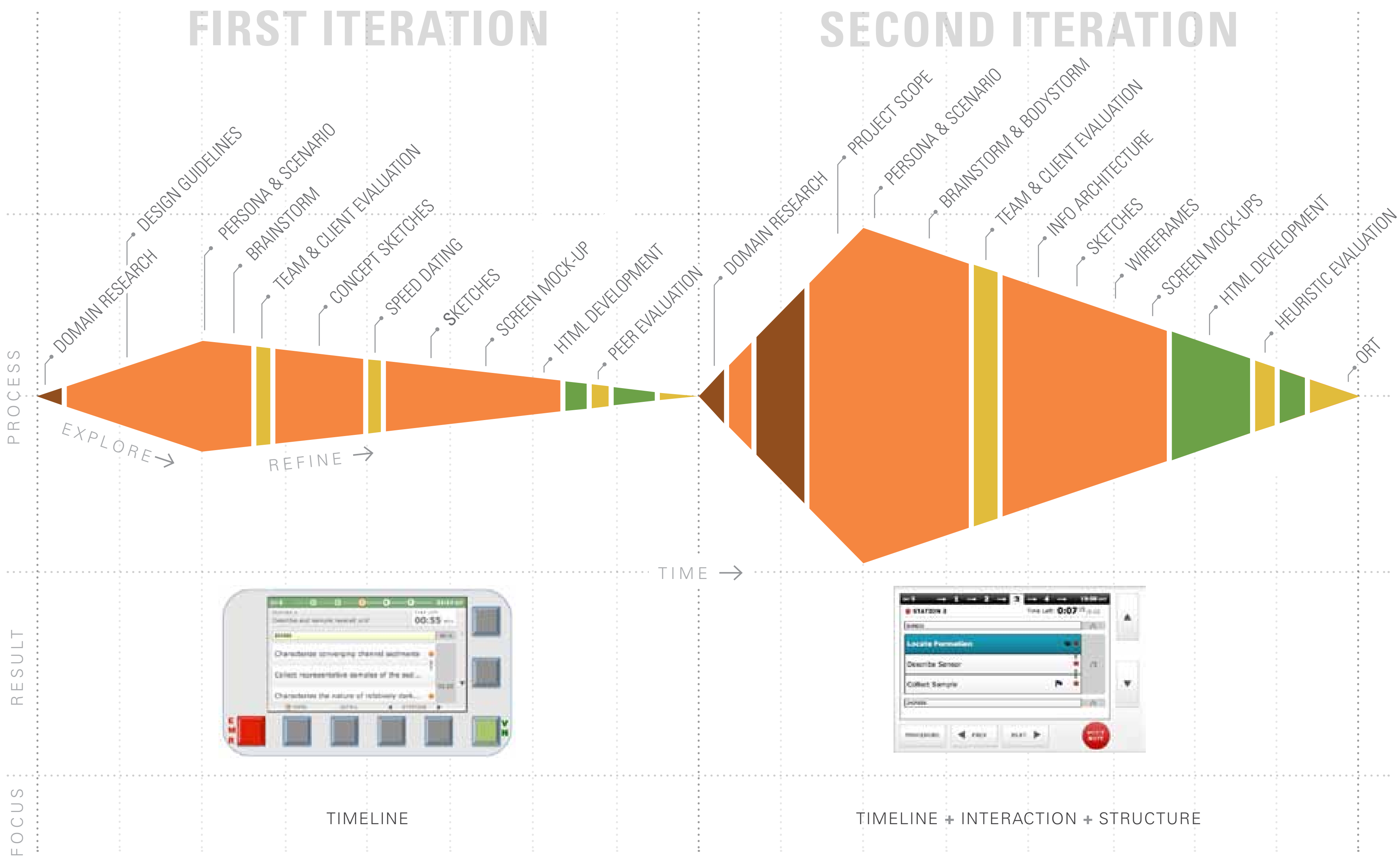
- HI-FI (SCREEN MOCK-UPS)
- ANDROID DEVELOPMENT
- HARDWARE DEVELOPMENT
- TARGET USER FEEDBACK
- OPERATIONAL READINESS TEST

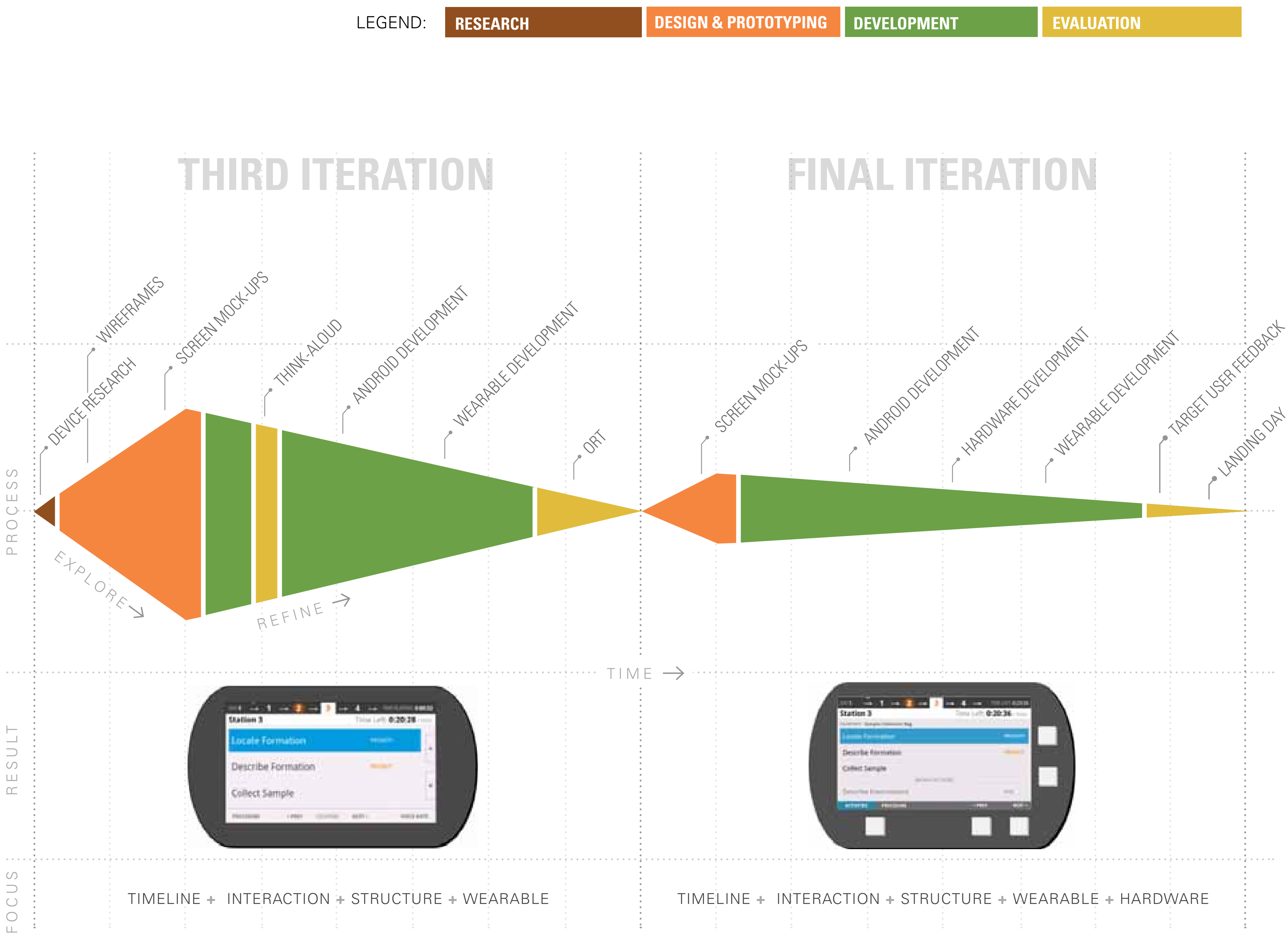
- RESEARCH
- DESIGN
- DEVELOPMENT
- EVALUATION

PROCESS

DESIGN SCHEDULE

After two weeks of ideating to reach a first iteration, our prototype went through three subsequent iterative cycles of exploration (taller kites) and refinement (shorter kites) to reach its final polished state.




LEGEND:
RESEARCH
DESIGN & PROTOTYPING
DEVELOPMENT
EVALUATION
THIRD ITERATION
FINAL ITERATION
PROCESS
RESULT
FOCUS
DEVICE RESEARCH
WIREFRAMES
SCREEN MOCK-UPS
THINK-ALOUD
ANDROID DEVELOPMENT
WEARABLE DEVELOPMENT
ORT
SCREEN MOCK-UPS
ANDROID DEVELOPMENT
HARDWARE DEVELOPMENT
WEARABLE DEVELOPMENT
TARGET USER FEEDBACK
LANDING DAY
EXPLORE
REFINE
TIME
Station 3
Locate Formation
Describe Formation
Collect Sample
TIMELINE + INTERACTION + STRUCTURE + WEARABLE
TIMELINE + INTERACTION + STRUCTURE + WEARABLE + HARDWARE

FIRST ITERATION

Summary: First Iteration

Our first iteration comprised of ideation, concept validation, and rapid prototyping to produce a mid-fi prototype for the Desert RATS team. Interviews with a former astronaut and Desert RATS team member proved to be invaluable in acquiring the domain knowledge of planetary surface missions.

We brainstormed 50 ideas and distilled them into four major concepts. The concepts were quite distinct because we wanted to test different ideas in each one, be it visualization or interaction. Subjecting all four concepts through a speed dating session helped us recognize the strengths and weaknesses of each concept. What resulted was a final concept incorporating a hybrid of all four concepts. Finally, we implemented a click-through prototype for delivery to the Desert RATS team.

For more information about the first iteration, please see Appendix A, pp. 79

Brainstormed and evaluated 50 ideas

We began our process by brainstorming 50 ideas for visualizing an optimized timeline for the Desert RATS mobile device. We constructed a very crude physical mock-up with readily available materials to understand the physical nature of the envisioned device. While many of the brainstormed concepts departed from a classic timeline structure, all aimed to communicate the plan as structured by sequenced activities.

After evaluating our concepts internally, we presented all 50 ideas to members of the NASA Ames Human-Computer Interaction group for early validation and feedback. Using their insightful feedback, we reconciled our evaluated brainstormed ideas into four more refined concept sketches (see next page).

The objective for each of the four sketches was to illustrate the information model of the concept, envisioned interaction design, and structure of the workflow.

Presenting the 50 sketches to our clients, the NASA Ames HCI group

> *"A checklist helps for when you might get distracted. There's always the chance that something comes up and knocks you off your game."*
>
> *Desert RATS Crew Member (5/12/2010)*

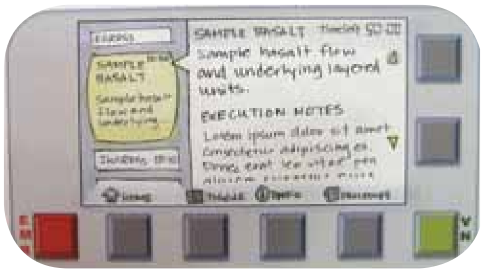
PROCESS

LO-FI SKETCHES

Distilled 50 ideas into four major concepts

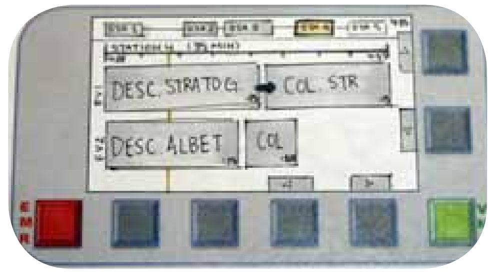
SPLIT VIEW

The timeline is displayed side-by-side with in-depth information about the currently selected activity. In the timeline, most of the screen real estate is devoted to the currently selected activity. The right hand side shows in-depth information about that activity, like Operation Notes and step-by-step Procedures.



BAR CHART

To facilitate collaboration, the bar chart shows the scheduled activities for two astronauts on EVAs. The breadcrumb at the top allows the astronauts to gauge their progress by comparing it to the Marcus-Bains line and view the plan for the entire mission day.

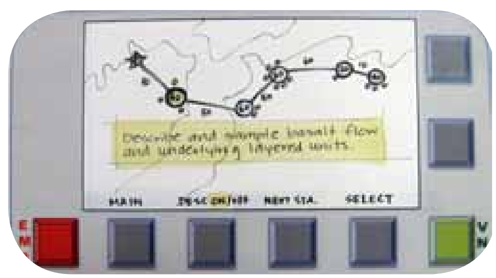


PAPER TOWEL

The Paper Towel concept presents activities in a sequential stream, with equal emphasis on all activities. Irrelevant activities, such as ones for another astronauts, can be hidden. The name of each activity is shown in large text for glanceability. Drilling down into an activity shows that activity's procedures.

STATION-CENTRIC

This design attempts to be as time-agnostic as possible. The map view gives astronauts an overview of their day, showing the number of stations and the busyness of each station. Selecting a station or traverse opens a list of activities with procedures displayed inline.



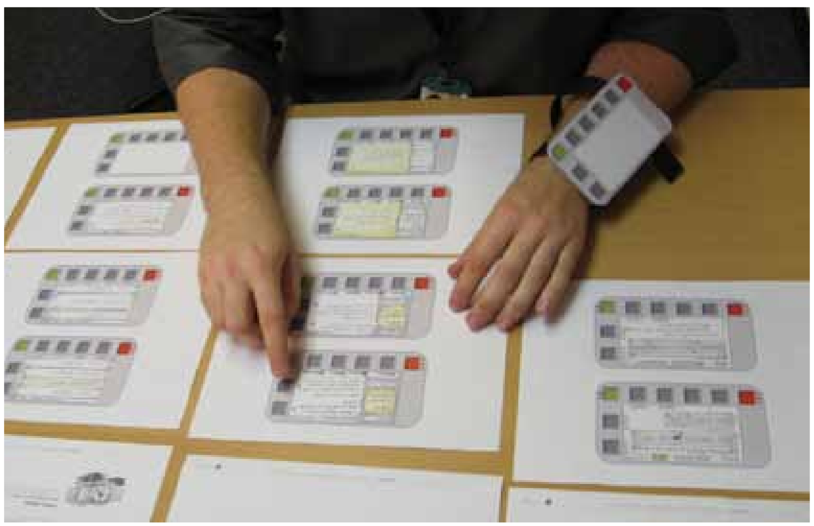
SPEED DATING

Performed Speed Dating with four participants

We evaluated the four concept sketches using a validation method called Speed Dating. We presented these concepts to participants with the purpose of eliciting feedback on features. We tested each of the four paper sketches with four participants, totaling 16 instances of testing overall.

From this needs validation session, we received useful feedback on features that worked well in serving perceived user needs and others that did not. With all of our user research in mind, we created a final refined sketch from which we started wireframing and development.

> *We received useful feedback on features that worked well in serving perceived user needs and others that did not*

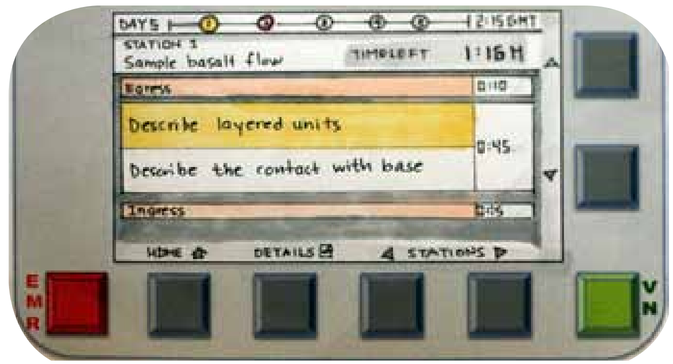


Version 2.0 of the physical mock-up, worn by participants during Speed Dating

User test session using the Speed Dating method

Summarized Speed Dating results

The chart below summarizes our speed dating results and maps the strengths and weaknesses of each concept against the list of features we found to be important. All four concepts lacked "Priority" and "Delta" but each of our participants found these features to be especially useful for dynamic replanning scenarios, where an astronaut needs to compare his progress to the expected progress and make sure high-priority tasks are not neglected. We used these results to create a hybrid structure for the timeline which incorporated the best features of each concept.



The final sketch incorporating the feedback from speed dating

	SPLIT VIEW	PAPER TOWEL	BAR CHART	STATION-CENTRIC
Progress	○	○	●	○
Priority	○	○	○	○
High-level overview (day's plan)	○	○	○	●
Low-level details (activity execution)	●	●	○	○
Activity constraints	○	○	●	○
Glance-ability	●	●	○	●
Current status	●	○	●	○
Delta (ahead vs. behind)	○	○	○	○
Summary	Large display is easy to read and glanceable, but the timeline is less relevant in the midst of execution	Large text is easy to read, but the interaction and sense of time need improvement	Breadcrumb and horizontal timeline are intuitive, but the information shown is neither high-level nor low-level	Map view is friendly for geologists, but it too time-agnostic

HTML DEVELOPMENT

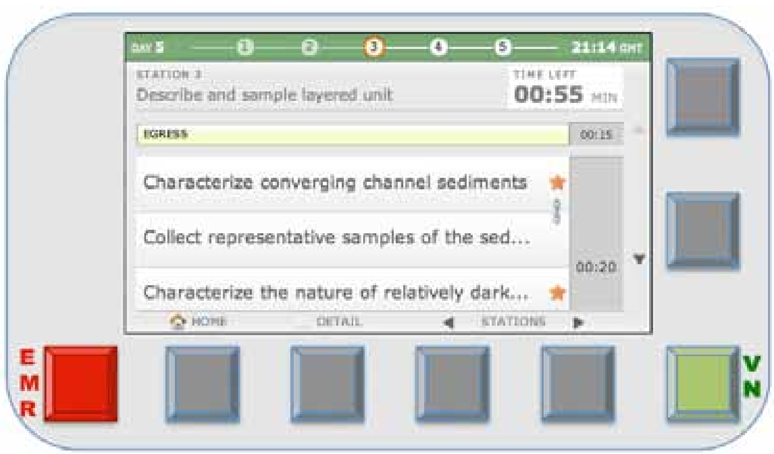
Developed an HTML prototype

From our final concept sketch, we created a click-through prototype for the Desert RATS team, implemented using static HTML and Javascript. Activities are bucketed by station (Station-Centric), and each station presents a stream of activities (Paper Towel). We also preserved the Segment Navigator (Bar Chart) and Time Left (Split View).

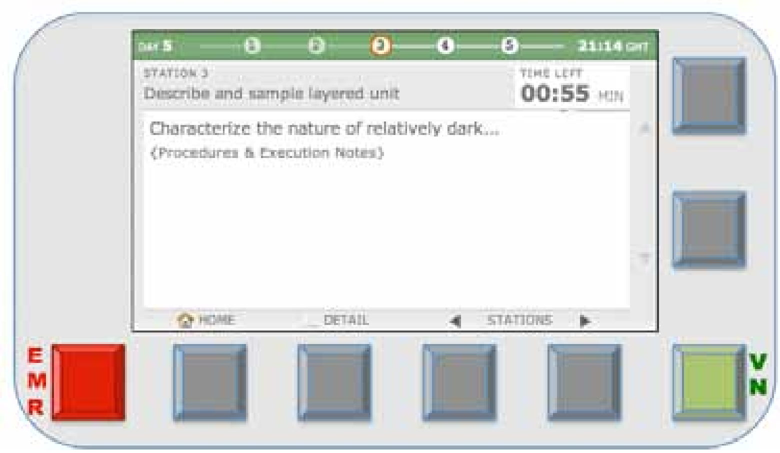
> *We created a click-through prototype for the Desert RATS team*

Notable Features:

- The plan header provides an overview of day
- Time Left shows how much time is left at each station or traversal
- The Activity List shows all activities in sequence at a given Plan Segment
- Priority Plan Segments are expressed using the color orange



The timeline shows the list of activities for the currently selected segment



Placeholder for the procedure viewer

For an interactive demo, please visit: **www.hcii.cmu.edu/M-HCI/2010/NASA/DRATS/prototype.html**

PEER EVALUATION

Solicited feedback from peers, faculty, and clients

After the delivery to the Desert RATS team, we solicited feedback from our client, faculty advisors, and peers at Carnegie Mellon. We used this feedback to inform the design of the next iteration.

> *"This looks interesting and novel...Our viewer serves as a menu to link to procedure pages. With the approach that [you] took, the timeline and procedures are intertwined."*
>
> *Desert RATS Team Member (6/18/2010)*

TOP FIVE ISSUES

For a complete list of findings, see Appendix A, pp. 95

FINDING	DESIGN IMPLICATION	SOURCE(s)
1. Plan Header Needs More Contrast	Increase the contrast, use animation, use different color for Station 3	Peers: Highlighting at the top seems really subtle, needs to be stronger Client: Hard to distinguish which one you are actually on.
2. Yellow Highlights Too Subtle	Increase contrast, use animation	(all): Contrast for yellow selection is too subtle
3. Don't Know Total Time For Segment	Add total time for the segment	Peers + Faculty: I want to know total time for segment without having to add it up.
4. Positive and Negative Time left is Confusing	Try again with interactive (counting down) prototype, do time elapsed instead, remove it.	Peers + Faculty: The negative time is confusing.
5. How Many Activities	Show a scrollbar, add an arrow for more activities, make use of empty white space	Peers + Faculty: Is there a way to show how many more activities there are? NASA Ames: Better way to utilize space if only one activity?

SECOND ITERATION

Summary: second iteration

To prepare for our first Operational Readiness Test (ORT), we completed a second complete cycle of research, design, and development. We began the iteration by conducting a short literature review to gain a deeper understanding of existing work in wearable devices for space exploration. The design process followed with brainstorming and concept validation sessions that eventually led to a more refined design and HTML prototype. The following discusses in detail the different phases involved in the creation of the interface, as well as the updated features of the second iteration of our prototype.

For more information about the second iteration, please see Appendix B, pp. 97

MIT Media Lab interview

On June 6 2010, we held a conference call with Christopher Carr, Steven Schwartz, and Ilia Rosenberg, who are authors of a highly relevant paper to the scope of our project: "A Wearable Computer for Support of Astronaut Extravehicular Activity."

Our goals for the conference call were to better understand their research on wearable execution support for astronaut extravehicular activity. We wanted to discuss the results of their work, as well as any additional knowledge and advice they could provide from their expertise in the domain.

> *"Every astronaut differs vastly in terms of preference."*
>
> *Christopher Carr (6/6/2010)*

The conversation provided a lot of insight into possible problems and lessons learned from their expert knowledge about the field. Listed here are the main take-aways:

- Although we are designing a visual interface, do not underestimate audio modality for input and output.
- Every astronaut differs vastly in terms of preference.
- Be aware of extreme environmental conditions. An idea or device that works on earth might not be suitable in space.
- Traditional user input in a space suit is very challenging.
- Certain activities are better suited for certain kinds of interfaces.
- Think about what would happen if the system fails, are astronauts able to continue working?

BRAINSTORM & BODYSTORM

Generated 50 ideas: interface, input/output, and physical form

As the next step, we conducted another brainstorming session, creating 50 new interface concepts and 25 ideas around physical form, including hardware, input, and output. As part of this process, we performed bodystorming during which we donned motorcycle gear, including a helmet, gloves, heavy jacket and pants. This exercise helped us empathize with our target users and perform some early concept validation.

Software Feature List

- Contextual info paired with Procedures
- Camera / Video Feed Sharing
- Delta between the Plan and Execution
- Activity Priority
- Scan Past and Future Activities
- Onboard Map Viewer
- Flag Exceptional Activities
- Plan Update/Change Notifications
- Mobile Device to Device Communication
- Auto Contrast Adjustment
- Backup / Unscheduled Activities

Hardware Input/Output

- Chiclet Edge Keys
- Audio Voice Notes
- Wrist Cuff Visual Display
- High Contrast / Large Text / Landscape
- Audio Output
- LED Indicators

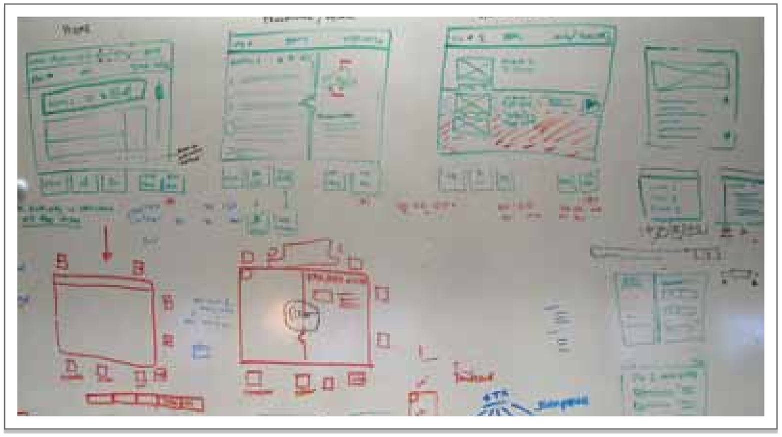
NASA staff members evaluating our 50 ideas

Bodystorming in a mock-space suit (motorcycle safety gear)

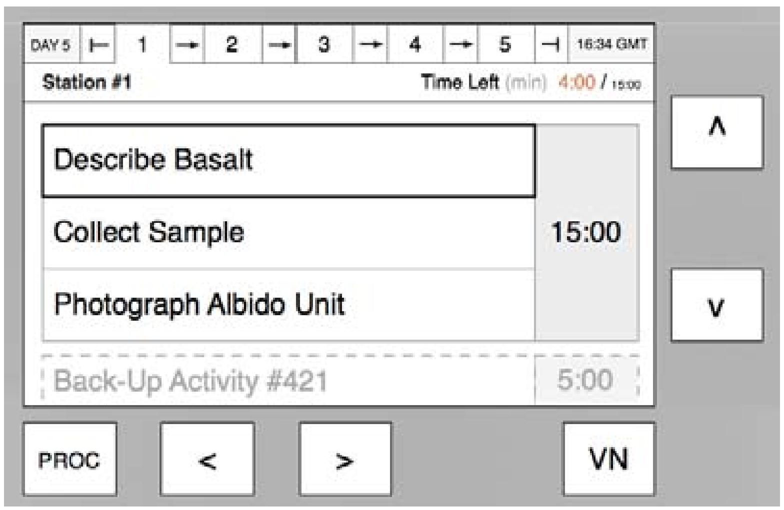
MID-FI WIREFRAMES

Wireframes allowed us to experiment with interaction design

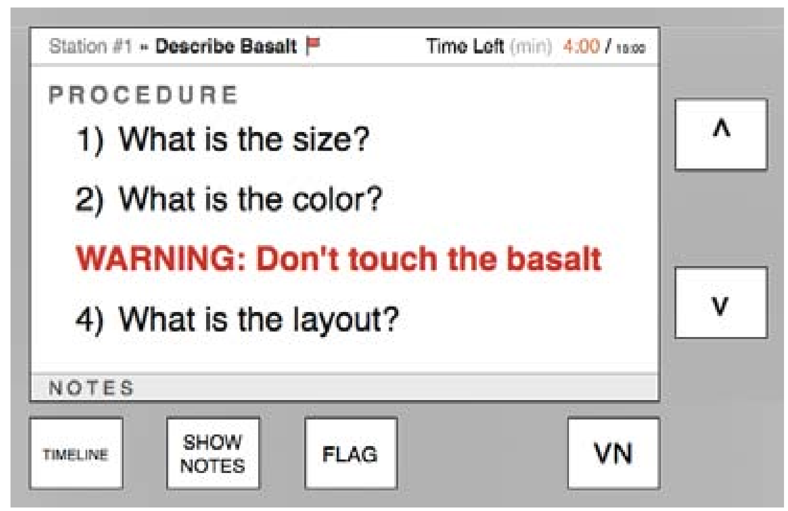
We found wireframes especially useful when we struggled with the fidelity of sketches. We wanted to be sure that each concept fit the small resolution, so creating a medium-fidelity prototype was the best way to deal with practical constraints like real estate without getting too hung up on look and feel. These translated nicely into hi-fidelity because we could reuse similar assets between Omnigraffle and Photoshop. Finally, the Omnigraffle wireframes allow for some level of interactivity, which was helpful when seeing if transitions between states of the interface felt natural.



Whiteboard sketches of the final interface



Wireframes helped us reach a new design for traversals in the Segment Navigator, which sported larger arrows to address the complaint of readability



The Procedure Viewer in this iteration had warnings displayed inline with steps

HTML DEVELOPMENT

Refined the previous HTML prototype

We synthesized the feedback from the previous iteration and implemented the revision in static HTML and Javascript. We then loaded the prototype onto a small handheld tablet.

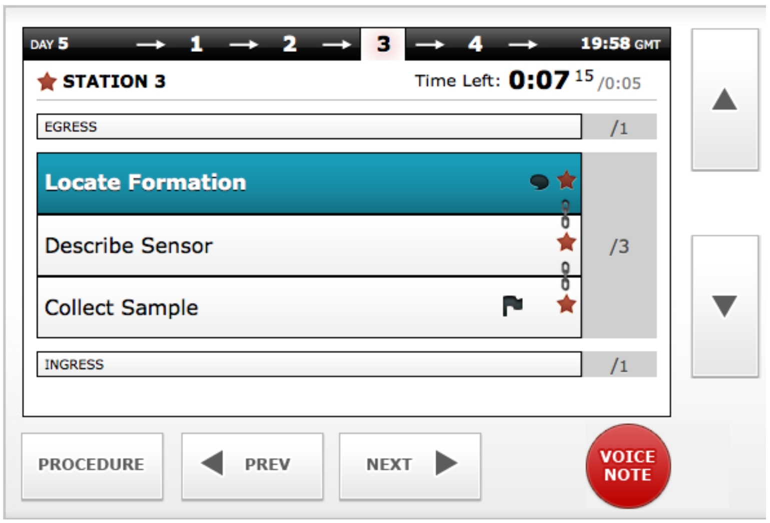
Notable Interface Updates

- Sharper contrast for breadcrumb and highlights
- Total time is part of the Time Left at station
- Integrate procedures and notes with activities
- Support execution and personal notes

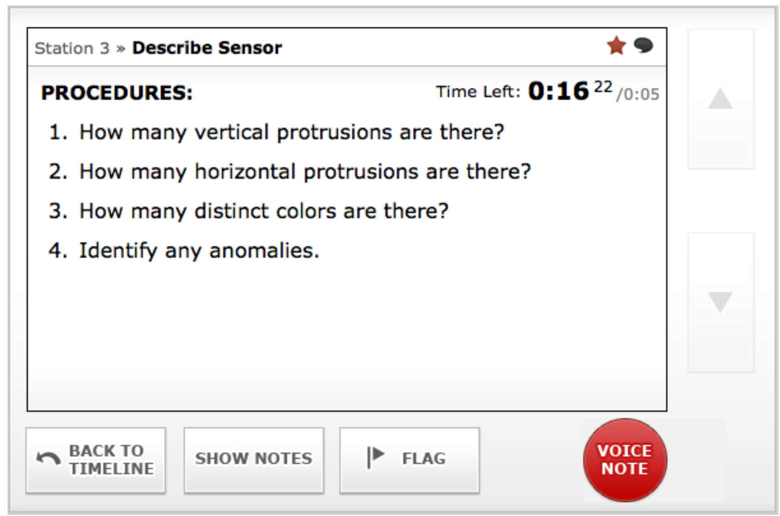
Performed Heuristic Evaluation to identify general usability issues

We performed an expert evaluation method, Heuristic Evaluation, to quickly identify potential usability problems. We considered each of Nielsen's 10 Usability Heuristics, and noted both positive and negative aspects of our design. For example, in terms of "Visibility of System Status," the system did a good job informing the user of a voice recording in-progress, but a poor job linking that voice recording to an activity.

For more information on the results of the heuristic evaluation, see Appendix B, pp. 114



Timeline view with sharper contrast



Procedure view with the option to see Notes (supplemental instructions)

For an interactive demo, please visit: **www.hcii.cmu.edu/M-HCI/2010/NASA/ORT1/prototype.html**

OPERATIONAL READINESS TEST

An Operational Readiness Test (ORT) is a modified think-aloud user study that implements a planetary surface mission simulation. Participants used our prototype to complete mock geological science tasks, specified by a time-constrained plan, at several locations around the NASA Ames Research Center campus. The simulation sought to reproduce the physical constraints of the space suit, remote communication with ground support, and the need to dynamically re-plan to return to base camp on time. We used this method repeatedly to test our design.

Created mock geological science formations

Deciding which activities to perform at each station was the hardest part of creating the ORT. After much brainstorming, discussion, and debate, we decided to use colored foam blocks to create "formations" for the participants to locate, describe, and use to perform mock geological science.

Participants completed a planetary surface mission simulation

We selected four locations (stations), and created detailed activities for each. At each station we placed mock geological science formations. Participants were given approximately 40 minutes to visit all four stations and execute activities specified in the plan. We requested that participants return on time, even if they did not finish all of the activities.

We encouraged the participants to think aloud while performing the tasks. In addition, we took copious notes and video throughout each session. At the end of each session, we had a 10-minute debrief session with each participant.

Participant reviewing the plan during egress

Participant performing mock geological science

Participants completed all four stations in time

All users completed all four stations with time to spare. In hindsight we had overestimated the traverse time so the need to dynamically replan due to time shortage never arose.

Participants liked sharp contrast and time left

The sharper contrast of the visual design proved to be critical since the ORT took place on a very sunny day. Time Left kept participants aware of the time, but they had to mentally leave a minute for the ingress activity at the end of each Station. Remembering to fetch the equipment was easy for some but difficult for others. While executing the activity, most participants found it difficult to pair Procedures with Notes, as the design displayed both pieces of information on separate views. All experienced confusion with when they should be recording voice notes.

> *"I mentioned I didn't need driving directions on the [mobile device]. I take that back...Actually, it's useful to look at during ingress."*
>
> *User 4 disussing the traverse directions (6/18/2010)*

TOP FIVE ISSUES

For a complete list of findings, see Appendix B, pp. 118

FINDING	DESIGN IMPLICATION	SOURCE(s)
1. Device too cumbersome	Support Wearable	(all users)
2. Difficult to calculate time how much total time left	Include mission time elapsed; indicate where executor is supposed to be	U1: (sta 2): Forgot which station she was at, when scanning ahead U2: (sta 4): "Oh my god we have to go back to camp" U3: (sta 1) - (debrief) Used negative time to find out which station to be at
3. Allocated Time to Egress/Ingress not factored into time left	Ingress / Egress should not be included in time left at stations	U4: (sta 2) "Let me know when there is 5 seconds until 1 minute left" U4: (debrief) had to mentally calculate actual time left U2: (sta 3): Discounted egress time for activities
4. Scrolling notes	Paginate them or segment them into groupings	U2: Scrolling is annoying for notes
5. Confused on procedure	Add voice note icon	U0: not sure when to make a voice note or talk to ground U1: (sta 1) didn't know how to get to procedures U2: (sta 1, 3) forgot to leave a voice note.

THIRD ITERATION

Summary: Third Iteration

[1] Appendix B, pp. 114

We identified the issues and insights from the first ORT to revise and improve the operation of the second ORT. In addition, we iterated on the design of the prototype and shifted from an HTML web-based prototype to a native Android application on a small Android internet tablet. In parallel, we started hardware development for the device, using an Arduino and a bluetooth module to send data from external push buttons.

For more information about the Third Iteration, please refer to Appendix C, pp. 121

Refined our design from ORT 1 findings

We began this iteration by processing the data gathered in the first ORT by reviewing the raw data (notes, observations, video) and noting major findings. We paired these findings with the supporting data and potential design implications. The findings fell into two broad categories, the design of our interface and the design of our ORT, where we made sure to label feedback accordingly before working to iterate both of facets.

In addition to the Heuristic Evaluation of the previous iteration [1], we used these findings to direct our discussions for the redesign. Though tempted to walk through each finding and design implication, "repairing" the design as appropriate, we attempted to step back and take a more holistic view. We looked for solutions that addressed many of the problems we saw, or solutions that made such problems obsolete.

> *We shifted from an HTML prototype to a native Android application on a small internet tablet device*

In this iteration, we had our participants wear the device to simulate physical constraints while performing activities

PROCESS

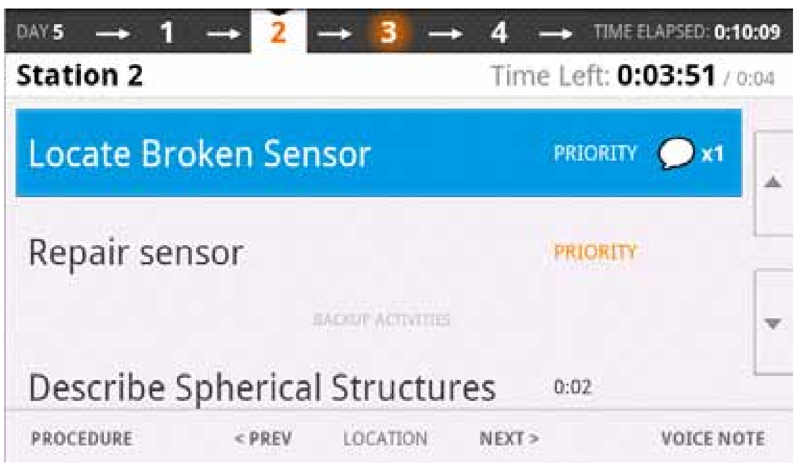
ANDROID DEVELOPMENT

Developed an Android application and physical buttons

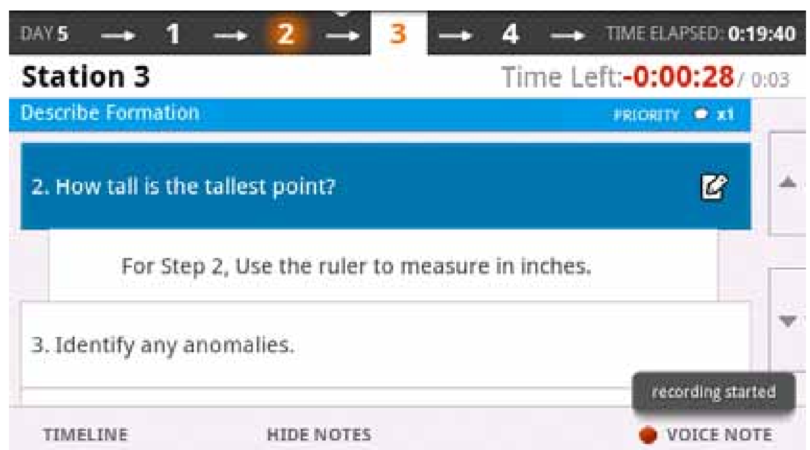
We selected Android as our development platform due to ease of interfacing with hardware and utilize external tactile buttons. We selected the Arduino LilyPad Microcontroller to prototype the hardware. In addition, we selected the Archos 5 Android internet tablet for its large screen real estate and relatively inexpensive price.

Notable Interface Updates

- Inline notes for each activity step
- Moved ingress and egress to Traverse segments
- Show Time Elapsed instead of Current Time
- Added target in Plan Header to show where executor should be



Activity list where ingress and egress activities are no longer part of a Station Plan Segment



Procedure view with embedded inline notes

OPERATIONAL READINESS TEST

Crafted a wrist-mounted Android tablet

We increased the fidelity of the physical form by crafting a wrist-mounted Android tablet. Our first ORT used a large touchscreen Windows device that participants had to hold in one hand while executing activities with the other. For this ORT, we mounted the prototpye onto participants' left wrist, freeing the second hand for activity execution. The hardware buttons were not quite ready, so we used soft touch buttons on the edge of the screen to prototype the interaction.

In addition, we recruited a repeat participant from the last ORT to gauge expert performance. We adjusted the traverse times so there is barely enough time for each participant to complete all activities.

Refined the ORT with time adjustments and point system

We shortened traversal times to increase the percentage of time spent on station activities using the mobile execution device. We also shortened the plan by 10 minutes in order to force executors to more closely monitor their progress against the plan and increase the likelihood of a replanning scenario.

In addition, to encourage participants to re-plan and use voice notes, we added a point system: 1 point for each scheduled activity, 2 points for good voice notes, and 4 points for each priority activity. We automatically disqualified participants if they returned late to basecamp.

The participant reassembles the sensor according to the picture on the device

The Archos tablet mounted to a wrist

Point system sparked competition

The point system worked well in motivating participants to complete activities correctly and record voice notes. In addition we quantified how accurate participants' completed the plan using the point system.

Voice Notes are a source of confusion

Voice Notes continued to be a source of confusion. Participants didn't find a need to be making a voice note versus verbally talk to Ground via the loop.

> *"It was really easy to just see if the [Time Left] text is red. If it is, I know, oh, I'm late."*
>
> *User 2 tracking time (7/9/2010)*

TOP FIVE ISSUES

For a complete list of findings, see Appendix C, pp. 134

FINDING	DESIGN IMPLICATION	SOURCE(s)
1. Missed Procedure	Highlighting Color, Change name to Activities, Procedures come in from the side and don't cover, change color of the background, show a toggle buttons, hide the breadcrumb, Change the way we do notes	U1: Did not know if he was looking at the procedure or the timeline so he missed a step. Also said this in debrief with a suggestion to show a "Timeline / Procedure" Toggle U2: Was unsure if she was looking at procedures or activities
2. Blue Highlight Seemed Touchable	Add hardware, also reduce spacing between list items, shrink texts a bit more, change color	U1: Kept trying to touch the selected activities U2: Kept trying to push the activity
3. Notes Similar to Steps	Extend the procedure instead of intending it, change the style of notes, change the highlight of the notes, fix scrolling to top	U1: When he had notes expanded, he treated them like steps
4. Didn't Look at Traverse for Directions	Put a map in the traverse views, bring pictures to be more relevant or treat directions differently than activities (pedestrians)	U3: Said "Didn't look at directions in traverse" during debrief
5. Voice Notes Unclear	Scrap voice notes, change ORT back to voice note for describing activities	U3: "What makes a good voice note?" U1, U2, U3: Unsure of when to take voice notes

PROCESS

FINAL ITERATION

Summary: Final Iteration

In preparation for Landing Day, we further refined our prototype. Specifically, we finished the hardware implementation and installed every component (display, buttons, micro-controller, bluetooth, etc.) onto the cuff-mounted prototype.

Removed Voice Notes

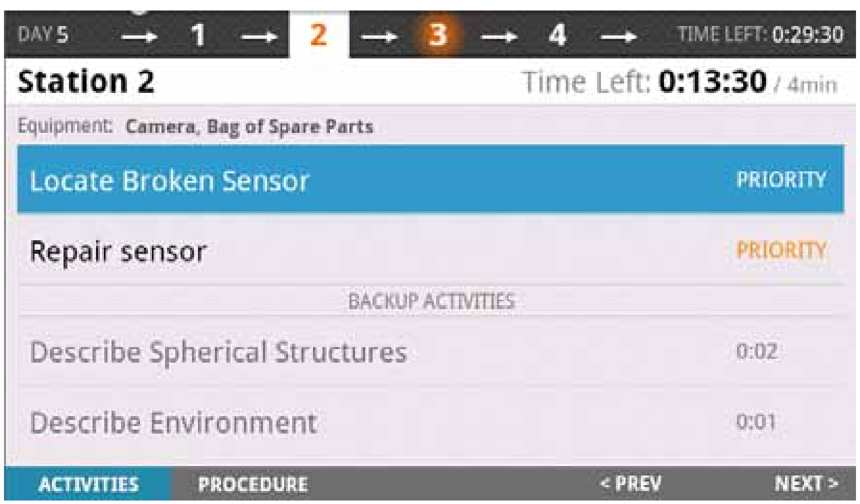
The Voice Notes feature has been a consistent source of usability and workflow confusion for our ORT participants. We at one point clarified the use case with our contact from Desert RATS, but it was difficult to encourage ORT participants to use the voice notes feature, even with a high reward. What is more, consistently refering back to the deive to take voice notes resulted in plan errors and wasted time. We maintain that since all video and audio from extravehicular activities are recorded, it is just as easy, if not easier, for astronauts to mark a certain point in execution history using a verbal keyword to instruct his ground support.

Refined the Android application interface

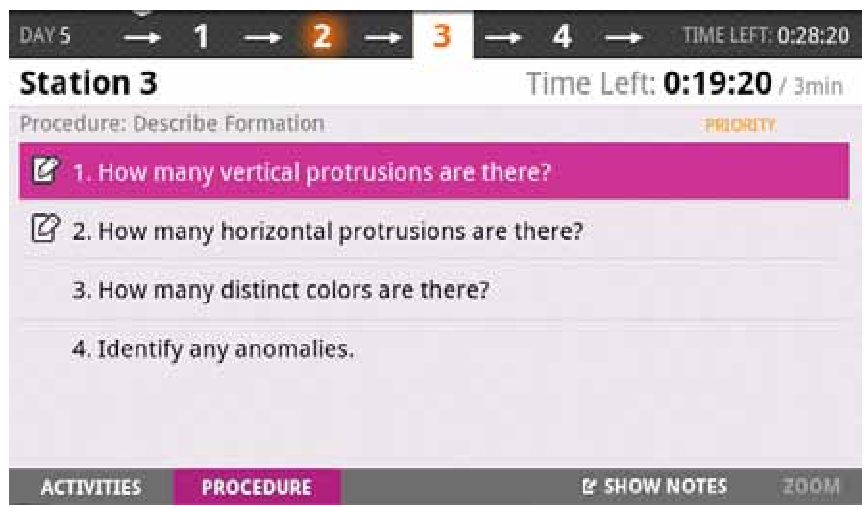
From our existing code base we continued to refine the user interface with the evaluation of the previous iteration. To prepare for interfacing with Arduino, we removed the touchscreen buttons from the previous iteration, and replaced them with physical LED buttons

Notable Interface Updates

- Removed of the Voice Notes feature
- Changed the selection color for procedure steps from blue to purple
- Added the Equipment List for each station
- Changed the mission time from Time Elapsed to Time Left
- Added the Zoom capability for images in Execution Notes



Activity List with a smaller, non-beveled blue selection to discourage touching the screen



Procedure Viewer with the new purple selection color

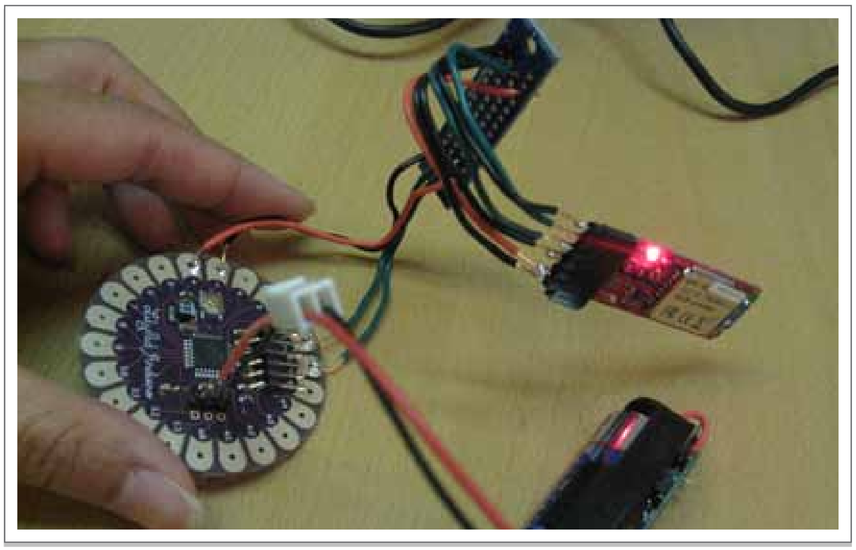
HARDWARE DEVELOPMENT

Hardware development to interface the external buttons with the Android tablet was critical for the final iteration of our prototype. The main components of hardware we needed for our design included: a Arduino LilyPad micro-controller, a BlueSmirf Gold bluetooth module, several LED push buttons, and the Archos 5 Android internet tablet. The LilyPad communicates button push events to the Archos 5 via the BlueSmirf bluetooth module, and the Archos 5 device receives the data and responds appropriately to the input.

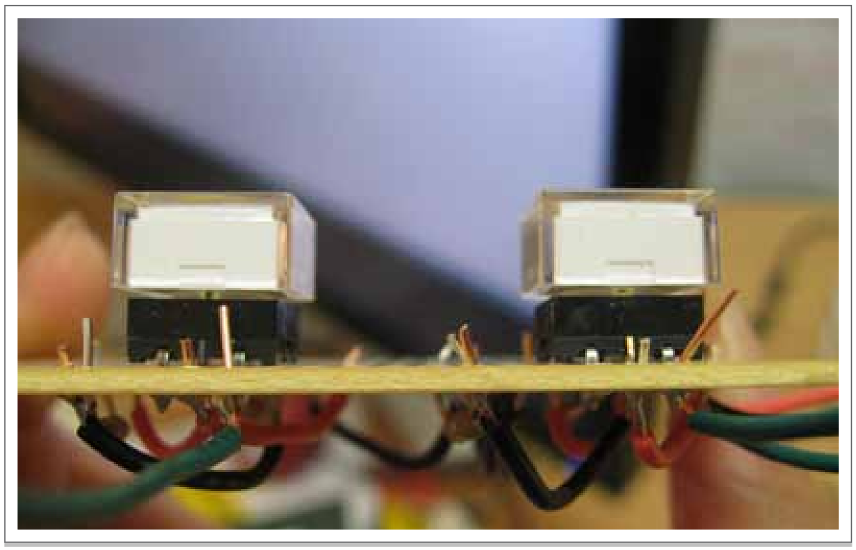
We wired the Arduino and bluetooth modules onto a small circuit board and powered by one AA battery, which is converted to the proper voltage for the LilyPad Arduino (3.3 volts). We also soldered LED buttons onto a circuit board and connected them to the LilyPad.

> *When we completed development, we found that the buttons correctly navigated the interface from up to 40 feet away*

Designing the hardware took us several weeks in total. We needed to be sure that it worked flawlessly, which was a tricky process when handling the bluetooth module. When we completed development, we found that the buttons correctly navigated the interface from up to 40 feet away. This created interesting opportunities for design, where the buttons could be placed anywhere on the Astronaut's suit to navigate the cuff-mounted interface. However, in the end we decided to stay with our original design of attaching them close to the device for efficiency in labeling the programmable buttons.



We connected and powered the Arduino micro-controller (LilyPad) and bluetooth component (BlueSmirf Gold).



We designed the hardware such that the LED buttons light up when pushed, giving the user both tactile and visual feedback of a successful interaction.

TARGET USER FEEDBACK

Received expert feedback from an Astronaut Geologist

[1] Persona, pp. 21

Throughout the summer semester, we had been in constant contact with a Desert RATS crew member and geologist from the Smithsonian. He provided us with the initial plan data and helped us vet the validity of our persona [1].

He paid us a visit during Landing Day and we demonstrated our finished prototype. We also showed him a picture album from the previous two ORTs to present our evaluation method. During our discussion, he pointed us to an artist's rendition of an electronic cuff-mounted checklist and thought that our prototype was a great proof of concept: "It looks like you guys made it real!"

A few of the features he especially liked:

- Short, concise description of the activities that act as reminders
- Ability to see more detailed procedure information via Execution Notes
- Ability to zoom in an image in an Execution Note

We explained our decision to remove Voice Notes and he agreed with our concern. He reiterated that an electronic cuff-mounted checklist should not teach the astronaut how to perform activities during execution, but rather to serve as a reminder. Although a paper checklist works just fine for short missions, a digital version allows for dynamic plan updates, which is almost guaranteed to happen on longer missions.

The geologist evaluating our prototype and giving us feedback

> *"WOW! This device represents exactly how I think. Plus, it's simple and doesn't get in the way."*
>
> *Desert RATS Geologist (7/22/2010)*

OPERATIONAL READINESS TEST

Tested software, hardware, and wearable

The previous two tests focused on testing the usability of the software, which allowed us to refine the interface and confirmed the validity of a wearable, but we had not been able to test the final envisioned prototype until this ORT. We mounted the Android tablet running our software and all of the hardware components on a wrist cuff wearable.

Added a mock space suit to evaluate physical constraints

Introducing the push buttons allowed us to use heavy gloves during the user test. To further simulate the extravehicular experience, we also asked our participants to don a helmet and full mock space suit.

The mock space exploration vehicle

The buttons worked well to accommodate heavy gloves

The cuff-mounted display frees the left hand for manipulating tools

All participants finished with extra time

All three participants finished the 30-minute mission on time and the second and third participants finished with several minutes to spare. Furthermore, participants completed an impressive number of Backup Activities in addition to the planned activities. This is a great improvement compared to the last iteration, where most participants gave up the last station in order to return to basecamp on time.

Synthesized our final user evaluation data

The participants were largely successful and fluent using the final interface. The prototype might have been a bit bulky for some participants, but it was more than adequate in supporting execution during the mock mission. All of the remaining issues (see below) were either minor or based on personal preferences.

> *"At this point, it's just personal taste, not the overall usability. I think this is pretty great already."*
>
> *User 2, finished 2:30 minutes ahead (7/22/2010)*

TOP FIVE ISSUES

For a complete list of findings, see Appendix D, pp. 148

FINDING	DESIGN IMPLICATION	SOURCE(s)
1. Traverse Information Not Shown on Time's Up Dialog	Show information for the last traverse in the dialog	U1: Had to compare notification of 4 minutes left to how long is the last traverse actually allocated to take
2. Traverse Map Was Not Used	Orient maps consistently, with North up	U1, U2, U3: "I didn't look at the map on the device." U2: Confused by the different orientations of the map view between paper and device
3. Confused About Which Activities Have Procedures	This could be marked with an icon or strengthening the dimmed procedure label	U2, U3: "I wasn't quite sure which activities had procedures."
4. Preparation of Plan Not Exactly Representative	Testing the device with more familiar plans and expert users might reveal different usability issues, which would be helpful for future tests on LuMo	U3: "I think the main weirdness was that we didn't get to spend enough time with the plan. Normally, you spend months and months on the plan so you know it really well."
5. Physical Prototype Buttons Too Far From Labels	Put the buttons closer to the labels when constructing the actual device	U3: "In an actual device, the buttons would be closer to the labels than they are now."

CONCLUSION

EVALUATION SUMMARY

Consistent performance improvements

We used a point system to evaluate the performance of each ORT participant for the final two iterations. We awarded points for correctly completed planned activities and backup activities, however, returning late to basecamp resulted in disqualification. Although the point system changed from Iteration 2 to the Final Iteration, after normalization, we found that the average number of points earned rose from **10.3 to 20 out of 23 total points.**

Furthermore, while all three participants from Iteration 2 were unable to finish the mission, all three participants from Landing Day **finished with time to spare**. During the last ORT, we were excited when participant 2 (a repeat participant) returned to basecamp with nearly three minutes ahead of schedule. When the last participant, who was testing our device for the first time, finished with four minutes to spare, we knew that all of the design adjustments had been validated.

Returning to the design guidelines

To further gauge the success of our project, we can evaluate our final design against the design guidelines we established in the beginning of the design phase [1].

Delta between Plan and Execution

Many features satisfied this guideline, including the Marcus-Bains Notch, Mission Time Left, and Station Time Left [2]. The advantages of having this redundancy was two-fold: users were always aware of whether they were early or behind schedule and used the appropriate feature depending on discrepancy between the schedule and execution.

> *"When I was ahead, I found the [Mission] Time Left to be more useful."*
>
> *User 2, Final Iteration (7/22/2010)*

[1] Design Guidelines, pp. 18

[2] Design: Header, pp. 32

Participant from the Final Iteration ORT giving her partner a high-five after completing the 30 minute mission with more than 4 minutes to spare.

ORT: Operational Readiness Test

EVALUATION SUMMARY

OSTPV: Onboard Short Term Plan Viewer

EVA: Extravehicular Activity

Timeline Optimized For Execution

Compared to OSTPV's bird's eye view of the plan, our design is much easier for an astronaut to digest because it contains only the most relevant information. A cuff-mounted paper checklist achieves the same goal, but is static and not able to accommodate dynamic plan changes.

With the help of the Equipment List, no participant from the final ORT spent time returning to the space exploration vehicle to fetch forgotten equipment, as those from previous iterations often did. The ease of browsing and looking ahead during egress and ingress allowed participants to rehearse prior to arriving at the station. Participants from the final ORT not only finished all of the scheduled activities correctly, but also were able to complete many of the backup activities.

Another advantage of the digital medium over paper is the availability of images and visuals. Images can be shown small or large, via the zoom functionality.

> *"It was A LOT better than last time. I liked how the items were needed were always on the screen."*
>
> *User 2, Landing day (7/22/2010)*

Autonomy When Appropriate

We witnessed ORT participants make real-time changes to the plan throughout testing. Those running late maintained situational awareness of the plan and knew when to return to basecamp. Those ahead of schedule were able to view backup activities and make real-time decisions about what could be accomplished. Participant 2 from the Final Iteration even performed activities out of order.

We observed participants give higher precedence to activities with a higher priority. For example, user 2 from the second ORT left a station early after completing the priority activities there because he was running late. Our geologist contact from Desert RATS also confirmed the observed user need for the priority feature.

> *"Having images is great. You're tired, exhausted, have a million things to talk about so visuals are very helpful... I really like the zoom."*
>
> *Desert RATS Geologist (7/22/2010)*

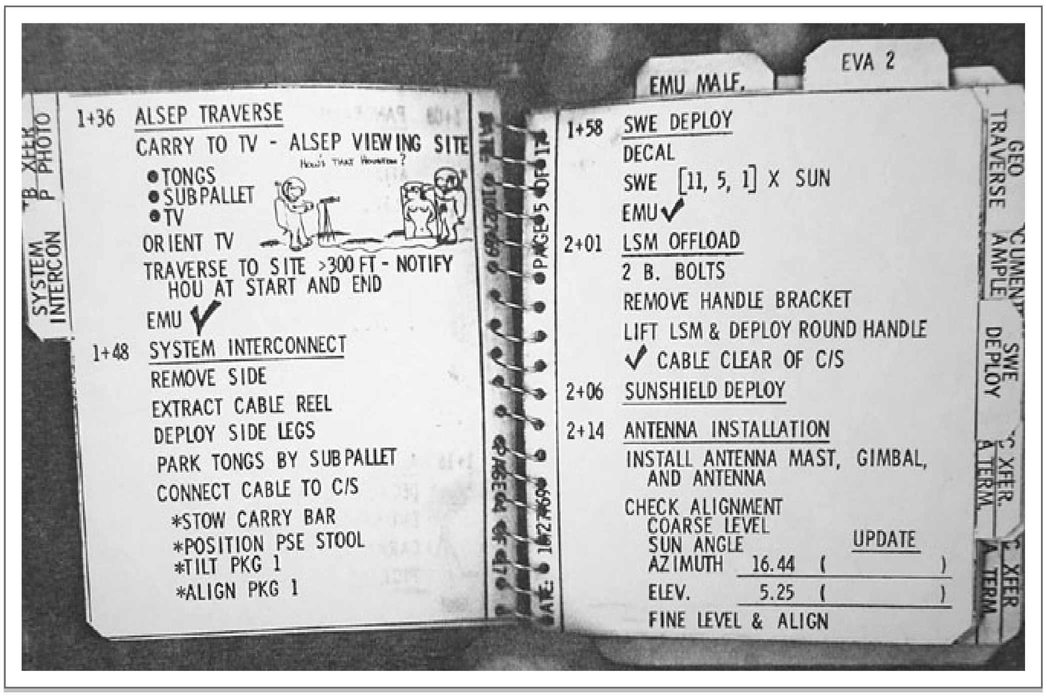
A repeat participant has extra time for back-up activities this time around

Glanceable and Unobtrusive

Station Time Left was the most successful feature in terms of glanceability. A quick glance at its color told the ORT participants about whether they're ahead or behind.

The large text used in the Activity List, often in short hand, made it not only easy for expert users to rehearse during egress, but also provided quick "cues" when participants forget. Our Desert RATS geologist compared it to the shorthand style used during the Apollo EVAs.

> *"I really like the red text, it sticks out. I can see, 'oh shoot, we're out of time.'"*
>
> *User 2 from ORT 2 (7/9/2010)*



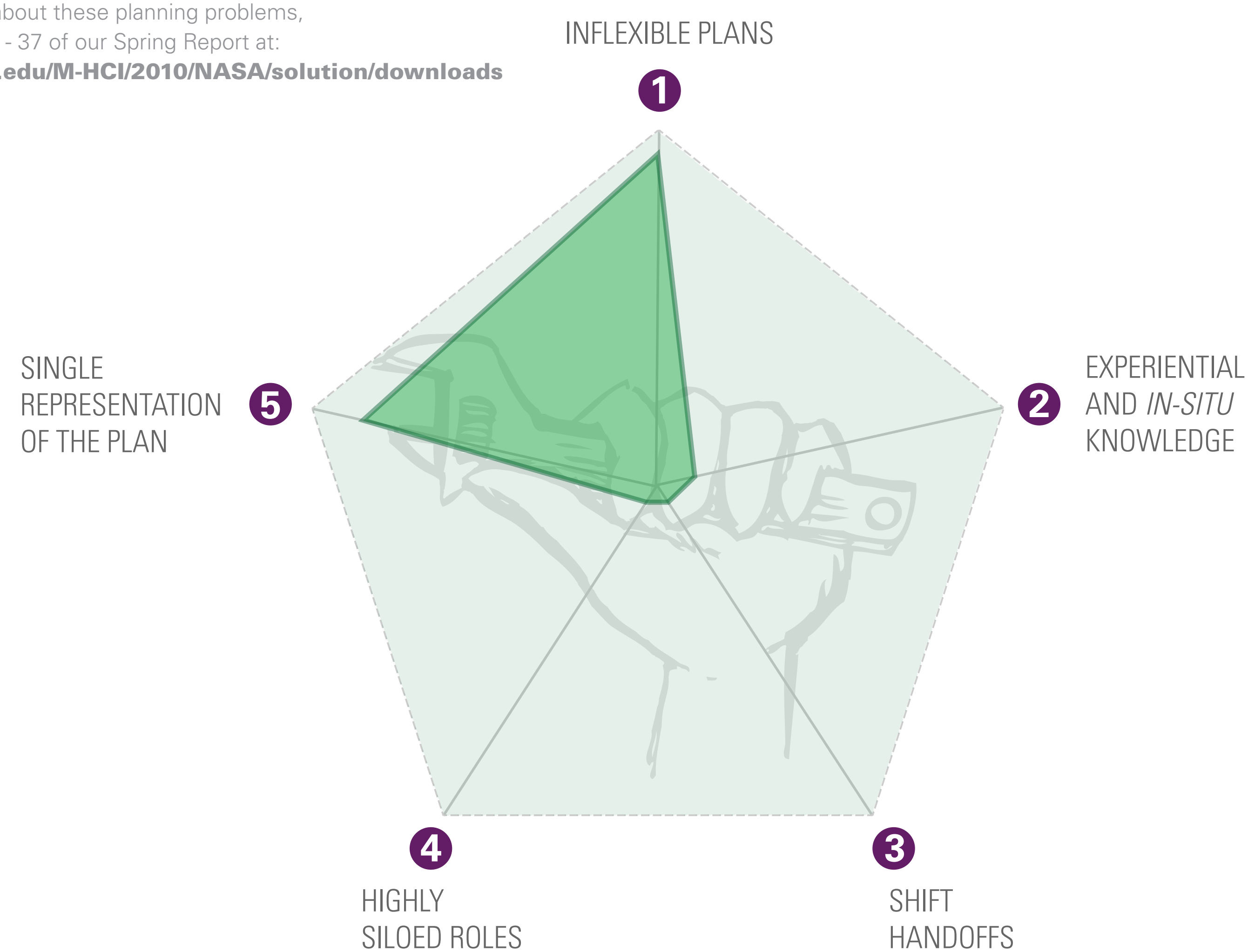
Paper checklist used during the Apollo EVAs.

CONCLUSION

FUTURE RESEARCH: PROBLEM SPACE

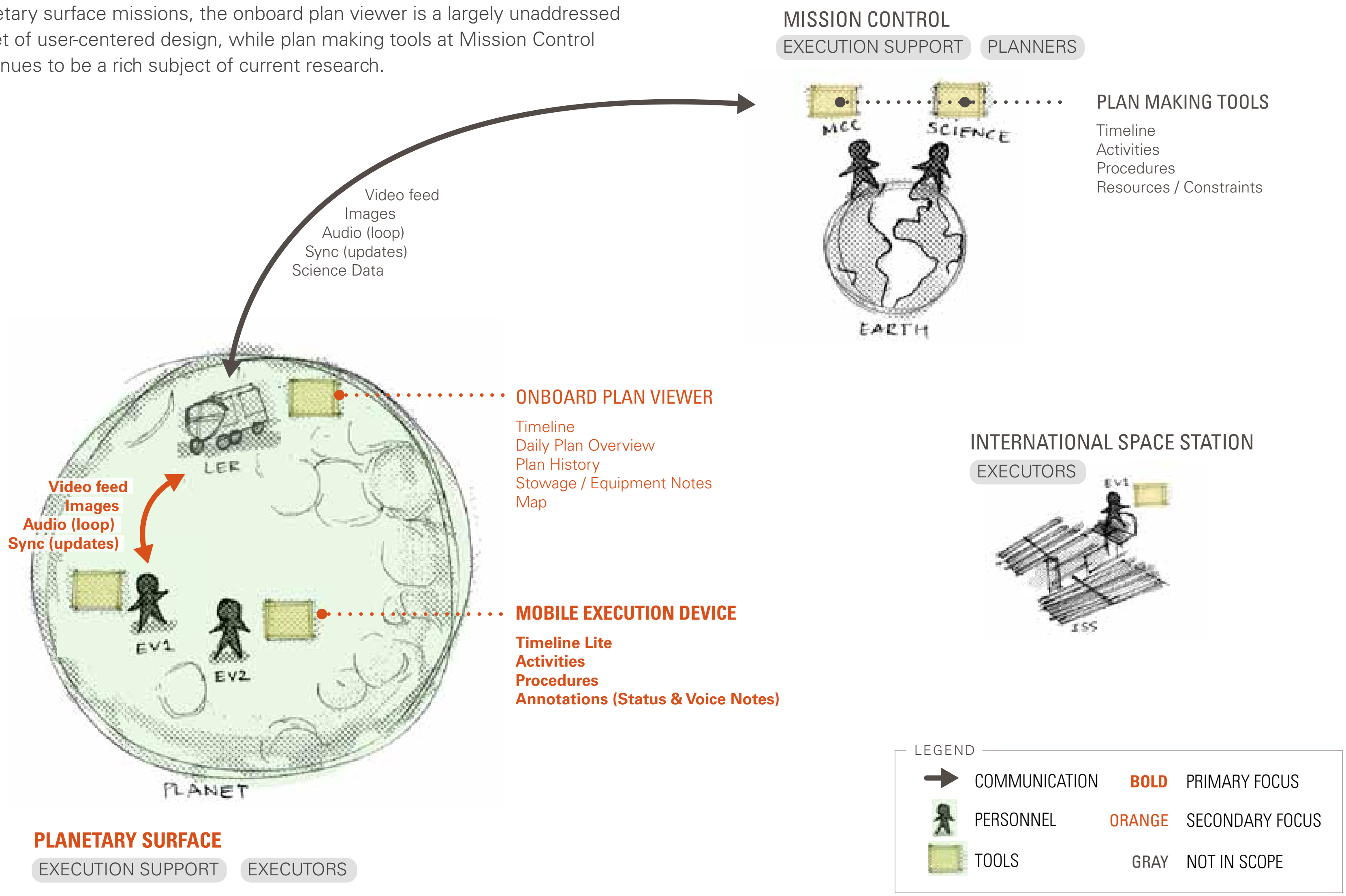
As described before, LuMo only focused on two out of the five planning problems we identified during our spring research. It would be prudent for future research to delve deeper into the other three planning problems: Experiential and *in situ* Knowledge, Highly Siloed Roles, and Shift Handoffs.

For more details about these planning problems, please see pp. 23 - 37 of our Spring Report at: **www.hcii.cmu.edu/M-HCI/2010/NASA/solution/downloads**



FUTURE RESEARCH: ECOSYSTEM

Our project focused on mobile execution for planetary surfaces, however there are components of the ecosystem that remain targets for future research For planetary surface missions, the onboard plan viewer is a largely unaddressed target of user-centered design, while plan making tools at Mission Control continues to be a rich subject of current research.



CONCLUSION

FUTURE RESEARCH: PLAN MAKING TOOLS

Much of our user research explored mission planning rather than execution, where we observed many opportunities for further optimizing plan making software. With LuMo, we addressed two of the five major problems identified from our research, however, three open planning problems that relate to planning making tools are:

See pp. 32-35 of our research report for more detailed descriptions, evidence, and recommendations for these three opportunities at **www.hcii.cmu.edu/M-HCI/2010/NASA/solution/downloads**

The difficulties of communicating experiential and in situ knowledge result in uninformed plan making.

Internalization of soft constraints gained from experiential knowledge supports a very efficient workflow for experienced planners. Some recommendations to externalize this knowledge are:

- Spread knowledge through shared work context
- Capture and expose knowledge where possible
- Offer contextual help to novices

Shift handoffs within roles often involve poor information transfer, resulting in poor situational awareness and increased operating expense.

Knowledge of events of a previous shift affects decision making in the next. Shift handoffs are a common mechanism to facilitate the transfer of information between individuals.

- Streamline shift handoffs
- Foster understanding between shifts
- Automatically integrate shift handoffs during execution

Dependencies between highly siloed roles ungracefully accommodate human error, which has cascading effects.

The multiple roles and tools required to create and update a single plan promotes input errors that go unnoticed until execution is impacted.

- Reduce diffusion of responsibility
- Consolidate tools to reduce human error
- Establish understanding and awareness between different roles

Mission Control Center at Johnson Space Center in Houston, Texas

The flight director's work station

FUTURE RESEARCH: ONBOARD PLAN VIEWER (LUMO+)

The smooth operation of LuMo assumes there is an existing interface in the space exploration vehicle, fully optimized to support the mobile device. We call this viewer LuMo+ and would sync with the mobile execution device in real-time. This is a realistic expectation when we look at the capabilities of today's technology and the current efforts to advance technology.

LuMo+ would provide all of the information found in the mobile execution device in a way that is optimal for the vehicular environment. It would also support features that are not in the mobile device.

These features are grounded in our user research include:

- Equipment Checklist
- Map View
- Plan History (Pictures, Voice Notes)
- Connectivity with Ground
- Input Personal Notes
- Both Crew Members' Schedules

The smooth operation of LuMo assumes there is an existing interface in the vehicle, fully optimized to support the mobile device

The habitat vehicle used during analogs at Desert RATs

Inside the vehicle during a Desert RATs analog

FUTURE RESEARCH: INTERNATIONAL SPACE STATION

EVA: Extravehicular Activity

While LuMo is optimized for planetary exploration, we briefly explored the prospects of EVAs on the International Space Station (ISS). Both environments substantially differ, however, each involving different types of activities, procedures, and tools, which ultimately result in different workflows. This disparity between the two drove us to focus on just one: planetary exploration. This leaves an open opportunity for further research to develop a mobile device for use on the ISS.

> *Unique workflows on the ISS leave an open opportunity for further research to explore a specialized mobile execution tool*

The International Space Station (ISS)

An astronaut performing an EVA on the ISS.

FUTURE RESEARCH: PLANETARY SURFACE MISSIONS

There are many opportunities for further research into mobile execution for planetary surface missions beyond what LuMo currently offers.

Replanning during communication blackouts

LuMo is currently a read-only mobile device. In our initial brainstorming, we explored the prospect of allowing astronauts to individually or corroboratively re-plan and propagate changes to the plan. While exploring this phase, we determined that designing an plan editing tool was outside of our project scope. Finding the best solution to allow the crew to modify the plan while mobile and without interrupting their workflow is a currently unaddressed research effort.

Completion status without interrupting workflow

Our user research suggested that communicating completion status from the field to Mission Control beyond existing verbal methods could be a useful feature. Presumably, this allows for better situational awareness among the many disparate roles involved in the team. Signaling completion status without requiring extra effort or a more complex workflow is a challenging problem to address.

Space Suit and Hardware constraints in planetary environments

As a prototype and proof of concept, our device is obviously not optimal for immediate use on planetary exploration. While we developed a device that can be mounted on an astronaut's arm, we are not human factors nor ergonomics specialists and have not extensively designed or tested the device in that aspect. Providing the best industrial design and hardware specifications suitable for space missions for the device is another interesting area that warrants further investigation.

LuMo digitally added into an artist rendering created for NASA by Pat Rawlings ©1995

ABOUT US

Our design team is comprised of five Carnegie Mellon University Masters students in the Human-Computer Interaction Institute with multi-disciplinary backgrounds including computer science, information systems, mathematics, communication design, and cognitive science.

Katy Linn
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Katy Linn is working toward a Masters Degree in Human-Computer Interaction at Carnegie Mellon HCII. She holds an Bachelor's Degree in Computer Science and Mathematics from Vanderbilt University. She most recently worked for Microsoft as a Software Development Engineer on the Solution Development Platform Team of Office Live Small Business. Outside of the office, Katy enjoys soccer, singing, and science fiction.

Christine Wu
Technical Lead
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Christine Wu is currently a masters student at Carnegie Mellon's Human-Computer Interaction Institute. She grew up in California and received her undergraduate degree in Computer Science from UC Berkeley. Prior to attending CMU, she worked at VMware for seven years as a developer, shouldering responsibilities from UI design to UI development. In her spare time, she enjoys reading, shopping, traveling and sharing good food with family and friends. On her recent trip to New Zealand, she swam with dolphins in the southwest Pacific Ocean.

Jesse Venticinque
Design Lead
jdventi@gmail.com

Jesse Venticinque, a Bay Area native, earned a B.S. in Cognitive Science and a Specialization in Computing from UCLA in 2007. Shortly after graduation, Jesse joined Google to battle web-spam and improve search quality, but quickly moved on to Predictify, a Bay Area startup providing a prediction platform that adds an interactive, forward-looking dimension to current events. As the sole UI Engineer, he led interaction and graphic design, user experience and front-end development. Outside of HCI, Jesse enjoys Bay Area sports, cycling, and current events.

Jennifer Lu
User Research Lead
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Jennifer Lu is a recent graduate from UCLA with a B.S. in Cognitive Science and a Specialization in Computing. During undergrad, she worked in the UCLA Statistics Department on various web development projects and conducted cognitive psychology research at UCLA's learning and memory lab. In her spare time, Jennifer enjoys gaming, playing her recently purchased ukulele, cooking/baking, and learning new things. When she was still in shape, she danced for 26 hours to fundraise for the battle against pediatric aids.

Noah Levin
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Noah Levin is currently an Accelerated Masters student at Carnegie Mellon finishing up a B.S. in Information Systems and Human-Computer Interaction with a minor in Communication Design. For the past two summers he worked as an Interaction Designer for a local strategic design consulting firm, LotterShelly, doing work for such clients as PNC Bank, Carnegie Mellon, and GigaPan Systems. Outside of HCI, Noah plays bass and sings in a folk-rock band, loves to row (kayaking and crew), and once appeared in a Sour Patch Kids commercial.

ACKNOWLEDGEMENTS

This project would not have been possible without the help of many individuals throughout our eight-month project. We would like to thank each and every one of you for your time and thoughtful contributions.

Special thanks to our faculty advisors at Carnegie Mellon University for guiding us through the design process and continually encouraging us to go the extra mile. We would like to thank our client at the NASA Ames Research Center for giving us this opportunity and for providing us with the necessary resources and support to carry out our vision from start to finish. In addition, we would like to thank our spring research participants for allowing us to gather valuable data to digest the complexity of real-time planning and execution. We also thank our summer user test participants for helping us evaluate our user interface, especially our repeat participants for allowing us to simulate expert users.

Finally, we would like to thank you — our reader — for taking the time to learn about LuMo and the thought behind it. We hope you found our research insightful and our design useful.

For additional information about our project, please visit our website at **www.hcii.cmu.edu/M-HCI/2010/NASA** or contact us at **info@teamlumina2010.com**.

For additional information about our program, please visit the HCI website at **www.hcii.cmu.edu/masters-program**. If you would like to speak with our faculty about future project opportunities, you can directly contact the Director of the Masters in Human-Computer Interaction:

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APPENDIX A

FIRST ITERATION

NASA's Desert Research and Technology Studies (RATS) program investigates planetary surface exploration concepts, such as manned rovers, planetary EVA timelines, and remote communication with Ground support. For the Desert RATS team, we designed and prototyped the a timeline viewer for a cuff-mounted device worn by astronauts during EVAs. We started by interviewing a former Desert RATS crew member, and held a brainstorming session of mobile timeline ideas. We developed our brainstorming ideas into four timeline concepts, conducted Speed Dating for concept validation, and created an HTML prototype.

DOMAIN RESEARCH

Retrospective Interview

On May 12, we held a conference call with a crew member from the 2008 and 2009 Desert RATS missions. From this phone call, we were able to gain a the domain knowledge of the end-to-end Desert RATS scenario from an executor's perspective. Our discussion revolved around a few themes:

- Life aboard the Lunar Exploration Rover (LER)
- Information flow between the crew, planners, and science backroom
- Collaboration between crew members
- Physical constraints of the space suit
- Dynamic re-planning due to unforeseen circumstances

Findings from this discussion fed directly into our persona and scenario, which we were also able to validate with this crew member.

> *"A checklist helps for when you might get distracted. There's always the chance that something comes up and knocks you off your game."*
>
> *Desert RATS Crew Member (5/12/2010)*

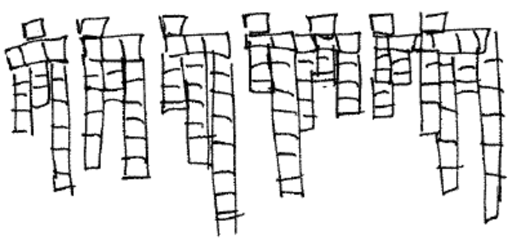
The Lunar Exploration Rover exploring the Arizona desert.

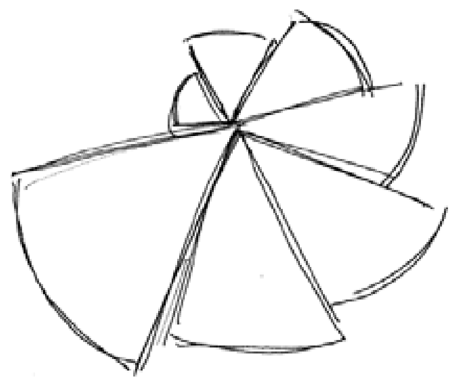
DESIGN GUIDELINES

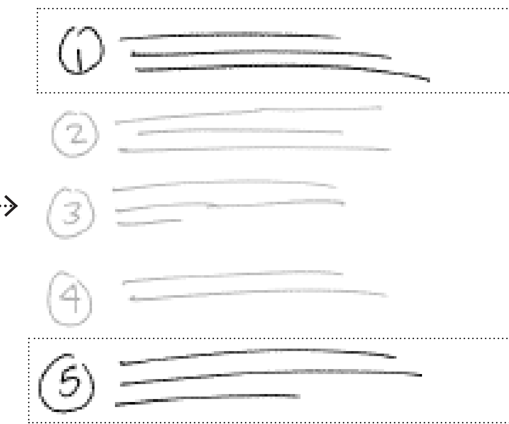
From our research findings we derived four guidelines to direct the design of a mobile execution tool for planetary surface missions. The steps in the process of research synthesis to creating these guidelines are illustrated below.

RESEARCH INSIGHTS

PROBLEM STATEMENTS







AFFINITY DIAGRAM

We collected over **300 findings** from our user research, literature review and competitive analysis. This affinity diagramming shows the many different categorizations of the data. One example of a finding was that Astronaut's do not necessarily care about all of the information that the ground needs to create the plan.

7 HIGH LEVEL CATEGORIES

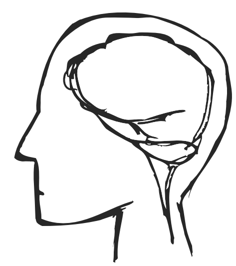
To illustrate the vast amount of data from our findings effectively, we created a visualization that shows the relative importance of each of the **7 categories** with size. Importance was determined by the impact and feasibility of solving the planning and execution. The categories include Tools, Execution, and Plan Updates.

5 PLANNING PROBLEMS

Five central planning problems were extracted from all of our research findings. Two of which were especially relevant toward our design focus in mobile execution:

Inflexible plans fail to capture the variable nature of execution.

Single representation of the plan fails to accommodate the varying needs and responsibilities across roles utilizing the plan.



4 KEY DESIGN GUIDELINES

Delta between Plan and Execution

Due to unforeseen circumstances, execution may be ahead or behind schedule. The delta is the difference between the ideal planned state and the current reality of execution. [1]

Timeline Optimized for Execution

Astronauts and planners have very different goals when viewing the timeline. A timeline optimized for execution displays planned activities in a way that matches an astronaut's unique workflow. [2]

Autonomy when Appropriate

Though many activities are constrained by sequence or time, several are not. Autonomy allows astronauts to execute activities as appropriate to the environment of execution. [1]

Glanceable and Unobtrusive

An execution device should support, rather than burden the astronaut's workflow. It should be helpful when needed but not require additional or unnecessary interaction. [3]

[1] Inflexible Plans

[2] Single Representation of the Plan

[3] May 12th Interview with Desert RATS Crew Member

BRAINSTORM

We began our process by brainstorming 50 ideas for visualizing an optimized timeline for the Desert RATS mobile device. We constructed a very crude physical mock-up with readily available materials to understand the physical nature of the envisioned device. While many of the brainstormed concepts departed from a classic timeline structure, all aimed to communicate the plan as structured by sequenced activities.

> *While many of the brainstormed concepts departed from a classic timeline structure, all aimed to communicate the plan as structured by sequenced activities*

Brainstorming with a physical mock-up of the Desert RATS mobile device

50 timeline visualization ideas on the whiteboard

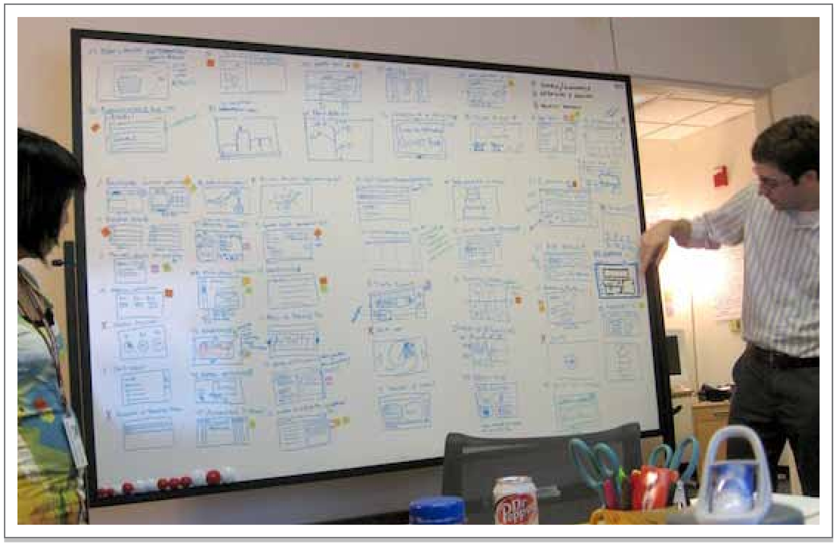
TEAM & CLIENT EVALUATION

After reviewing our concepts internally, we presented all 50 ideas to members of the NASA Ames Human-Computer Interaction (HCI) group to get early validation and feedback. We briefly led them through the Desert RATS scenario and persona for context and had them vote on what they thought the most successful ideas were based on their background in planning and execution. Using their insightful feedback, we fed our brainstorming ideas into four more refined concept sketches.

Each of the 4 sketches, presenting in the following pages, illustrates the information structure of the concept, some of the interactions, and the structure of the workflow. We named them after how they structured time:

- Split View
- Paper Towel
- Bar Chart
- Station-Centric

We presented all 50 ideas to [experts] to get early evaluation and feedback



Presenting the 50 sketches to member of the Ames HCI group

Our clients from the NASA Ames HCI Group voting for their favorite ideas

CONCEPT SKETCHES: SPLIT VIEW

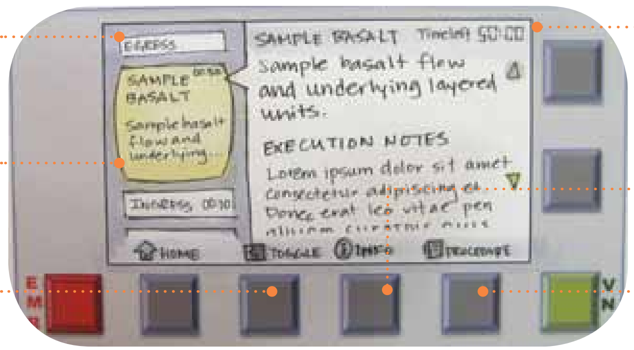
The timeline is displayed side-by-side with in-depth information about the currently selected activity. In the timeline, most of the screen real estate is devoted to the currently selected activity. The right hand side shows in-depth information about that activity, like Operation Notes and step-by-step Procedures.

TIMELINE VIEW

The left column displays all the activities for the day, with the current activity (by time) enlarged

The system highlights what is currently selected

Toggle button switches between the left and right columns



The time left for the selected activity. Time starts when the procedure is selected

Info button displays activity details

Procedure button displays step-by-step procedures for the selected activity.

PROCEDURE VIEW

Current step / total steps

High-level overview of this step in the procedure

The down arrow 'jumps' to the next step.

FEEDBACK

Pros

- Timeline design is less "pushy", while Time Left is very useful
- Tutorial-like procedures are appropriate due to cognitive impairment in space
- Right side is suitable for detailed instructions
- Detailed text for an activity is readily available in case the astronauts need it

Cons

- The timeline on the left takes up too much space. It's not obvious how to coordinate between two astronauts.
- The design does not convey whether the astronaut is ahead or behind.
- Egress and Ingress happen all the time - may not be worthwhile to show.
- Toggle button is almost guaranteed to cause confusion

Recommendations

- Keep the timeline for context, but reduce its size
- Try to convey priority to inform decision making when behind schedule

CONCEPT SKETCHES: PAPER TOWEL

The Paper Towel concept presents activities in a sequential stream, with equal emphasis on all activities. Irrelevant activities, such as ones for another astronaut, can be hidden. The name of each activity is shown in large text for quick glanceability. Drilling down into an activity shows that activity's procedures.

TIMELINE VIEW

ACTIVITY INFO

FEEDBACK

Pros

- The design makes good use of real estate
- List of activities is better for experts because it serve as a checklist reminder
- The big, clear display is very easy to view

Cons

- The 'Show/Hide (collapse)' feature is unnecessary
- The design doesn't convey whether the astronaut is early or behind
- Arrow buttons and 'Back/Next' buttons are confusing
- The timeline does not convey urgency
- The priorities of activities are not shown
- It may not be necessary to show a partner's activities

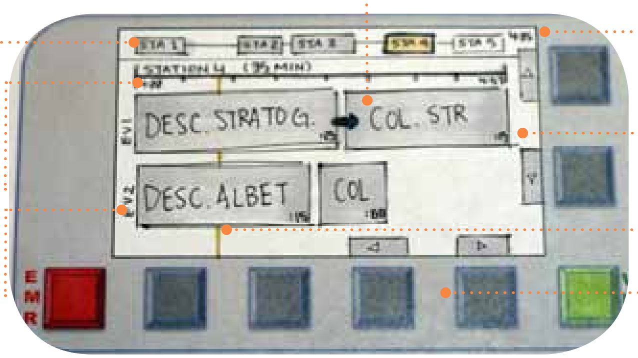
Recommendations

- Show priority using two levels: normal vs important
- Always hide or allow hide-all for partner's activities

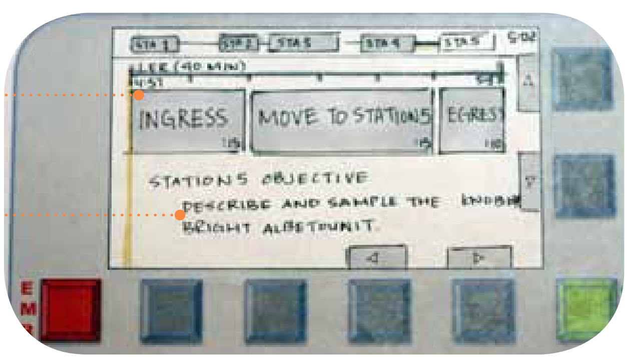
CONCEPT SKETCHES: BAR CHART

To facilitate collaboration, the bar chart shows the scheduled activities for two astronauts on EVAs. The breadcrumb at the top allows the astronauts to gauge their progress by comparing it to the Marcus-Bains line and view the plan for the entire mission day.

TIMELINE VIEW



TRAVERSE ACTIVITY VIEW



FEEDBACK

Pros

- Traverse info shows overall station objectives
- Breadcrumb presents a very useful view of "where you are"
- Marcus-Bains line is good for orientation
- Arrows display sequence constraint nicely

Cons

- 'Up/Down' and 'Left/Right' arrows are confusing
- The meaning of varying widths on the breadcrumb is unclear
- Multiple displays of time are confusing (time elapsed, time start, time end...etc)
- It's not obvious two astronauts are involved
- Segmented Gantt chart display doesn't show overview or detailed info
- The design doesn't convey whether astronaut is early or behind

Recommendations

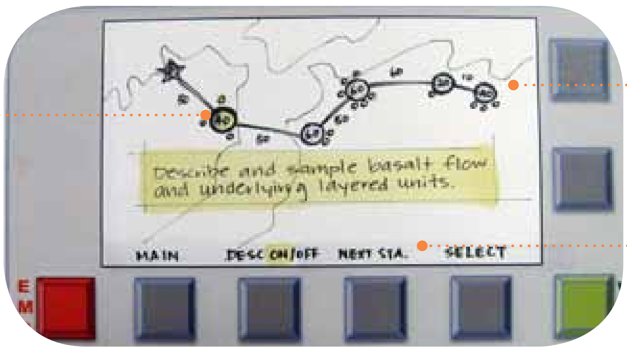
- Present a sense of "progress". Am I ahead?
- Present "Time Left" prominently
- Give more weight to the user's activities and less to his partners

CONCEPT SKETCHES: STATION-CENTRIC

This design attempts to be as time-agnostic as possible. The map view gives astronauts an overview of their day, showing the number of stations and the busyness of each station. Selecting a station or traverse opens a list of activities with procedures displayed inline.

MAP OVERLAY

Bubbles represent scheduled activities



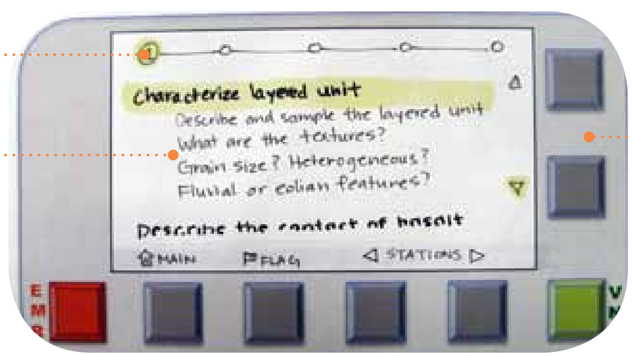
The Timeline overlay shows the "time allocated" for stations.

The button "Next Station" steps through the stations in order.

STATION DETAIL VIEW

A breadcrumb displays the current station

Hierarchical view of activities & procedures.



The "Up" and "Down" buttons step through the procedure, highlighting each step.

FEEDBACK

Pros

- Map overlay is geologist friendly and good for spatially oriented people
- Flagging may be a quick way for 'Crew Notes'
- The dots representing the number of activities are informative
- Map overlay is very glanceable

Cons

- The design doesn't convey whether astronaut is early or behind.
- Directly showing a document in the procedure view is too much information
- The design is too time-agnostic; there is no sense of priority or "where I am"
- This design might be the most difficult to design and implement because of the map interaction

Recommendations

- Convey a sense of priority for each station
- Show at least one piece of contextual time information

SPEED DATING

From Speed Dating results we synthesized one concept grounded in user needs

We evaluated the four concept sketches using a validation method called Speed Dating. We presented these concepts to participants with the purpose of eliciting feedback on features. We tested each of the four paper sketches with four participants, totaling 16 instances of testing overall.

> *We received very useful feedback on features that worked well and features that did not*

From this needs validation session, we received useful feedback on features that worked well in serving perceived user needs and others that did not. With all of our user research in mind, we created a final refined sketch from which we started wireframing and development.

Participant trying out Version 2.0 of the physical mock-up

Explaining each of the 4 concepts to the participant

Speed Dating Summary

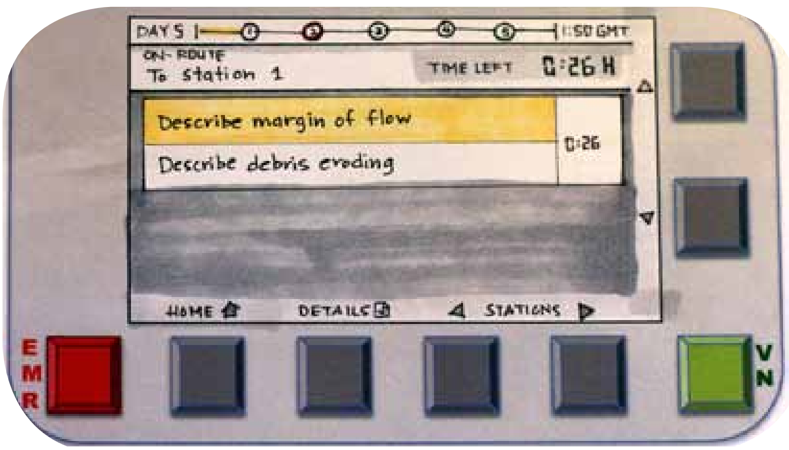
The chart below summarizes our speed dating results and maps the strengths and weaknesses of each concept against the list of features we found to be important. All four concepts lacked "Priority" and "Delta" but each of our participants found these features to be especially useful for dynamic replanning scenarios, where an astronaut needs to compare his progress to the expected progress and make sure high-priority tasks are not neglected. We used these results to create a hybrid structure for the timeline which incorporated the best features of each concept.

	SPLIT VIEW	PAPER TOWEL	BAR CHART	STATION-CENTRIC
Progress	○	○	●	○
Priority	○	○	○	○
High-level overview (day's plan)	○	○	○	●
Low-level details (activity execution)	●	●	○	○
Activity constraints	○	○	●	○
Glanceability	●	●	○	●
Current status	●	○	●	○
Delta (ahead vs. behind)	○	○	○	○
Summary	Large display is easy to read and glanceable, but the timeline is less relevant in the midst of execution	Large text is easy to read, but the interaction and sense of time need improvement	Breadcrumb and horizontal timeline are intuitive, but the information shown is neither high-level nor low-level	Map view is friendly for geologists, but it too time-agnostic

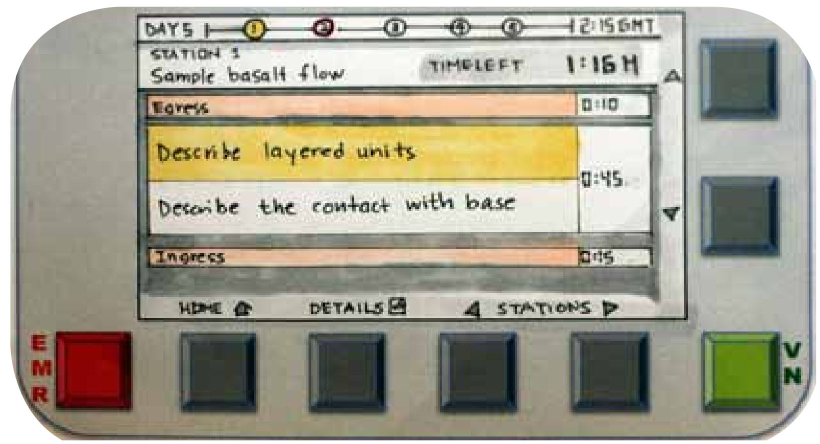
LER: Lunar Exploration Rover

LOW-FI SKETCHES

We synthesized the Speed Dating results to create the following concept for the structure of the timeline, which represents a hybrid of the best aspects of each of the four concepts. Activities are bucketed by station (Station-Centric), and each station presents a stream of activites (Paper Towel). We also preserved the Segment Navigator (Bar Chart) and Time Left (Split View) which were well recieved by every participant.



The list of scheduled activities while astronauts are driving in the LER on their way to Station 1



The list of scheduled activities for th EVA at Station 1

HTML DEVELOPMENT: DESIGN RATIONALE

We developed an HTML prototype to deliver to the Desert RATS team. We also designed a scenario to help illustrate the significance of the Segment Time Left which was shown statically in this first prototype. We used our research findings, design guidelines, and user evaluation to help drive design discussions as we increased the fidelity of our initial concept.

SEGMENT NAVIGATOR

The Segment Navigator serves two main goals. It provides context when looking at specific portions of the plan, and displays an overview of the day. Our Speed Dating results indicated that while useful, it should be small, so that the majority of the screen real estate be devoted to the more detailed activity listing. Also, we chose this simple Segment Navigator over other mechanisms to provide overview (like the map overlay) because the crew members would already have a good sense of the day's plan before execution, and would have access to the onboard computer in the LER if they need to dive deeper [1].

SEGMENT TIME LEFT

The Segment Time Left gives crew members a sense of progress. Speed Dating participants found it useful and encouraged us to display it prominently, despite obviously limited screen real estate. Because manual status updates are burdensome for crew members, it is difficult to know exactly where they are in the plan, or if they are ahead or behind. Segment Time Left is calculated based on the time of day and the activity that is currently being viewed. If the allotted time for a station has elapsed, the time left is negative, indicating to the crew that they should hurry to get back on schedule [2].

ACTIVITY LIST

The final design of the Activity List is most like the original design of the Paper Towel concept. Our Speed Dating participants found that it was the best use of screen real estate. Differently sized activities (from Split View or Bar Chart) convey the relative lengths of activities, but do not make the best use of screen real estate in the case of very long or very short activities. We modified the Paper Towel view to shrink the real estate used by the Egress and Ingress activities. One Speed Dating participant suggested leaving them off entirely since they are so common and screen real estate is so limited [3].

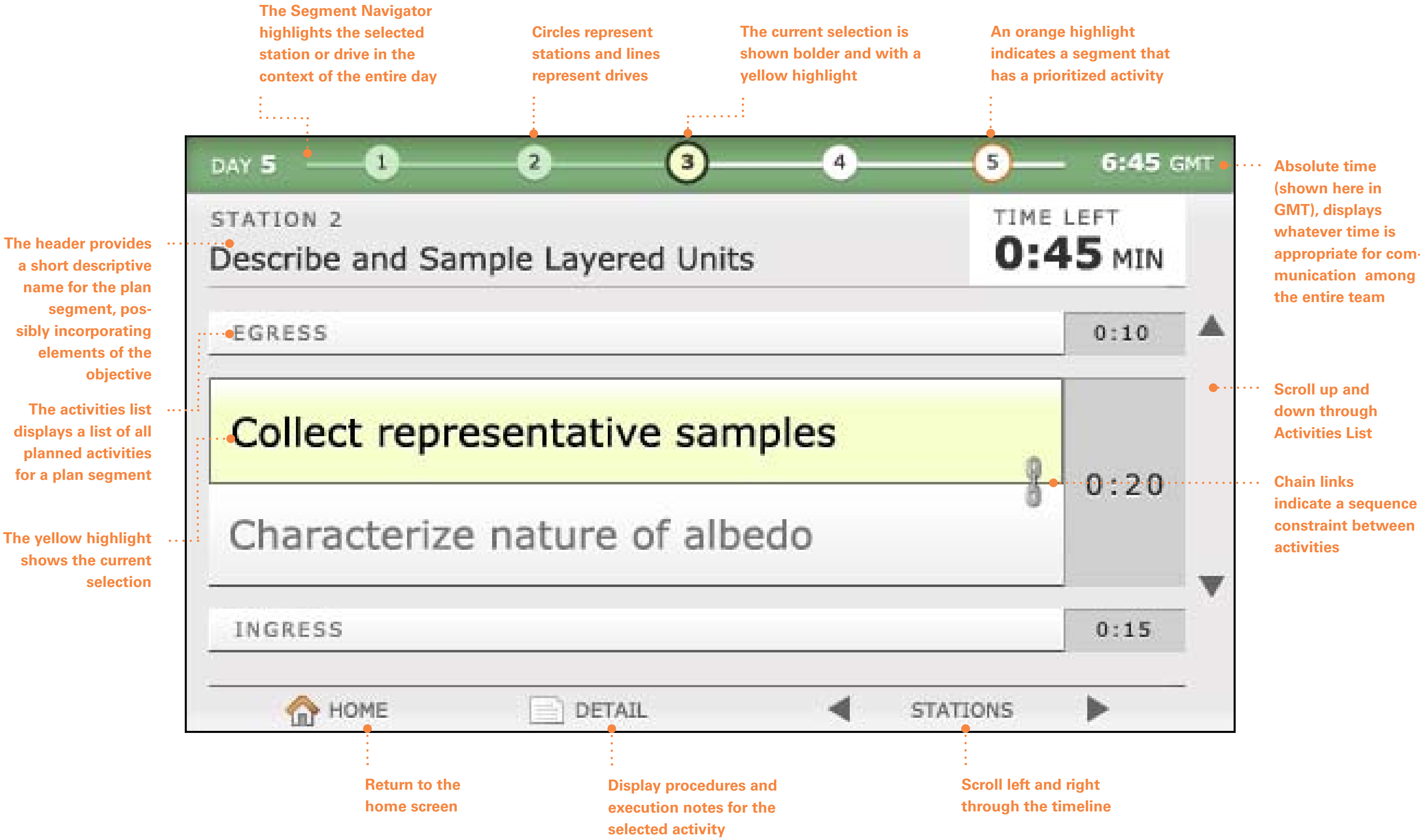
PRIORITY INDICATOR

One major point of feedback from Speed Dating was that none of our original concepts conveyed any sense of the relative priorities of the different activities. Because the plan is so rarely executed perfectly, it is crucial for executors to understand the high level priorities of the plan, so they can make appropriate decisions in cases of dynamic re-planning. This feature also serves our guiding principle of supporting astronaut autonomy when appropriate by providing them with the information necessary to make informed decisions [4].

[1] [2] [3] [4] Speed Dating Results

HTML DEVELOPMENT: TIMELINE

In this timeline, crew members can view the activities for each station and traverse. Sequence constraints and the highest priority activities for the day are visible with iconography. They can also see when they are ahead or behind schedule. This information is important to help them dynamically replan throughout the day.

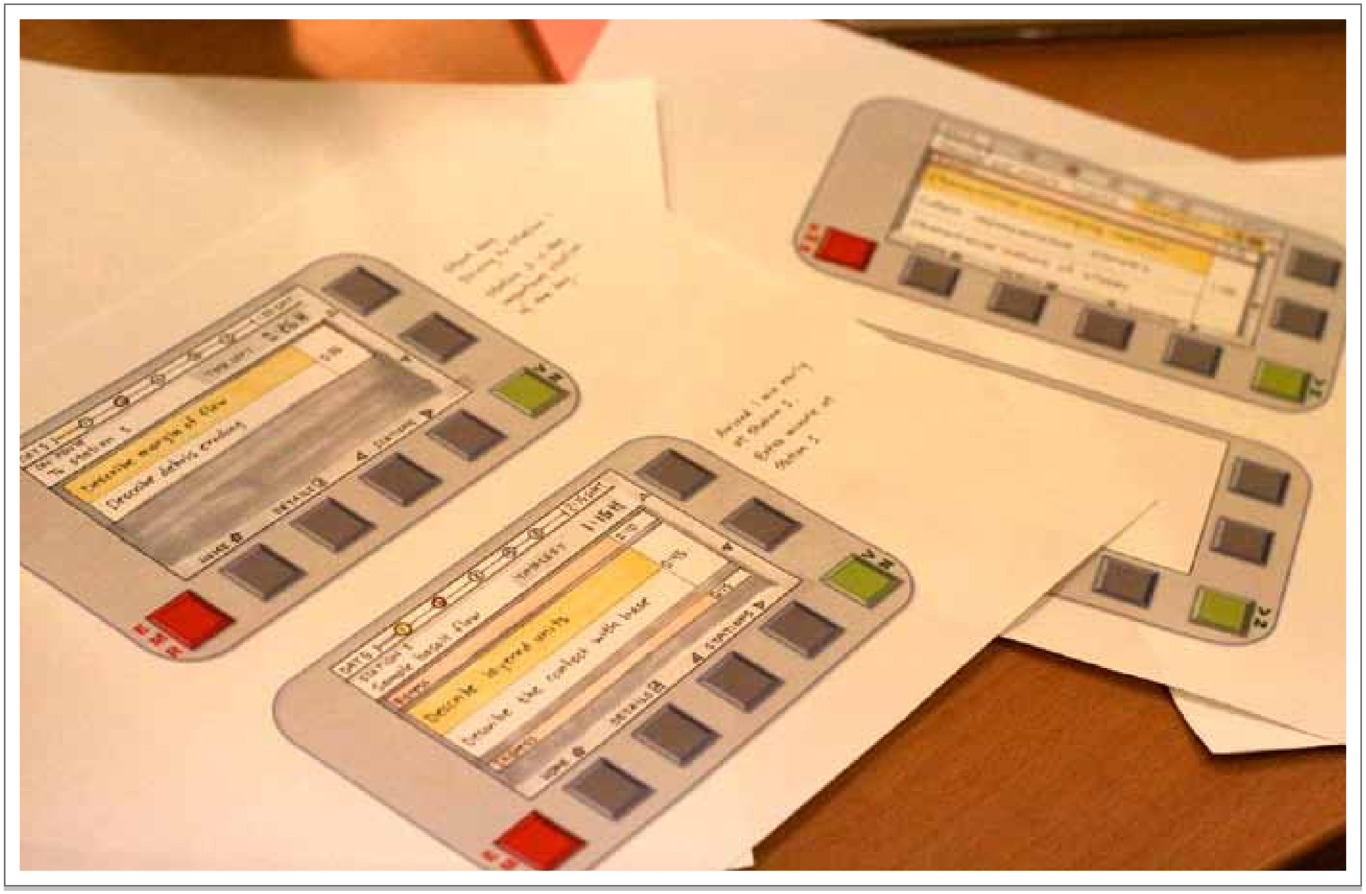


PEER EVALUATION

After the delivery to the Desert RATS team, we solicited feedback from our client, faculty advisors, peers at Carnegie Mellon. We used this feedback to design our interface for the next iteration.

TOP 5 ISSUES

FINDING	DESIGN IMPLICATION	SOURCE(s)
1. Segment Navigator Needs More Contrast	Increase the contrast, use animation, use different color for Station 3	Peers: Highlighting at the top seems really subtle, needs to be stronger Client: Hard to distinguish which one you are actually on.
2. Yellow Highlights Too Subtle	Increase contrast, use animation	(all): Contrast for yellow selection is too subtle
3. Don't Know Total Time For Segment	Add total time for the segment	Peers + Faculty: I want to know total time for segment without having to add it up.
4. Positive and Negative Segment Time Left is Confusing	Try again with interactive (counting down) prototype, do time elapsed instead, remove it.	Peers + Faculty: The negative time is confusing.
5. How Many Activities	Show a scrollbar, add an arrow for more activities, make use of empty white space	Peers + Faculty: Is there a way to show how many more activities there are? NASA Ames: Better way to utilize space if only one activity?
6.Timeline is Overwhelm-ing At First	Add welcome screen, provide training	Peers: It's not really clear what you're looking at right after you hit start.
7. Icons are Unclear	Remove them, block sequence activities	Peers: Connected activities aren't clear if the link icon is below line of sight. Faculty: The chain link icon looks like its floating. Client: How important is that I do these in order?
8. Naming Conventions	Expand the picture, scrollbar be present at all times, indicate how many steps there are at the top	Client: There is always a short name or an acronym. Verbs are confusing. Naming conventions for Traverses don't seem necessary, Think about Name vs Description of activity. Peers: Confusing - am I part of a Traverse or part of a Station?
9. Overall Color		Peers + Faculty: Pale and non-contrast. Check out the different color schemes for night mode on GPS units.
10. Buttons	Add point-down arrows, match the colors of the buttons to their labels, show what's being selected or what is being pushed.	Peers: The association could be stronger. Faculty: Check out ATM buttons.
11. Future Research Ideas	VR glasses $200, Digital photo frame, OLED buttons, Whack gestures, Airline mechanic research (Francine Gemperle, Dial + Button, View finder on glasses, Vibrating as source of feedback)	(all)



APPENDIX B

SECOND ITERATION

To prepare for our first Operational Readiness Test (ORT), we completed a second complete cycle of research, design, and development. We began the iteration by conducting a short literature review to gain a deeper understanding of existing work in wearable devices for space exploration. The design process followed with brainstorming and concept validation sessions that eventually led to a more refined design and HTML prototype. The following discusses in detail the different phases involved in the creation of the interface, as well as the updated features of the second iteration of our prototype.

DOMAIN RESEARCH

Interviewed MIT Media Lab researchers

On June 6 2010, we held a conference call with Christopher Carr, Steven Schwartz, and Ilia Rosenberg, who are authors of a highly relevant paper to the scope of our project: "A Wearable Computer for Support of Astronaut Extravehicular Activity."

Our goals for the conference call were to better understand their research on wearable execution support for astronaut extravehicular activity. We wanted to discuss the results of their work, as well as any additional knowledge and advice they could provide from their expertise in the domain.

The conversation provided a lot of insight into possible problems and lessons learned from their expert knowledge about the field. Listed here are the main take-aways:

- Although we are designing a visual interface, do not underestimate audio modality for input and output.
- Every astronaut differs vastly in terms of preference.
- Be aware of extreme environmental conditions. An idea or device that works on earth might not be suitable in space.
- Traditional user input in a space suit is very challenging.
- Certain activities are better suited for certain kinds of interfaces.
- Think about what would happen if the system fails, are astronauts able to continue working?

> *"Every astronaut differs vastly in terms of preference."*
>
> *Christopher Carr (6/6/2010)*

WearSAT reduces mental and physical load for astronauts

Wearable computers can enhance the mental and physical capacity of astronauts executing extra-vehicular activities (EVA). Better information management can lead to more efficient use of time, less cognitive load, and better safety.

Current methods of information management are largely unchanged from the Apollo era. A small booklet of emergency procedures are mounted on the left arm of the space suit. Intra-vehicular and ground personnel assist the extra-vehicular astronauts via voice communication. The benefits of a hands-free information display has long been recognized since the 1980s. Jose Marmolejo's electronic cuff checklist was the most successful, but problems like glare, lack of contrast and small fonts were noted after the prototype was flown in four Shuttle flights. [1]

WearSAT (wearable situational awareness terminal) aims to reduce mental and physical load of astronauts while maintaining cognizant of cost. Suit-external components must withstand pressure and thermal stress, but modifications to the suit are very expensive. Cost is an important factor for WearSAT when partitioning components between the suit-external and suit-internal worlds. It must also minimally impact the existing EVA process, which is a culmination of decades of experience. [2]

An external display might interfere with the EVA tasks, so WearSAT employs a near-eye display inside the helmet. Suit-external components are mounted on the upper back of the suit. With respect to control, direct voice control is a poor option because EVA operations rely heavily on voice communications with the execution support personnel. Remote control by support personnel seems the most reasonable so that astronauts can request information without the need for direct manipulation.

A series of simulated EVA tasks were performed based on either an audio command or a graphic images associated with a task. A blank black screen was shown on the display when the support personnel had important information to communicate to the astronauts. Astronauts were quicker to respond to commands given via visual display rather than audio commands. The location of the display (a 320x240 display clipped on the glasses for the simulation) allowed astronauts to nod his head easily and did not interfere with helmet donning and doffing.

[1] Marmolejo, J., An Electronic Cuff Checklist Information Display for Extravehicular Activity, 26th International Conference on Environmental Systems, July 1996

[2] Carr, C. E., Schwartz, S. J., Rosenberg, I. A Wearable Computer for Support of Astronaut Extravehicular Activity, 6th International Symposium on Wearable Computers, 2002 IEEE

PERSONA & SCENARIO

PERSONA

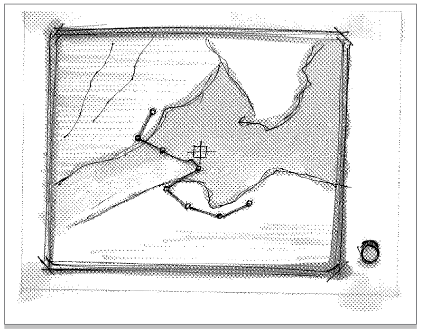
Tim Saunders (38 years old)

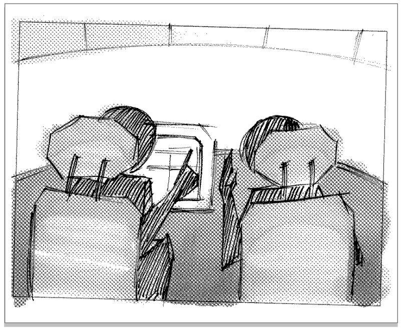
Occupation
Geologist (Vehicle / EVA Crew)

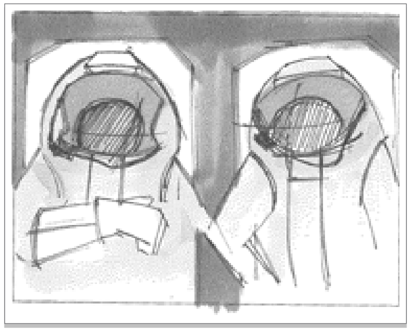
Background
Stanford Ph.D in Planetary Geography
Extensive analog experience
First time on the lunar surface

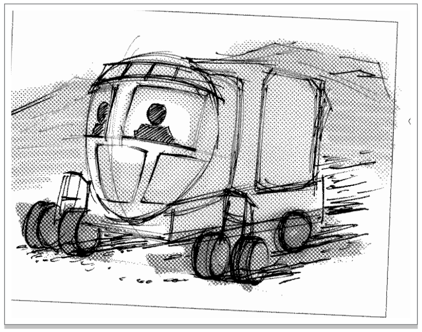
Responsibilities
Executes from the plan
Completes 8-hour shifts in vehicle
Takes photos / collects rock samples
Describes geological formation through Voice Notes
Communicates with Science-Ops and Mission Control
Collaborates with partner in the field
Drives the vehicle

SCENARIO









DRATS: Desert Research And Technology Studies

EVA: Extra-Vehicular Activity

SCICOM: Science Communicator

CAPCOM: Capsule Communicator

Day 7 out of 14 day mission

Goal: Validate satellite picture of possible water in soil

Constraint: Water will evaporate by lunar noon

Notified of plan change at Daily Planning Conference

During the conference at the beginning of the day, ground informs Tim and Bernard that satellite photos indicate possible hydrogen in the soil at Station 3. Ground needs soil samples to verify the presence of lunar water and that will be the day's top priority.

Decides to cut activities to ensure timely arrival to Station 3

The team decides to cut EVAs at Stations 1 & 2 to ensure that the team arrives at Station 3 on time, as any water molecules evaporate into space by lunar noon.

Performs in-vehicle observations at Stations 1 & 2

At Stations 1 & 2, Tim and Bernard describe the geological formations at those stations. They save time by staying in the vehicle during these observations.

Life Goals

Advance space exploration

Keep science central to NASA

Experience Goals

Feel confident while completing tasks

Feel unhindered by workflow

Wants system to be reliable

Doesn't want to be fatigued

Feel in confident & in control

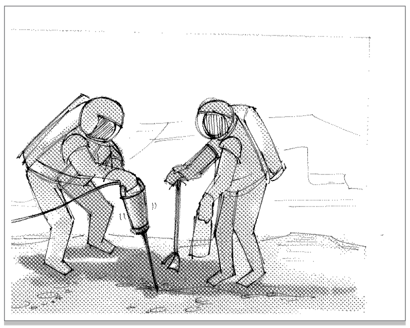
End Goals

Execute as best as he can to the plan

Work ahead when possible

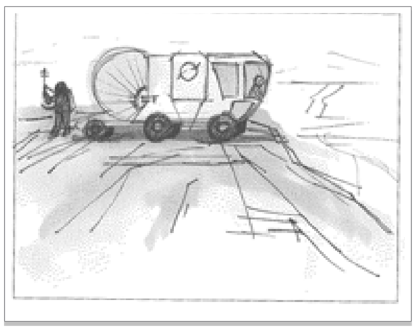
Know how much time is left

Use time effectively



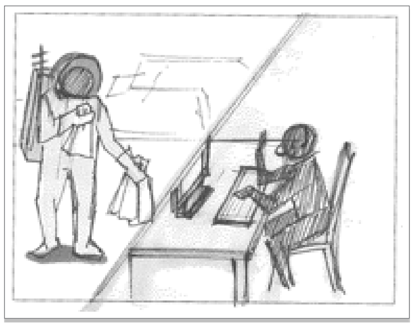
Collects samples and observations at Station 3 for possible water

Tim and Bernard arrive at Station 3 on time, nearly two hours before lunar noon. Bernard operates the drill while Tim collects and describes soil samples from the suspected lunar water site.



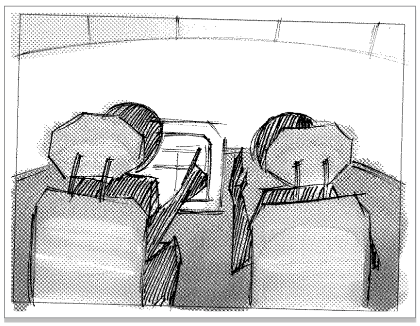
Drives to high point (Station 4) to take more pictures

Tim and Bernard drive to a high-point for Station 4. Here, Bernard stays inside the vehicle to take a panoramic picture of the suspected water site. Tim makes observations about nearby geological formations.



Decides to forego Station 5 because behind schedule

Stations 3 & 4 delayed the team by nearly half an hour. Because they would only have half of the time allocated for Station 5, Tim and Bernard suggest that they skip the last station in favor of a longer debrief at the end of the day to discuss the soil sample findings from suspected water site.

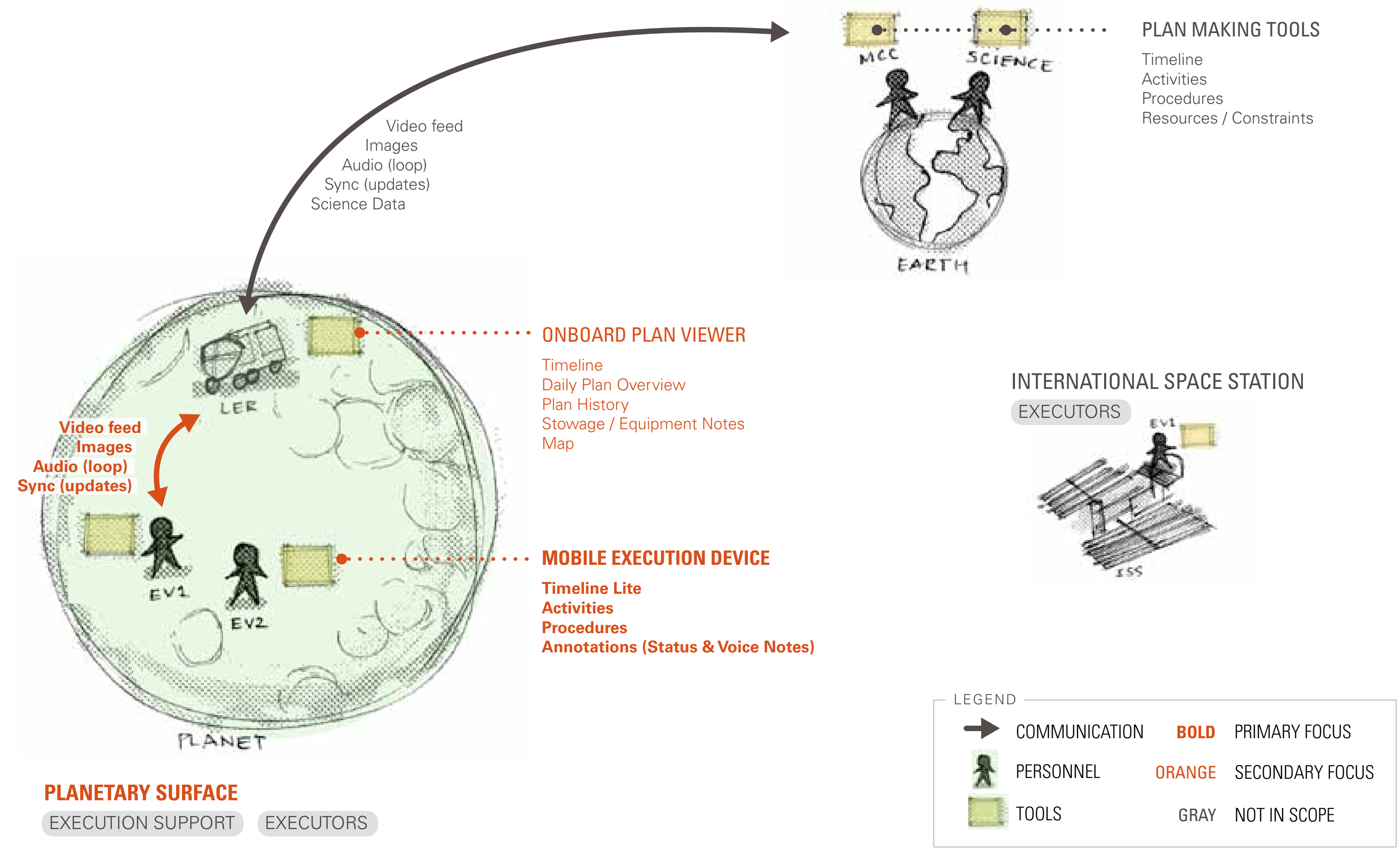


Maintains vehicle and debriefs with ground

At night camp, Tim and Bernard perform their daily maintenance. The normal 30 minute debrief is lengthened to an hour. Tim and Bernard describe their findings and downlink the geological data for further analysis.

PROJECT SCOPE

After the First Iteration, we took a step back to define the scope of our project for the rest of the summer. In our discussions, we considered the focus of our research, the findings from our work on the Desert RATS prototype, feasibility of prototyping and user testing, domain research on EVA procedures, and our personal interests. The following diagram illustrates our focus on the mobile execution of procedures on planetary exploration missions.



BRAINSTORM & BODYSTORM

As the next step, we conducted another brainstorming session, creating 50 new interface concepts and 25 ideas around physical form, including hardware, input, and output.

As part of this process, we performed bodystorming during which we donned motorcycle gear, including a helmet, gloves, heavy jacket and pants. This exercise helped us empathize with our target users and perform some early concept validation.

Brainstorming and sketching on the whiteboard

Bodystorming in a motorcycle outfit

BRAINSTORM & BODYSTORM: INTERFACE

Next, we reduced our 50 ideas to a core set of features that were most appropriate for a mobile execution interface. During the selection process, we validated each feature against our scenario to confirm a valid need or use case, verified popular ideas with our design guidelines [1], and incorporated the feedback from our early concept validation session. The following list provides a short description for each of these features.

INTERFACE FEATURES

[1] Design Guidelines, pp. 18

CONTEXTUAL INFO PAIRED W/ PROCEDURES

Selectively displaying supplemental information with a procedure, such as execution notes, equipment lists, warnings and cautions, or personal notes

CAMERA / VIDEO FEED SHARING

Viewing a feed from a partner's camera on the mobile device

DELTA BETWEEN THE PLAN AND EXECUTION

Viewing the discrepancy between the plan and execution of the plan, and indicating the consequences of plan changes

ACTIVITY PRIORITY

Indicating station and activity priority

SCAN PAST AND FUTURE ACTIVITIES

Scanning the plan to view activities scheduled in the future or completed activities in the past

ONBOARD MAP VIEWER

Displays an overview of the plan's station and traversal activities aboard the vehicle

FLAG EXCEPTIONAL ACTIVITIES

Supporting the generic flagging or marking of activities to indicate importance, error, payload, or any other arbitrary meaning

PLAN UPDATE/CHANGE NOTIFICATIONS

The onboard plan displays plan updates when syncing with the ground plan. Additionally, plan updates are indicated on the mobile device

MOBILE DEVICE TO DEVICE COMMUNICATION

Mobile devices can send and receive data between each other

AUTO CONTRAST ADJUSTMENT

Use a light sensor to modify the display to accommodate varying lighting conditions

BACKUP / UNSCHEDULED ACTIVITIES

Display backup activities that aren't time or location constrained and can be accomplished if/when time permits

BRAINSTORM & BODYSTORM: INPUT AND OUTPUT

In addition to our core set of features, we determined appropriate input and output methods for the mobile execution device based on our bodystorming exercise and previous research, like those from NASA or MIT Media Lab.

INPUT

CHICLET EDGE KEYS

Cumbersome gloves suggest that large, easily depressed buttons are the most appropriate form of input. Frequent communication with ground consumes the audio modality, restricting audio forms of input. Limited mobility in the space suit and uncertain atmospheric and gravitational conditions eliminates gestural modes of input that have become popular with consumer electronics.

AUDIO VOICE NOTES

Instead of requiring key input from the astronaut to document activities, audio is the best, unobtrusive method of documentation from the crew. Audio input is a simple, but effective way to capture observations and notes from science activities during execution. It does not require too much attention, leaving the astronaut to focus on their tasks without distractions.

OUTPUT

CUFF-MOUNTED VISUAL DISPLAY

Because astronauts execute activities in the field and the utility of their hands is crucial, the interface should be in a location that is easily accessible. A cuff-mounted display provides the astronaut with information that can be easily accessed without physical strain. Astronauts can naturally incorporated the action of viewing the display on the wrist into their workflow.

HIGH CONTRAST / LARGE TEXT / LANDSCAPE

A display with large text and high contrast will facilitate readability and glanceability in varying lighting conditions. The landscape orientation is best suited to accommodate the free-form, textual information found in the plan.

AUDIO OUTPUT

Allowing the device to provide simple audio feedback in the form of ‘beeps’ gives additional confirmation to the executor that his or her actions were registered with the system. Although this was not tested in the first iteration, simple audio output that does not interfere with communication can be useful for resolving ambiguous actions.

LED INDICATORS

The use of LEDs in a near-eye display is a simple, yet effective way to provide astronauts with an alert to pay attention to the device. For example, in the event of an emergency, a red LED light could trigger the astronaut to look at the interface for additional details.

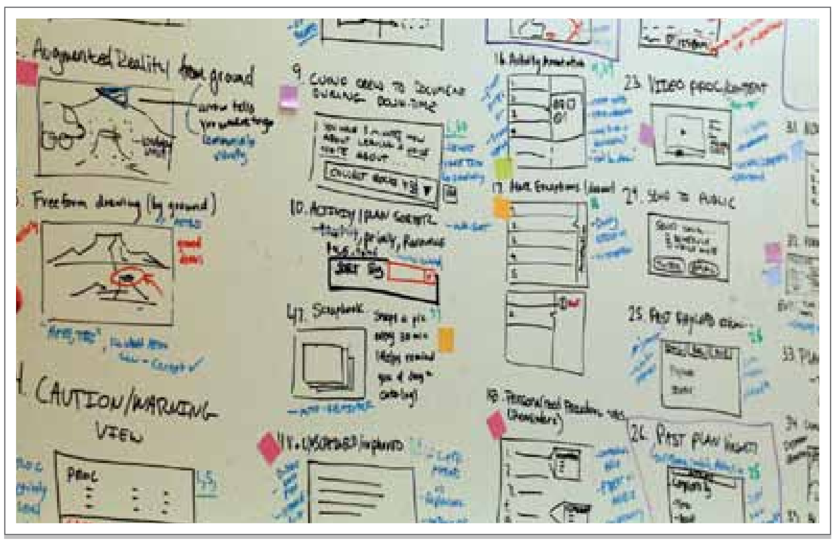
TEAM & CLIENT EVALUATION

ISS: International Space Station

EVA: Extra-Vehicular Activity

To perform some early concept evaluation, we recruited three NASA staff members to provide a critique of each idea, based on their prior experience and understanding of planetary surface activities and ISS EVAs.

After introducing our project scope and focus of a mobile execution device, we pitched each idea, and invited these experts to "vote" on the four ideas they found most appropriate or insightful. In addition, we received critical feedback on ideas that may have been flawed or based on incorrect assumptions or limited information.

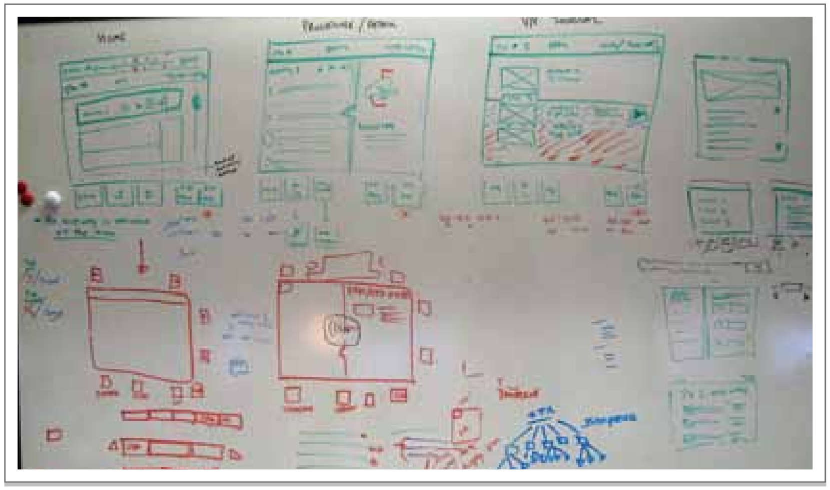


Voting results

NASA Ames HCI Group staff voting for their favorite ideas

LOW-FI SKETCHES

Using feedback from NASA employees, we narrowed our ideas down to a set of core features to incorporate into the final interface. We split into two groups to create more refined sketches and when both groups produced relatively similar interfaces and interaction specifications, we were confident in our design direction. After this process, we had a solid shared understanding of the final design and interaction.



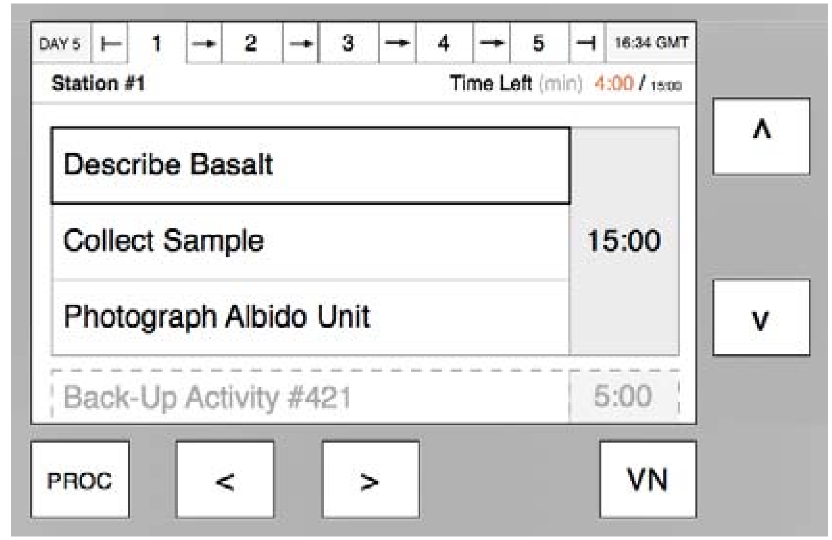
Whiteboard sketches of the final interface

MID-FI WIREFRAMES

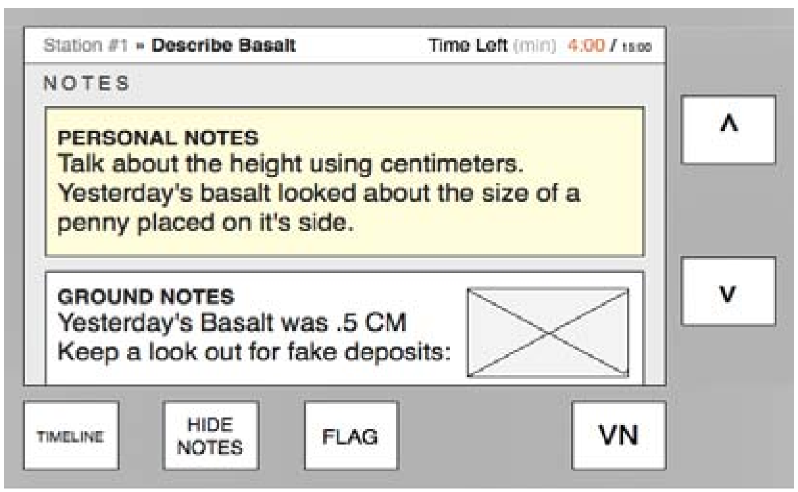
Wireframes allowed us to experiment with interaction design

Armed with the refined sketch, we continued the process by working out the details of the interface. This step included designing the specific iconography, layout, and text size of our prototype. To do this, we created a medium-fidelity wireframe template in Omnigraffle because it was easier to go back to and refine rather than redrawing the interface multiple times in sketches.

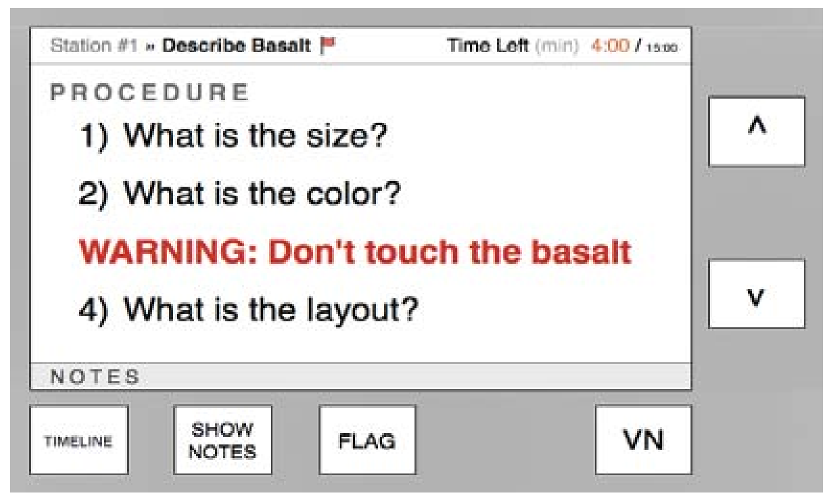
We found wireframes especially useful when we struggled with the fidelity of sketches. Creating medium-fidelity wireframes was the best way to design with practical constraints like real estate without getting too hung up on look and feel. These translated nicely into hi-fidelity because we could reuse similar assets between Omnigraffle and Photoshop. Finally, the Omnigraffle wireframes allow for some level of interactivity, which was helpful when seeing if transitions between states of the interface felt natural or jarring.



Wireframes helped us reach a new design for traversals in the Segment Navigator, which sported larger arrows to address the complaint of readability



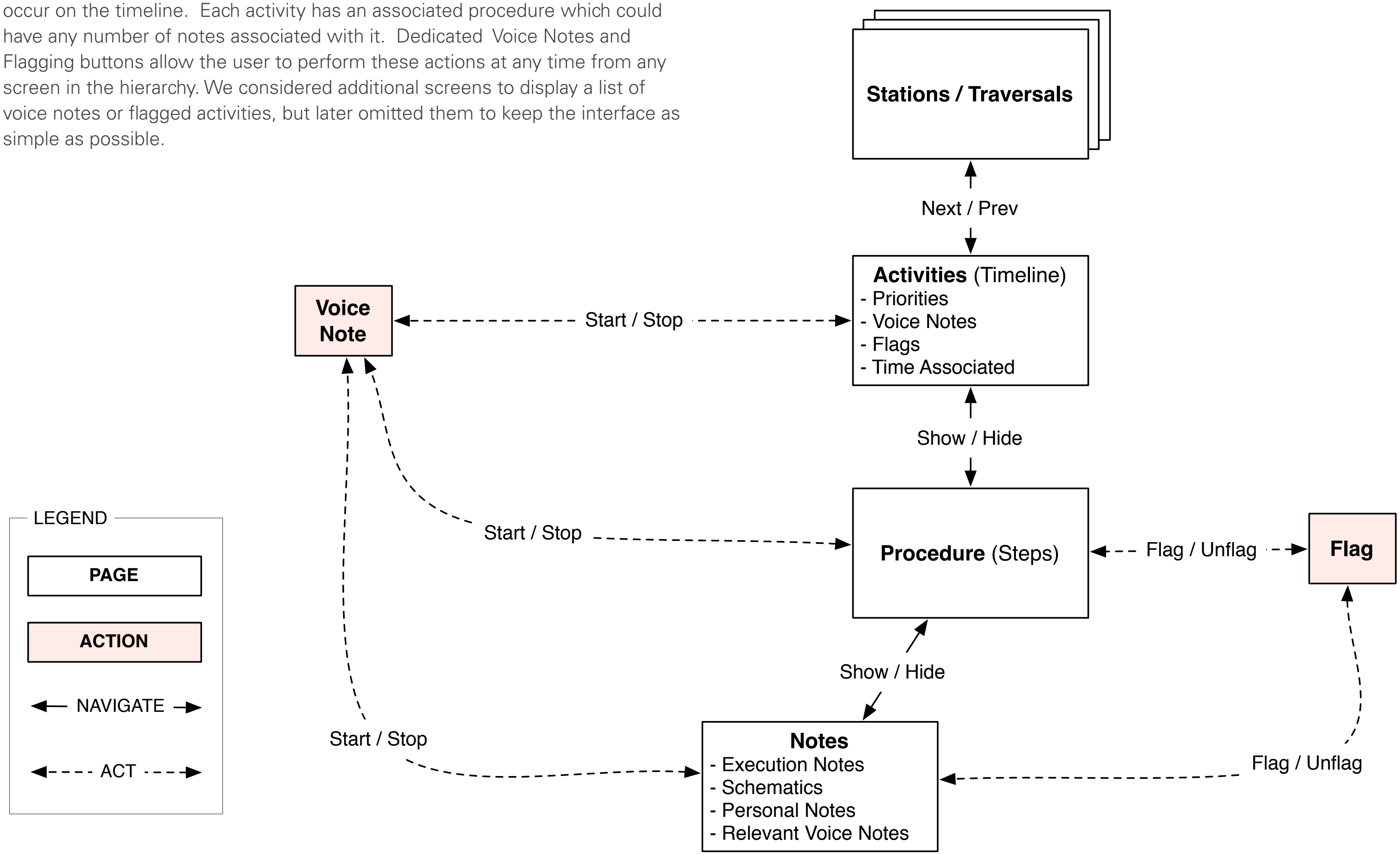
In this iteration, any given activity could have multiple notes associated with it, where some notes could be placed in their by the Astronuats themselves



The Procedure Viewer in this iteration had warnings displayed inline with steps

INFORMATION ARCHITECTURE

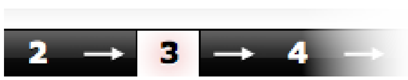
We created a map to visualize the flow of information through the mobile device. At its core, the interface is a list of activities organized by where they occur on the timeline. Each activity has an associated procedure which could have any number of notes associated with it. Dedicated Voice Notes and Flagging buttons allow the user to perform these actions at any time from any screen in the hierarchy. We considered additional screens to display a list of voice notes or flagged activities, but later omitted them to keep the interface as simple as possible.



HTML DEVELOPMENT: DESIGN RATIONALE

We used client, faculty, and peer feedback from the First Iteration to improve the design of the Second Interation. We also used our research and design guidelines to inform the design of new features. The resulting prototype contained a refined version of the timeline and a new Procedure Viewer with Execution Notes to round out the mobile execution scenario. This prototype was again developed using static HTML pages, Javascript, and CSS for the sake of development speed.

SEGMENT NAVIGATOR

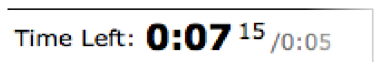


[1] [2] Appendix A: First Iteration. pp. 95

[3] Our spring report can be found online at: www.hcii.cmu.edu/M-HCI/2010/NASA/solution/downloads

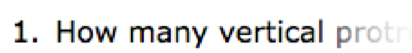
Many comments from the evaluation of the First Iteration critiqued the Segment Navigator for its subtlety and lack of contrast. Also, the use of a line segment to indicate traverses was ambiguous and, again, too subtle [1]. The new Segment Navigator employs much more contrast and gives a much stronger indication of selection on both station and traverse segments.

SEGMENT TIME LEFT



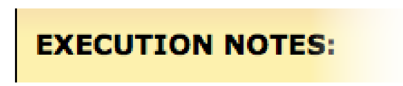
The Segment Time Left display also received a lot of feedback during the previous evaluation. We believe that the majority of the confusion was caused by this issue. For this iteration, however, we implemented the dynamic count down to better communicate the design. We also changed the display to specify the Segment Time Left as a fraction to address the feedback about needing to know the total time allocated for a segment without needing to add it up mentally [2].

INTEGRATED PROCEDURES



A large departure from the status quo in current NASA tools, the tight coupling of activities of the timeline and their associated procedures is the cornerstone of our design. Though procedures are quite unrelated to the timeline from a planner's perspective, they are very closely related from an astronuat's point of view. Also, our spring research revealed many problems resulting from a large set of decoupled tools [3]. Our interface serves this information together, rather than creating an artificial divide between them.

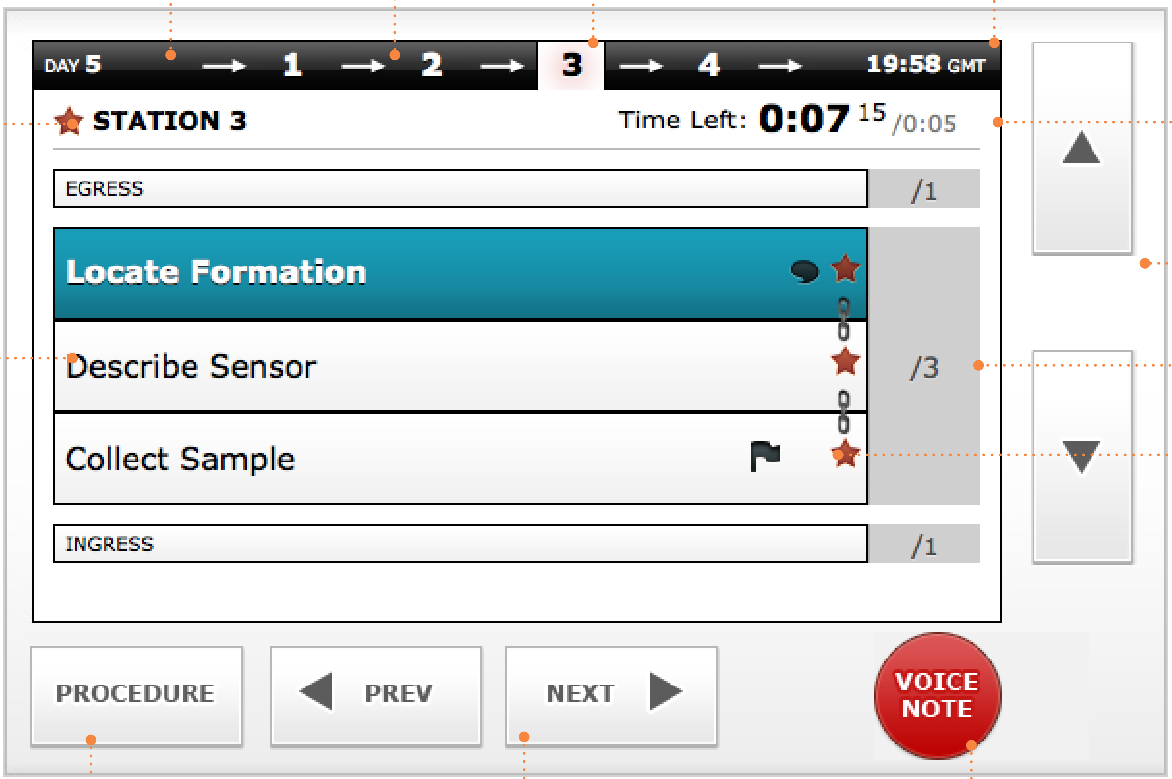
EXECUTION & PERSONAL NOTES



The Execution and Personal Notes appear as a drawer over the Procedure Viewer. In the current system, notes must first refer to a procedure for context before relating useful content. Here they are presented in the context of the activity and its procedure.

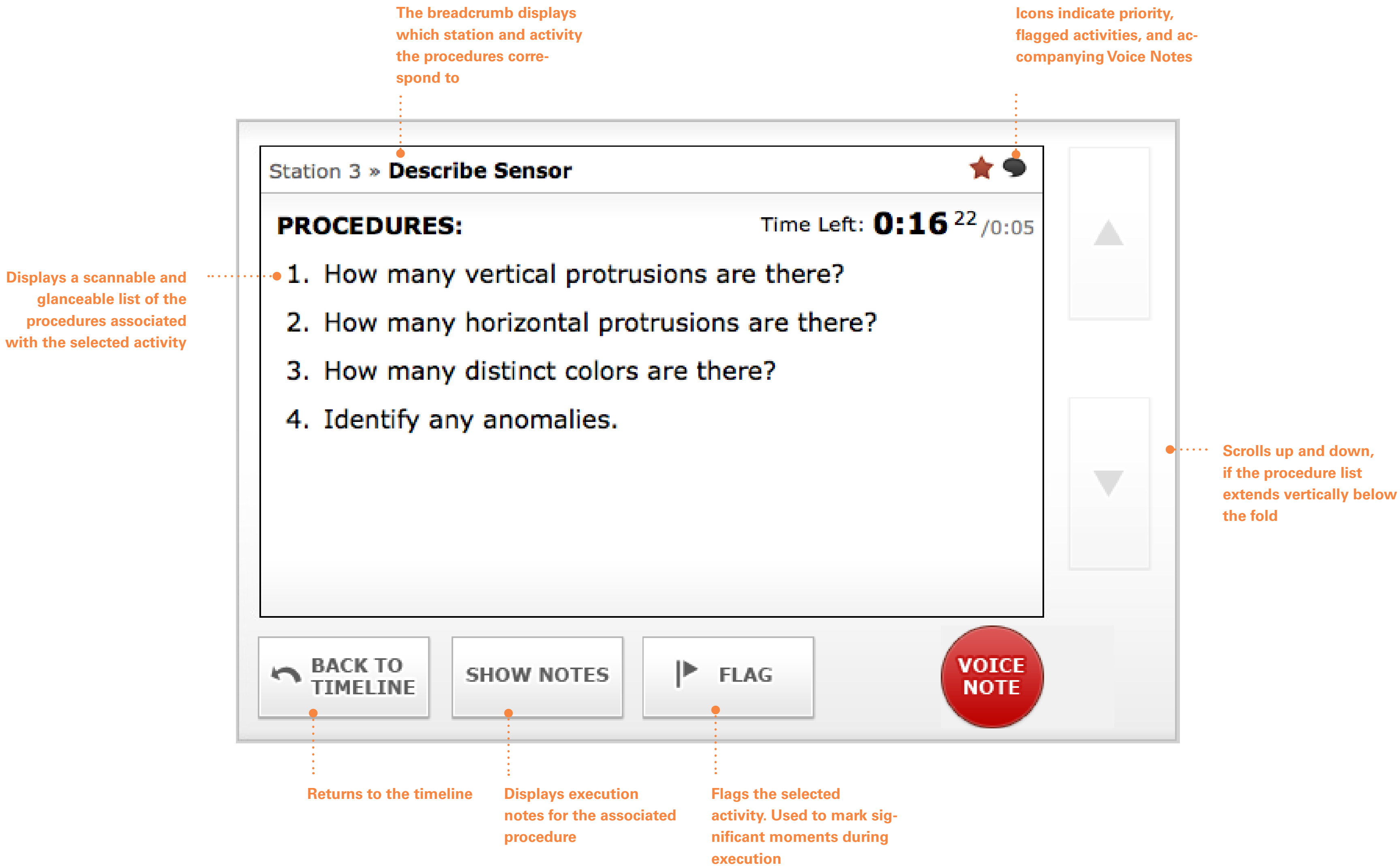
HTML DEVELOPMENT: ACTIVITY LIST

This iteration updates styles to increase contrast and text size, and introduces a number of features to support mobile execution, including Voice Notes, Procedure Viewer, Execution Notes, and Flagging.



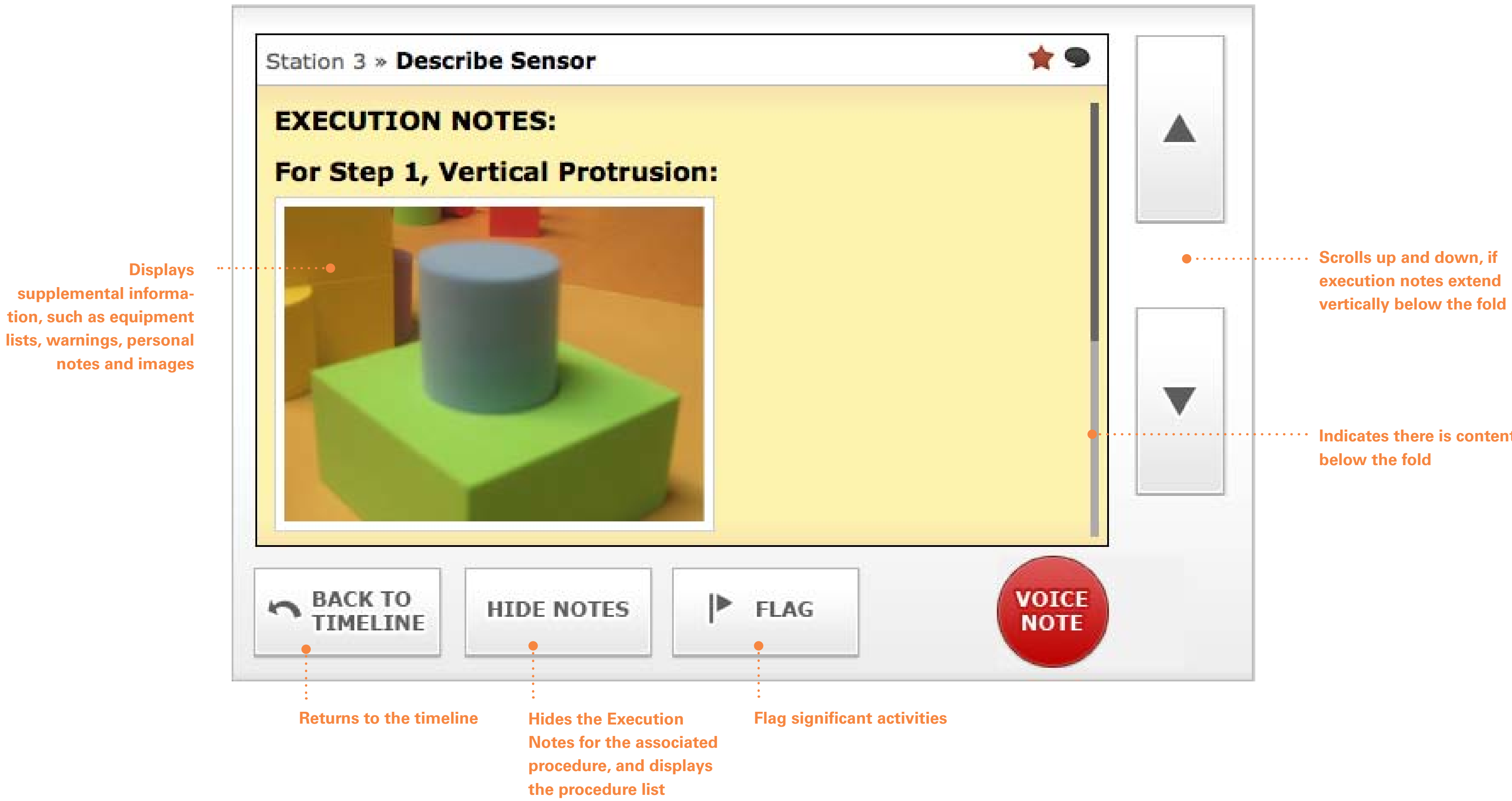
HTML DEVELOPMENT: PROCEDURE VIEWER

The Procedure Viewer displays a scannable and glanceable list of the procedure steps associated with the selected activity.



HTML DEVELOPMENT: EXECUTION NOTES

The Execution Notes display supplemental information, such as operation notes, equipment lists, warnings and cautions, personal notes and images.



HEURISTIC EVALUATION

We performed an expert Heuristic Evaluation to quickly identify potential usability problems. We considered each of Nielson's 10 Usability Heuristics, and noted both positive and negative aspects of our design. Some negative aspects had obvious fixes, but others required further brainstorming.

HEURISTICS	GOOD	BAD	SUGGESTIONS
1. Visibility of System Status	Voice Note indicator when VN is pressed	Poor indication linking Execution Note with activity	More visible Note indicator
	Loading icon during time calculation	Segment Time Left requires user to mentally calculate	Distinguish and display total time and time at station
	Highlighting of currently selected activity	No indication of where you're supposed to be	Mark somehow in Segment Navigator
	Button press indications		
	Segment Navigator is a clear indication of current position in the interface		
2. Match Between System and Real World	Procedure button	Voice Note color (red) looks too urgent	Red outline, white button, or some other way
	Timeline wording	Star != Priority	Maybe make activity text red to show importance
	Prev/Next buttons	Activity time allocation is ambiguous (time next to activities: ex: /6)	Indicate that it is time
	Voice Note button		
3. User Control and Freedom	Flag / Unflag	Cannot remove a Voice Note	Add feature to remove Voices Notes
	Can go 'back'	Going 'back' from notes screen is not intuitive	Restructure navigational buttons
	Toggling between stations is easy	Cannot Flag/Unflag from Activities List	Add flagging capabilities in Activity List

HEURISTICS	GOOD	BAD	SUGGESTIONS
4. Consistency and Standards		Traversals and stations are too similar even though they are distinctly different	Make them more distinct somehow. ex: give activities different background color
		Back button is not consistent	Reorganize navigation
		Segment Navigator isn't always there	Persist Segment Navigator on every screen
		Time is not always shown	Always show time
5. Error Prevention	Allowing Unflag	Don't know when to do a Voice Note	Include 'icon' or something to show that a voice note is required
		Can't remove Voice Note	Record over Voice Note, allow remove/append Voice Note
6. Recognition > Recall	Current activity displayed when viewing procedures	Segment Navigator is hidden during procedures	
	Segment Navigator displays which station/ traverse is selected	Had to mentally calculate time	
		Must recall Flagged activities in later screens	Distinguish differences between time
		Recall previous notes from previous activities that are related	
7. Flexibility and Efficiency of Use	Don't have to see procedures if unneeded	Must view Procedures to view Execution Notes	Allow viewing of Executive Notes on Activities List
	Can go back to timeline from any screen	Can't loop around from first to last station	
8. Aesthetic and Minimalist Design	Only show text that's relevant to user	Time is not big enough when needed	Make time size bigger
9. Help Users Recognize, Diagnose, and Recover from Errors	N/A		
10. Help / Documentation	N/A		

OPERATIONAL READINESS TEST

Created mock mission around NASA Ames campus

An Operational Readiness Test (ORT) is a modified think-aloud user study that implements a planetary surface mission simulation. Participants used our prototype to complete mock geological science tasks, specified by a time-constrained plan, at several locations around the NASA Ames Research Center campus. The simulation sought to reproduce the physical constraints of the space suit, remote communication with ground support, and the need to dynamically re-plan to return to base camp on time. We used this method repeatedly to test our design.

Deciding which activities to perform at each station was the hardest part of creating the ORT. After much brainstorming, discussion, and debate, we decided to use colored foam blocks to create "formations" for the participants to locate, describe, and otherwise use to perform mock geological science.

Practiced the Mock Mission with a walkthrough

Because our device and scenarios rely heavily on planning, scheduling, and therefore timing, we needed to walk thru our ORT scenario in order to create activity and traversal time estimates in our mission plan. Jesse volunteered to perform the walk through, since he was the most isolated from the planning process (was busy creating the prototype).

During the walkthrough, we realized that one of our sites for geologic observation was quartered off and unreachable. We also had Jesse try to understand the procedures and reworded several items due to ambiguity. Also, we had completely overlooked a key component of execution. Specifically, there was no prompt to collect necessary equipment from the Vehicle before going to locate the formations. We therefore created an equipment checklist to include with the paper prototype for the onboard system, which listed equipment necessary for each station.

ORT: Operational Readiness Test

An example of the mock geological formation

Testing out the physical constraints of the space suit

Briefed participants and completed the simulation

We selected four locations to complete a set of mock geological activities. At each station we placed mock geological science formations. Participants were given approximately 40 minutes to visit all four stations and execute activities specified in the plan. We requested that participants return on time, even if they did not finish all of the activities.

The activity began with a training presentation to simulate the planning conference Astronauts receive before they go on any mission. This training session served as an orientation, allowing us to communicate background information, walk through the scenario and the mission plan, train them on any operation procedures, and explain the technical logistics of the ORT. Participants then embarked on the mock mission around NASA Ames campus.

A participant performing an activity: measuring the height of the foam formation

A participant attending the briefing before the mission.

OPERATIONAL READINESS TEST: RESULTS

All participants were able to visit each of the stations and make it back to base camp on time, despite various unforeseen circumstances. Overall, our prototype proved quite successful, though there was certainly no shortage of excellent feedback to incorporate into our next iteration.

We began synthesizing all the data we gathered in the ORT by going through our notes and discussing major findings. Along with each finding, we determined possible design implications.

TOP 5 ISSUES

FINDING	DESIGN IMPLICATION	SOURCE(s)
1. Device too Cumbersome	Support Wearable	(all users)
2. Difficult to calculate current / time how much total time left;	Include mission time elapsed; indicate where executor is supposed to be	U1: (sta 2): Forgot which station she was at, when scanning ahead U2: (sta 4): "Oh my god we have to go back to camp" U3: (sta 1) - (debrief) Used negative time to find out which station to be at
3. Allocated Time to Egress/Ingress not factored into Segment Time left	Ingress / Egress should not be included in time left at stations	U4: (sta 2) "Let me know when there is 5 seconds until 1 minute left" U4: (debrief) had to mentally calculate actual time left U2: (sta 3): Discounted egress time for activites
4. Scrolling Notes	Paginate them or segment them into groupings	U2: Scrolling is annoying for notes
5. Confused on Procedure	Add Voice Note icon	U0: not sure when to make a Voice Note or talk to ground U1: (sta 1) didn't know how to get to procedures U2: (sta 1, 3) forgot to leave a Voice Note.
6. Navigational Problems		U0: (sta 3) navigate: Execution Notes -> going 'back' -> doesn't go back to the previous screen U1: (debrief) I'm not sure which (Execution) Notes refer to which procedure"
7. Forgets Equipment	Support Equipment Checklist on the device	U0: (sta2) U1: (sta 1) (debrief) - didn't use checklist U2: (trav 1) x2 - forgets rulers, finds out while reading device
8. Preview Plan Device During Egress	Supports looking ahead (walking to site, egress, ingress)	U1: (sta 2) U2: (trav 1) - looked at map before going
9. Asks Bernard for Time	Support timer for ingress / egress	U0: during egress
10. Read Tasks Out Loud		U0: (sta 3)

FINDING	DESIGN IMPLICATION	SOURCE(s)
11. Segment Time Left Not Apparent	Make Segment Time Left very visible (at all times: Vehicle, Device, and during Notes)	U4: Couldn't see time left while in the notes view U1: (sta 2, trav 4) didn't know time during activities x2, "time left in seconds is too small!"
12. Don't Know Notes Content	Stronger Indication in activity Execution Notes	U1: (sta 2, 3, 4): Collected wrong sample. Skimmed and was wrong, but double checked and corrected.
13. Confused on What's Pushable	Clarify what's an input and what's not	U1: (sta 2) U2: (debrief)
14. Device Sleeps	Make it no auto sleep	U1: (debrief) U4: (debrief) "I wish I could glance without touching it again"
15. Don't Know My Location	(In vehicle) indicate current location	U2: (trav 1)
16. Misses Activity By Looking at Vehicle Plan	Indicate what they're supposed to do	U2: (sta 1)
17. Didn't Care about Allocated Time to Egress / Ingress	Ingress / Egress shouldn't be included in Segment Time Left	U4: (sta 2) "Let me know when there is 5 seconds until 1 minute left" (debrief) had to mentally calculate
18. Time was not Clear that it is Paired w/ Station	Distinguish 'time left' to: total, this station	U4: (sta 2): Like it in the beginning but not afterwards. Wanted something more immediate during execution (sta 4): "Oh my god we have to go." Device gave a sense of urgency
19. Contrast	Make it easier to read in the sun	U2: (trav 4) U4: (sta 4) (debrief) "Biggest problem is the sun and lack of contrast"
20. Color	Better use of color	U2: (debrief)
21. Size	Make things bigger	U2: (debrief)
22. Previews Vehicle Plan During Traversals		U0: (sta 2)
23. Likes Checklist on Back of Vehicle	Support checklist on bin (out of vehicle)	U4: (sta 1)
24. Driving Directions		U4: (trav 2) "I don't need driving directions on Vehicle" (later on...) -> "Actually I take it back, it's useful because I could look at it during ingress.
25. Information is Related to Recording	Allow scrolling while recording, which implies that the recording symbol should not occlude the information behind it	U2: Took time to prepare information before recording

POSITIVE FEEDBACK

APPENDIX C

THIRD ITERATION

We identified the issues and insights from the first ORT to revise and improve the operation of the second ORT. In addition, we iterated on the design of the prototype and shifted from an HTML web-based prototype to a native Android application on a small Android internet tablet. In parallel, we started hardware development for the device, using an Arduino and a bluetooth module to send data from external push buttons.

APPENDIX C: THIRD ITERATION

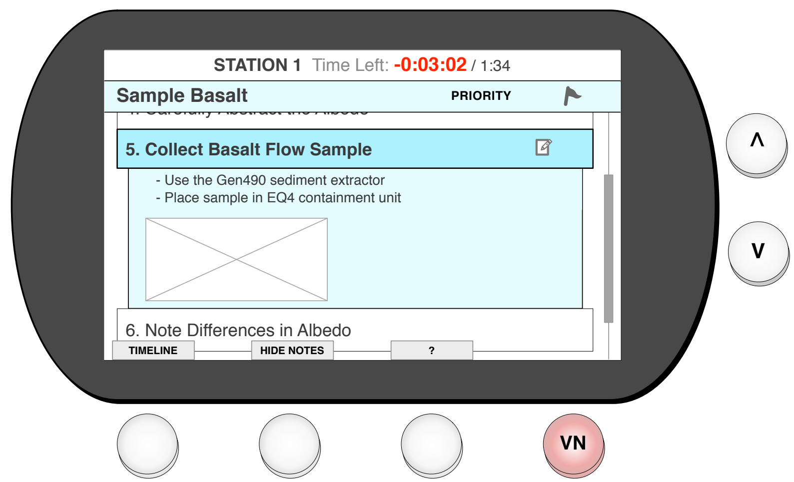
MID-FI WIREFRAMES

We began this iteration by processing the data gathered in the first Operational Readiness Test (ORT) by reviewing the raw data (notes, observations, video) and noting major findings. We paired these findings with the supporting data and potential design implications. The findings fell into two broad categories, the design of our interface and the design of our ORT, where we made sure to label feedback accordingly before working to iterate both of facets.

In addition to the Heuristic Evaluation of the previous iteration], we used these findings to direct our discussions for the redesign. Though tempted to walk through each finding and design implication, "repairing" the design as appropriate, we attempted to step back and take a more holistic view. We looked for solutions that addressed many of the problems we saw, or solutions that made such problems obsolete.

We looked for solutions that addressed many of the problems we saw, or solutions that made such problems obsolete

The new design for the Activity List, made interactive using Omnigraffle



Wireframe design for the Procedure Viewer

THINK ALOUDS

To test our new design elements, we used this medium-fidelity prototype to conduct Think Alouds with NASA domain experts. We asked them to use our prototype to complete a task which we specifically designed to incorporate the following items:

- New notes layout
- Iconography
- Meaning/ Use of Voice Notes
- Flagging

The feedback from these tests validated some of the concerns we heard in the ORT 1, but also provided new insights that we incorporated into the design before moving forward in development. Specifically, one expert suggested that the execution notes have a global visibility toggle rather than the more localized interaction we had originally designed.

> *The feedback from these tests validated some of the concerns we heard in the first ORT*

Participant playing with the interactive Omnigraffle Mid-Fi wireframes

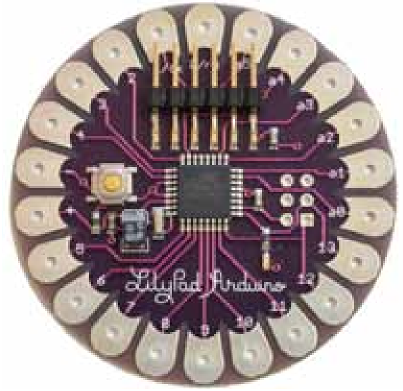
We met after each user test to debrief and record notes

DEVICE RESEARCH

We selected Android as our development platform due to the feasability of interfacing with hardware, allowing us to use physical buttons. We selected the Arduino LilyPad to prototype our hardware support of the wearable device.

We selected the Archos 5 Android internet tablet for its large screen real estate and relatively inexpensive price. It provided a 4.8 inch screen for approximately $300, an obvious bargain when compared to Android phones which cost $700+ for at most a 4.3 inch screen.

Archos 5 internet tablet, with a resolution of approximately 710 x 410.



Arduino Lilypad

We spent several days researching different devices on the web

ANDROID DEVELOPMENT: DESIGN RATIONALE

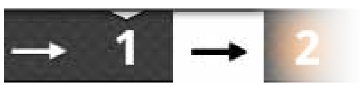
This iteration incorporated many design improvements found through the synthesis of user data, expert evaluation, and feedback from domain experts, including a crew member from the Desert RATS team.

For this iteration, we moved from HTML to Android development. We considered reusing our HTML prototype on the Android device's browser, but worried about Javascript performance, server connectivity, and hardware interfacing.

Desert RATS: Desert Research and Technology Studies

ORT: Operational Readiness Test

MARCUS-BAINS NOTCH

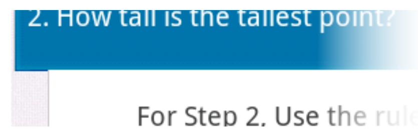


The Marcus-Bains Notch indicates which plan segment the astronaut should be completing given the elapsed time since the start of the mission. The previous iteration lacked this explicit indication, so participants deduced this information by looking at the color of Segment Time Left to see if it is red or black. The Marcus-Bains Notch also provides more visibility into the delta between the plan and execution.

MISSION TIME ELAPSED

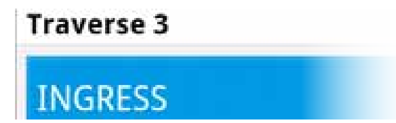
The Mission Time Elapsed displays the total time elapsed since the start of the mission day in the Segment Navigator. In the previous iteration, absolute time in GMT was never used by users in our simulation. In addition we found that human space missions typically utilize time elapsed to measure and communicate mission time. Lastly, user testing revealed a need to know exactly how much total time had elapsed without having to calculate based on start time and current time.

INLINE EXECUTION NOTES



Execution Notes appear inline with the procedure step. They are hidden by default, but the Show/Hide Notes button globally toggles the visibility of all Execution Notes for the selected procedure. An Execution Note icon indicates the presence of a note for a particular procedure step. ORT data from the previous iteration revealed that it was not obvious which procedures or activities had associated execution notes. Additionally, a separate note screen divorced each Execution Note from the qualified procedure and occluded the relevant information like Segment Time Left and procedure steps.

INGRESS/EGRESS ACTIVITIES



The reoccurring activities of Ingress and Egress, and the allocated times, now appear in the 'Traverse' segments of the plan. In the previous ORT, users had to mentally calculate the total time allotted for a station's activities by subtracting the ingress & egress times. What is more, users tended

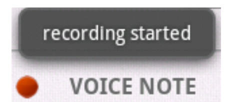
SIMPLIFIED ICONOGRAPHY

Priority activities are indicated by a bold PRIORITY label. We combined Flagging and Voice Note and they are now indicated by a single speech bubble icon. Participants from the previous iteration's ORT found the priority star icon ambiguous. Also, research with domain experts revealed that Voice Notes are used primarily to document notable an extraordinary occurrences. Thus, we combined the Flagging and Voice Note features.

SIMPLIFIED APPLICATION FLOW

This iteration has only two major screens: Activity List and Procedure View. The Timeline/Procedure button toggles between the two. User testing revealed navigational problems largely resulting from a third screen (Execution Notes) and inconsistencies with the back button. The simplified navigation addresses these issues and greatly reduces application complexity.

VOICE NOTES RECORDING



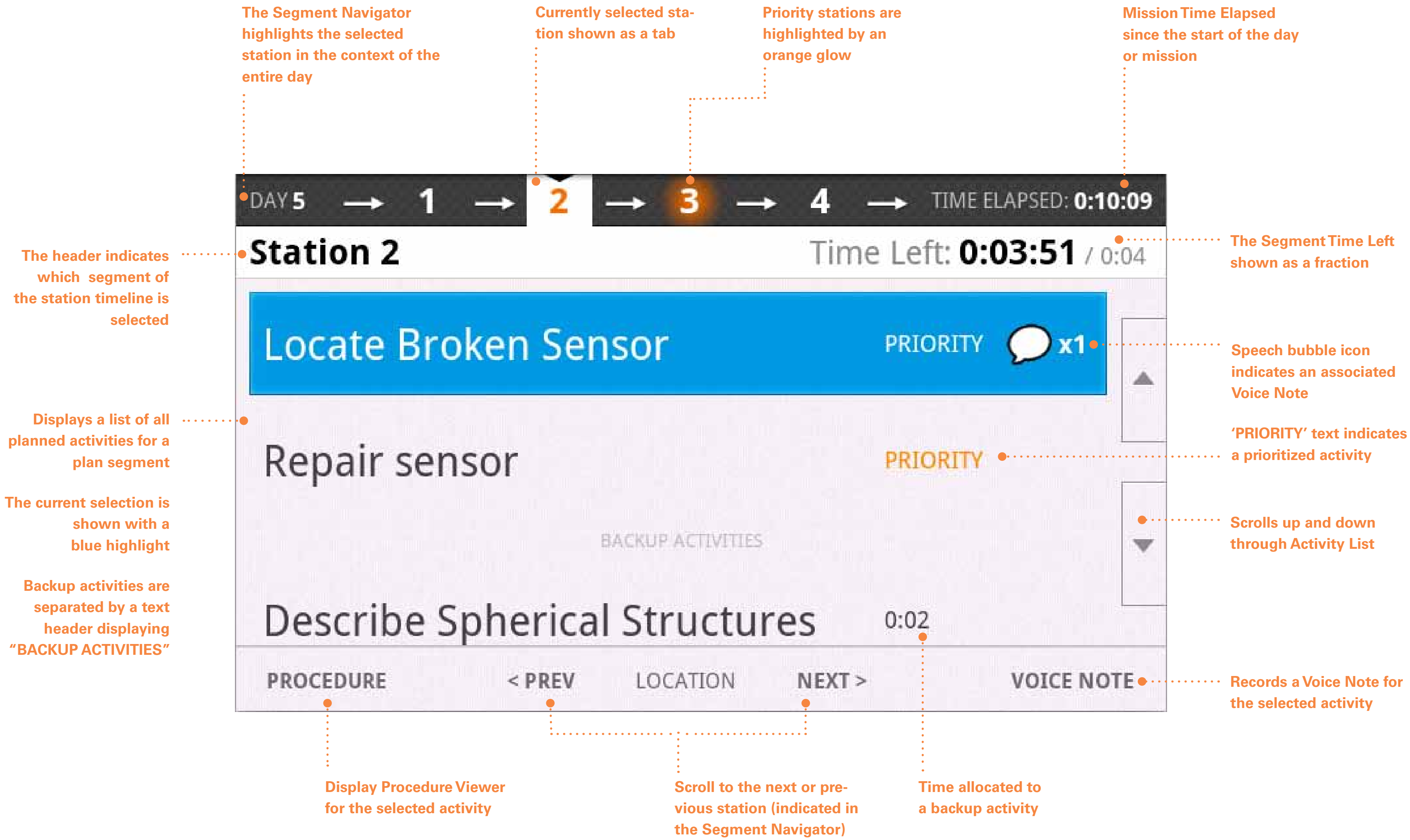
Recording Voice Notes requires the user to start and stop a recording, assisted by a subtle overlay and red icon. In the previous iteration, the Voice Note recording indications occluded much of the screen, reducing visibility of core elements, like procedure steps. We redesigned the Voice Note overlay to optimize screen real estate in iteration 3. Additionally, users can add multiple Voice Notes to a selected activity, providing more flexibility and freedom with the Voice Note functionality.

SEGMENT TIME LEFT DESIGN

The Segment Time Left is displayed alongside the allocated time. This countdown continues into negative numbers (and turns red) if the executor goes 'over' the time allocated. User testing revealed that the previous display did not adequately pair the Segment Time Left with the Activity List of that segment. This iteration displays the Segment Time Left in the Segment Info Bar alongside the segment name.

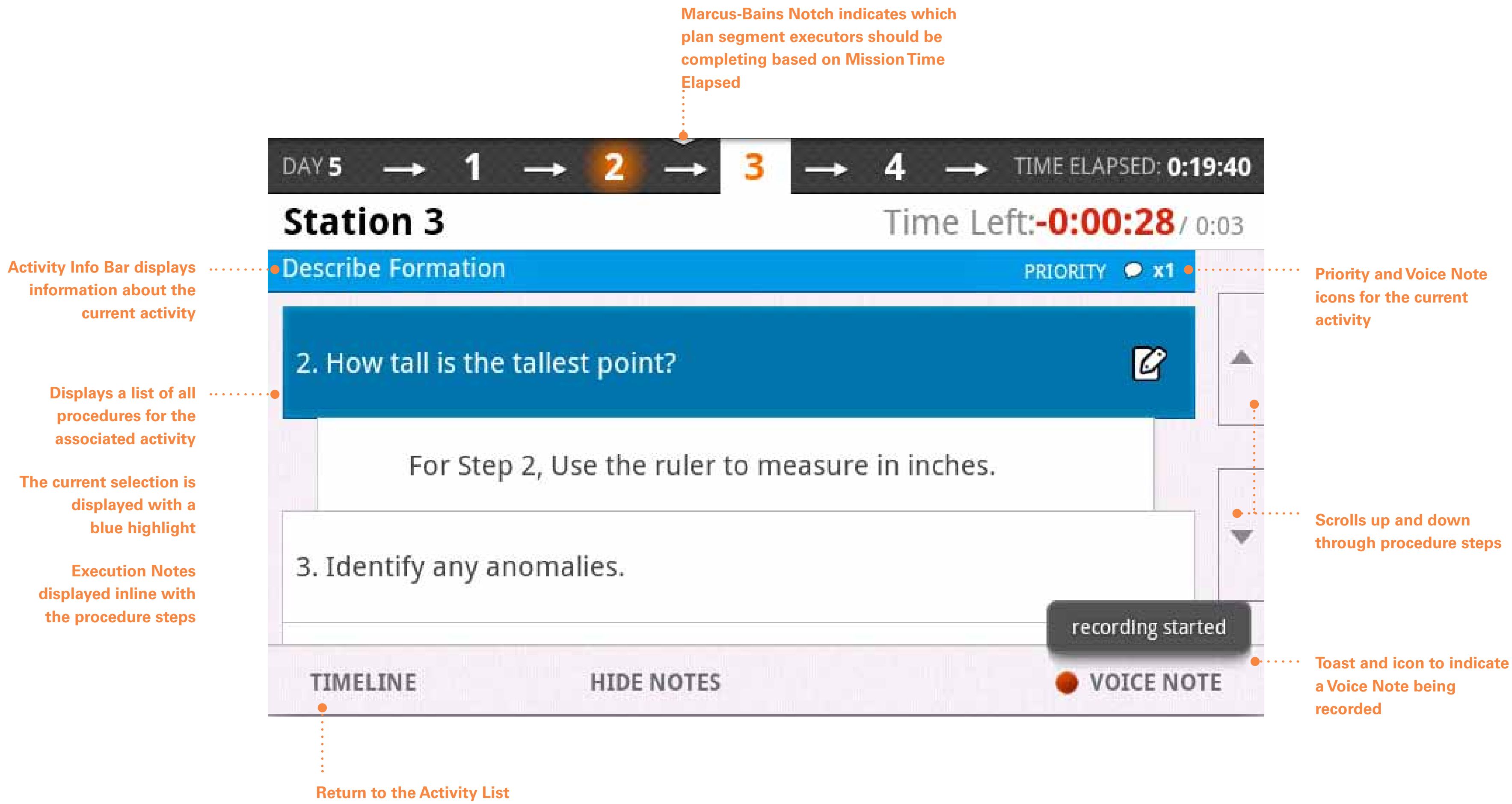
ANDROID DEVELOPMENT: ACTIVITY LIST

This iteration addressed many of the usability and conceptual breakdowns discovered in the user evaluation process of the previous iteration.



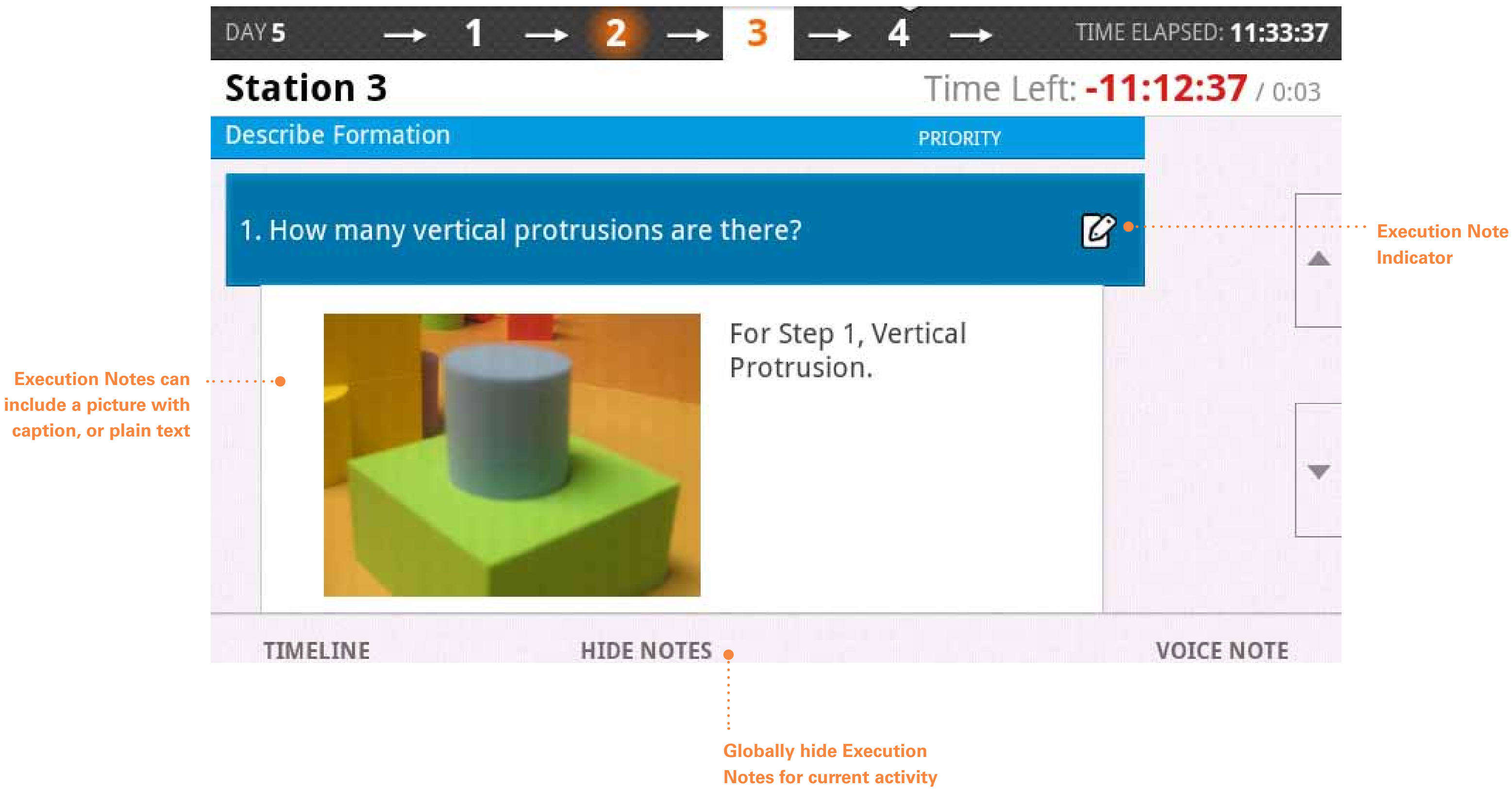
ANDROID DEVELOPMENT: PROCEDURE VIEWER

The Procedure Viewer displays a scannable and glanceable list of the Procedures and Execution Notes associated with an activity.



ANDROID DEVELOPMENT: EXECUTION NOTES

This iteration includes a major update to the information structure to support inline Execution Notes.



WEARABLE DEVELOPMENT

We were unable to complete the hardware development in this iteration, so we approximated the interaction with soft screen buttons instead of the external physical buttons. We crafted the wearable prototype by mounting the Android tablet to an elbow relief brace using extra strong velcro.

The arm brace could be adjusted using velcro straps to accommodate participants with varying forearm sizes. The most important for the wearable was that it felt secure. We had to be sure there was no change the device would fall off while the participants completed their activities.

> *We had to be sure there was no change the device would fall off while the participants completed their activities*

Brace was custom fitted to each ORT participant

The Archos 5 device attached onto the arm brace using velcro and elastic

OPERATIONAL READINESS TEST

EVA: Extravehicular Activity

For our second Operational Readiness Test (ORT), we significantly increased the fidelity of our simulation. We made several changes to the plan. We shortened traverses to increase the percentage of time spent on EVA using the mobile execution device. We also shortened the plan by 10 minutes in order to force executors to more closely monitor their progress against the plan and increase the likelihood of a replanning scenario.

We also increased the fidelity of the physical form. The previous ORT employed a large touchscreen Windows device that participants had to hold in one hand while executing activities with the other. For this ORT, participants used a cuff-mounted prototype, freeing both hands for execution.

We explained the usage of the device to each participant during the briefing

Participant donning the helmet so we can test visibility of the interface

We used screen buttons for this ORT, which led participants to treat the entire device as a touch screen

Participant referring to the wrist cuff to repair the foam sensor to spec with both hands.

OPERATIONAL READINESS TESTS: RESULTS

With reduced allocated time for each station, all of the participants were forced to cut activities and even an entire station. Everyone except the repeat participant did not anticipate the amount of time wasted walking to and from the vehicle. One participant was disqualified for being 30 seconds late despite completing nearly all activities. We began synthesizing all the data we gathered in the ORT by going through our notes and discussing major findings. Along with each finding, we determined possible design implications.

TOP 5 ISSUES

FINDING	DESIGN IMPLICATION	SOURCE(s)
1. Missed Procedure	Highlighting Color, Change name to Activities, Procedures come in from the side and don't cover, change color of the background, show a toggle buttons, hide the Segment Navigator, Change the way we do notes	U1: Did not know if he was looking at the procedure or the timeline so he missed a step. Suggested using to a "Timeline / Procedure" Toggle U2: Was unsure if she was looking at procedures or activities
2. Blue Highlight Seemed Touchable	Add hardware, Reduce spacing between list items, shrink text a bit more, change color	U1: Kept trying to touch the selected activities U2: Kept trying to push the activity
3. Notes Similar to Steps	Extend the procedure instead of intending it, change the style of notes, change the highlight of the notes, fix scrolling to top	U1: When he had notes expanded, he treated them like steps
4. Didn't Look at Traverse for Directions	Put a self-drawn map in the traverse views, bring pictures to be more relevant or treat directions differently than activities (pedestrians)	U3: Said "Didn't look at directions in traverse" during debrief
5. Voice Notes Unclear	Scrap voice notes, change ORT back to voice note for describing activities	U3: "What makes a good voice note?" U1, U2, U3: Unsure of when to take voice notes
6. Station Pictures > Driving Directions	They were familiar with the locations so they didn't necessarily read directions, we could change ORT location or ignore it	U1: Recognized a station from a totally different view while reviewing the in the Note Sections in the Traverses
8. How Many Steps?	Expand the picture, scrollbar be present at all times, indicate how many steps there are at the top	U1: Notes took up the whole screen, hid later procedure steps
8. Slash Left Was Unclear	Move the number to the left of the semi-color, 4 min, adding seconds, take it out to move it to the header	U1: "The time for each station looks like it's in seconds"
9. Wanted a Map	Use maps in the traversal screens for context	U1: "I could've used a map on the device"
10. Which Steps Have Notes	Put icon in button label, Do nothing because notes are for novice users only, move the icon to the left / more prominent, line the icon with the button	U1: "I couldn't tell which steps had notes"

FINDING	DESIGN IMPLICATION	SOURCE(s)
11. Labeling Backup Activities	Make the backup activities more prominent / obvious, change the style of the backup activities	U1: Didn't see the label for Backup Activities or the difference.
12. Suggested a Equipment Check-List	Do nothing because Brent said it's not useful, attach it as a comma seperated on the top of the activities.	U3: I review on the device, so why not have more helpful points for reviewing"
13. Holding up Arm for Long Time is Unfamiliar and Stressful	Put on forearm facing up, vertical display, change display based on accelerometer, project onto hand	U3: Reading on the back of the hand might be easier
14. Segment Navigator Confusion	Do nothing, have a car above the arrow, etc,.	U1: Didn't understood motion vs stop
15. Time Elapsed Unhelpful	Remove it, have it count down, ask an executer from Desert RATS how they communicate time, add marker when you hit the end	U3: "At first I thought it should be counting down for consistency, but then again I didn't use that ever anyways"
16. "Where you should be" too small and not useful	Remove it, make it bigger, do nothing	U3: "It was hard to see in the sun, and I used the time left instead"
17. Routine was Helpful	Supports expert users understanding the device into a routine	U3: Strap helmet, review device, go. Unstrap helmet, take off device, get in.
18. Backup Activities Were Utilized	Validates both automony and display of activities	U3: Saw how much time she had left and did two extra activities.
19. Time Left (Red Text) Helped Inform Lateness	Don't change this part of the interface	U1: Correctly skipped activities because he saw he ran out of time U2: "Oh shoot, we're out of time." Skipped station 4. "I really like the red text, it sticks out" U3: Referred to time CONSTANTLY
20. Cuff-mounted design worked	Validates the placement of the device	U3: Last time I did it I kept having to ask Bernard to hold things"
21. Reviewed the Next Station During Ingress	Validates the need to show future stations	U3: Saw her reviewing next station's activities during ingress for the previous station
22. Improvement Validations	These worked	U3: "I liked the splitting up the notes inline by step instead of all at once," "Ingress and Egress time being left out was helpful"
23. Check off activities	Allow them to check off activities, active items scroll to the top, when you view a procedure it marks the activity as having been read	U1: "I wanted to check-off finished activities to know where I am"
24. Navigation was Clear	Keep it similar	U1: Up/Down and Prev/Next navigation was good
25. Training was Helpful	Keep training how it is, don't try to shorten	U2: Remembered part of an activity from training even though she couldn't find it in the device

APPENDIX D

FINAL ITERATION

In preparation for Landing Day, we further refined our prototype. Specifically, we finished the hardware implementation and installed every component (display, buttons, micro-controller, bluetooth, etc.) onto the cuff-mounted prototype.

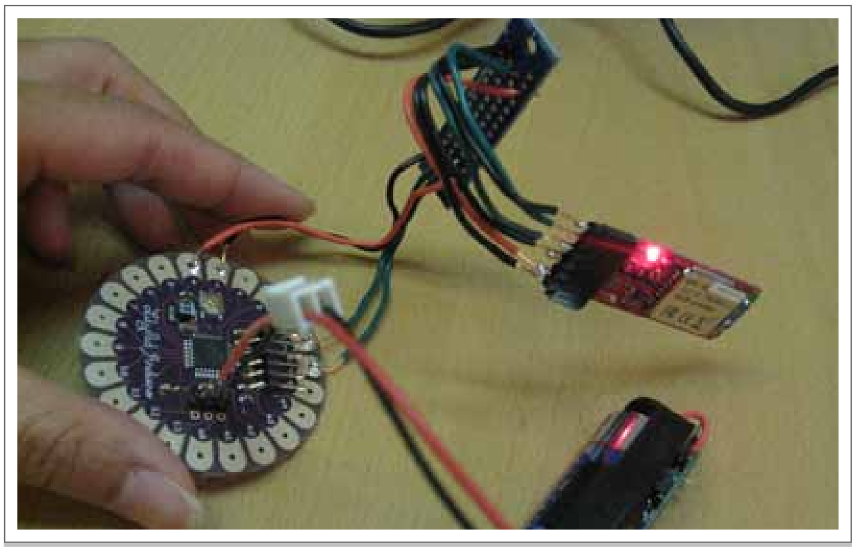
HARDWARE DEVELOPMENT

Hardware to interface the external buttons with the Android tablet was critical for the final iteration of our prototype. The main components of hardware we needed for our design included: a Arduino LilyPad micro-controller, a BlueSmirf Gold bluetooth module, several LED push buttons, and the Archos 5 Android internet tablet. The LilyPad communicates button push events to the Archos 5 via the BlueSmirf bluetooth module, and the Archos 5 device receives the data and responds appropriately to the input.

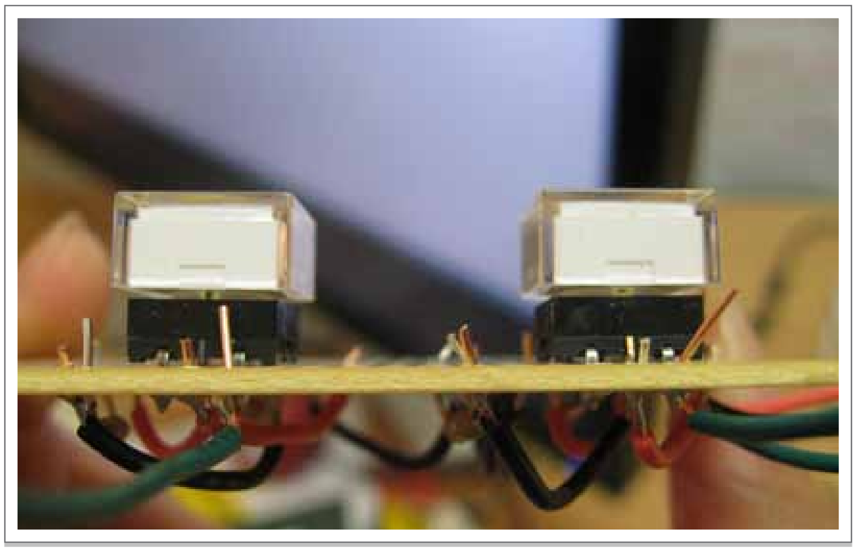
We wired the Arduino and bluetooth modules onto a small circuit board and powered by one AA battery, which is converted to the proper voltage for the LilyPad Arduino (3.3 volts). We also soldered LED buttons onto a circuit board and connected them to the LilyPad.

> *When we completed development, we found that the buttons correctly navigated the interface from up to 40 feet away*

Designing the hardware took us several weeks in total. We needed to be sure that it worked flawlessly, which was a tricky process when handling the bluetooth module. When we completed development, we found that the buttons correctly navigated the interface from up to 40 feet away. This created interesting opportunities for design, where the buttons could be placed anywhere on the Astronaut's suit to navigate the cuff-mounted interface. However, in the end we decided to stay with our original design of attaching them close to the device for efficiency in labeling the programmable buttons.



We connected and powered the Arduino micro-controller (LilyPad) and bluetooth component (BlueSmirf Gold).

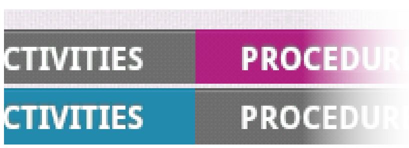


We designed the hardware such that the LED buttons light up when pushed, giving the user both tactile and visual feedback of a successful interaction.

ANDROID DEVELOPMENT: DESIGN RATIONALE

For the final iteration, we addressed major issues from the evaluation of the previous iteration,and we evaluated our prototype against our design guidelines [1], discussing any deviations that we noted. We refined our Android prototype and completed the hardware implementation.

VIEW TOGGLE BUTTON



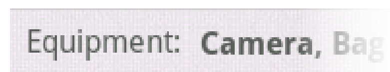
We differentiated Activities and Procedures with different highlight colors in the View Toggle Button to address navigation confusion from previous iterations. In the previous iteration, participants expressed confusion between the two types of information because the visual treatment was similar [2]. We decided to make the highlight colors distinct, but maintain good visual coherence.

NO MORE VOICE NOTES

Voice notes were removed from this iteration

Participants expressed confusion over its use case, since audio and video feeds are constantly recorded on space missions [3]. After much discussion, we decided that although it is useful for the astronaut to be able to mark "cool points" for the data processing staff, the burden of bookmarking data should be placed on the ground over the astronaut.

EQUIPMENT CHECKLIST



An Equipment Checklist displays all necessary equipment to accomplish the planned activities for the selected station. Participants often forgot to collect equipment during egress before walking away from the vehicle. Returning to the vehicle to retrieve equipment was often a costly mistake [4]. The upper right corner of the Segment Navigator displays, the Mission Time Left, the total time left to complete the day's plan.

MISSION TIME LEFT

While the Mission Time Elapsed (from the previous iteration) is the standard communication language for planners on the ground, it confused participants because it was juxtaposed to the Segment Time Left which was counting down. For these reasons we decided to optimize for the use case of the executors in alignment with our design guidelines.

[1] Design Guidelines, pp. 16

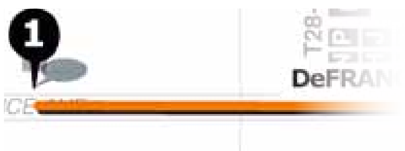
[2] [3] Third Iteration ORT Results, pp. 134

[4] Second Iteration ORT Results, pp. 118, Third Iteration ORT Results, pp. 134

[5] [6] Third Iteration ORT Results, P. 134

[7] Second Iteration Domain Research, P. 99

TRAVERSE MAPS



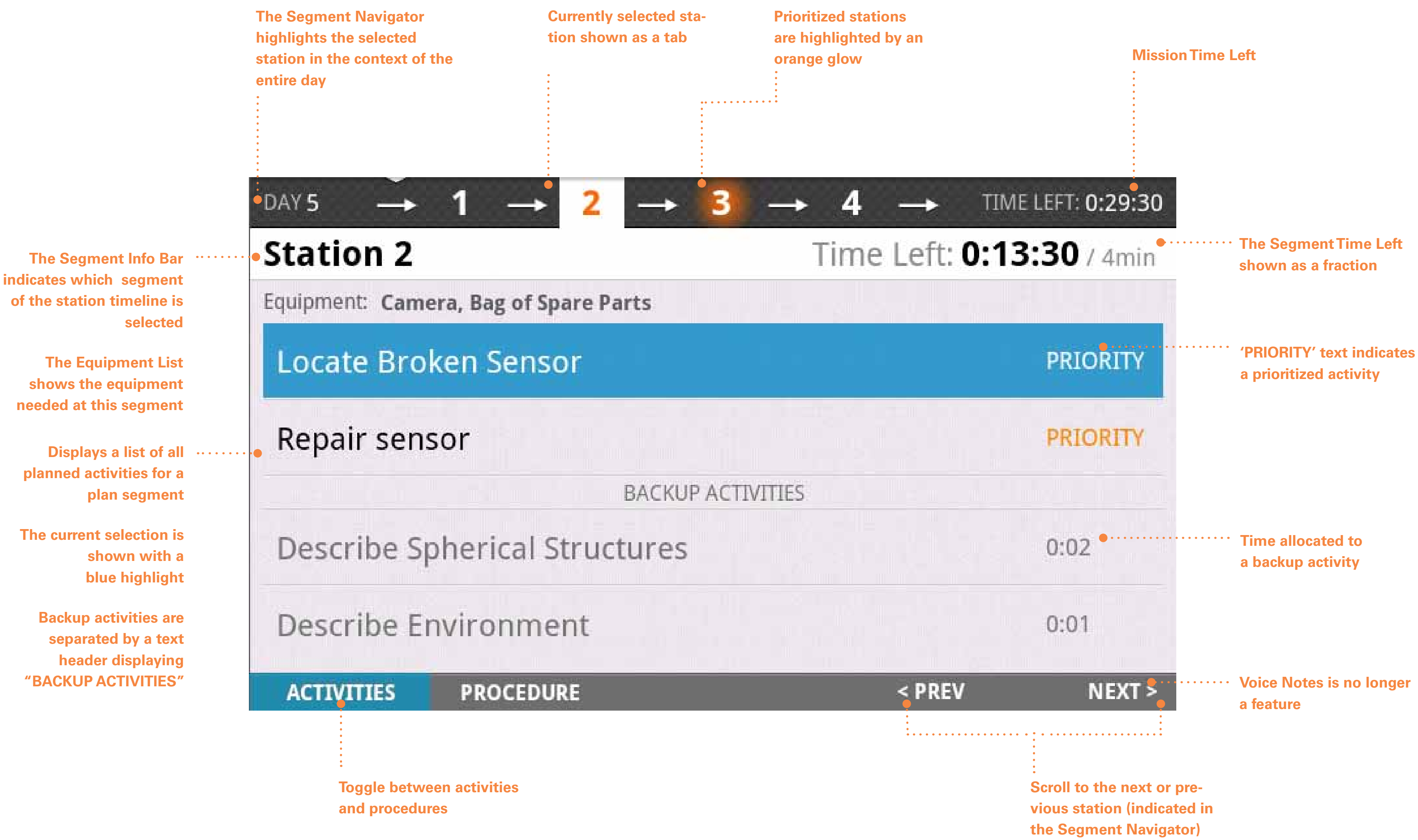
Each traverse segment displays a map of the corresponding traverse. During previous iterations, participants expressed interest in seeing a map along with driving directions [6].

ZOOM

A zoom function was add for Execution Notes with pictures, allowing a larger view of the picture. While participants did not express the need to zoom any of the Execution Notes in the plan for our ORT, domain research revealed that many schematics could be more complex, making a zoom feature very useful [7].

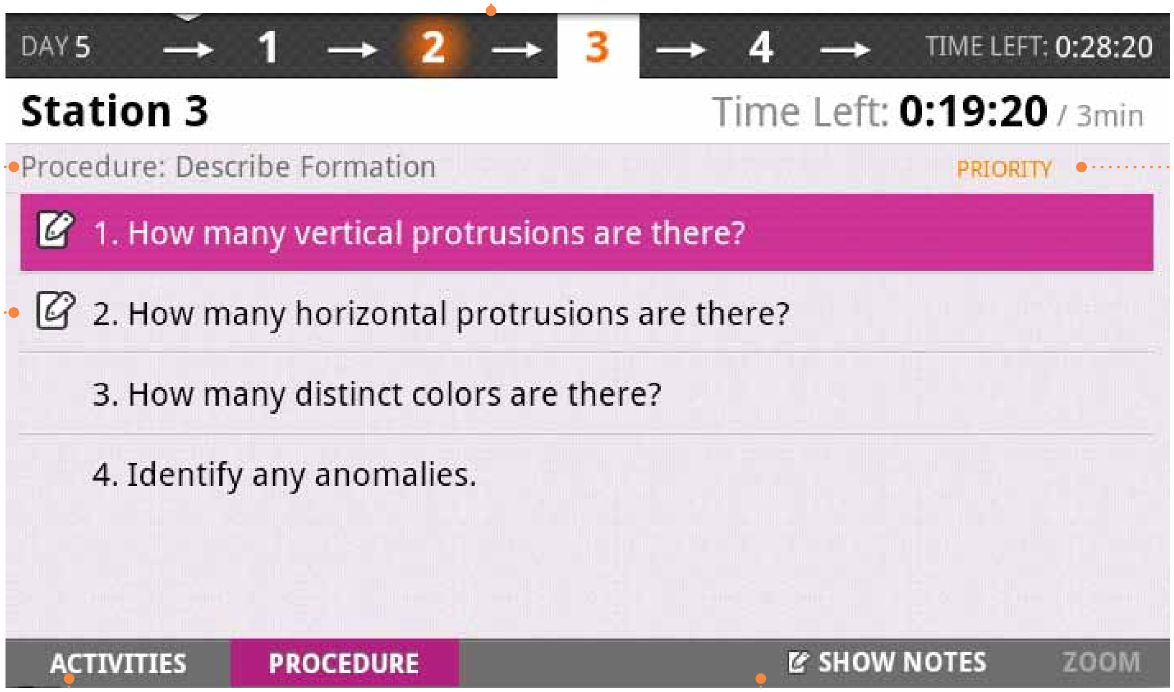
ANDROID DEVELOPMENT: ACTIVITY LIST

Core improvements in the last iteration of the Activity List included the removal of Voice Notes, addition of the Equipment List, and visual refinements.



ANDROID DEVELOPMENT: PROCEDURE VIEWER

The Procedure Viewer, although still a list, has a different highlight to help distinguish it from the Activity List.



Marcus-Bains Notch indicates which plan segment executors should be completing based on Mission Time Elapsed

Activity Info Bar displays information about the current activity

Priority icons are displayed for the current activity

Displays a list of all procedures for the associated activity

The current selection is displayed with a purple highlight

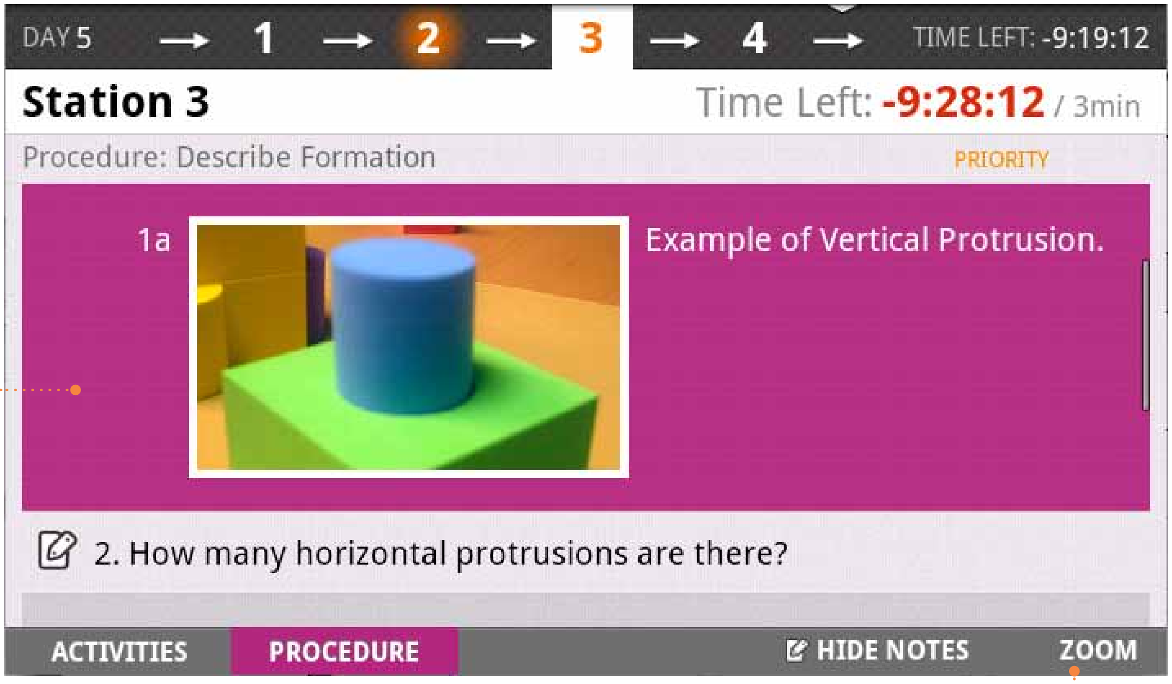
Steps with Execution Notes are indicated by an icon

Toggle between activities and procedures

Show Execution Notes

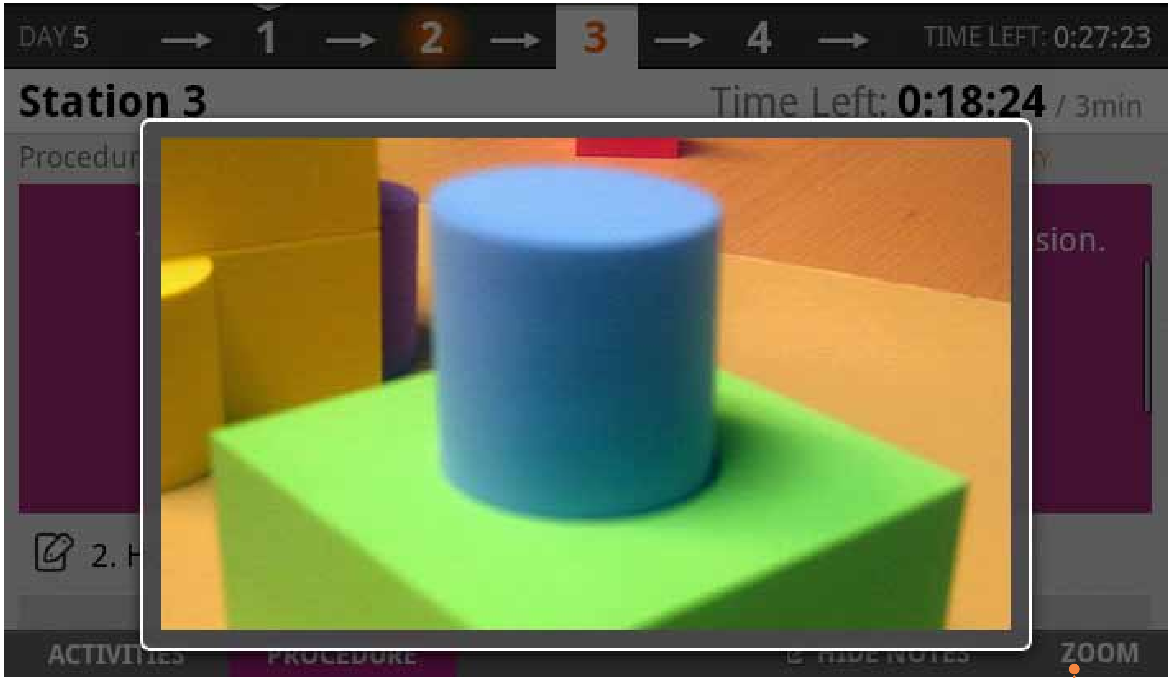
ANDROID DEVELOPMENT: EXECUTION NOTES

To help differentiate from Procedure Steps, Execution Notes are now numbered according to their corresponding procedure step. If the note contains a picture, the user can zoom in on that picture.



Execution Notes are displayed inline and indented

Zoom in on the picture of the selected Execution Note



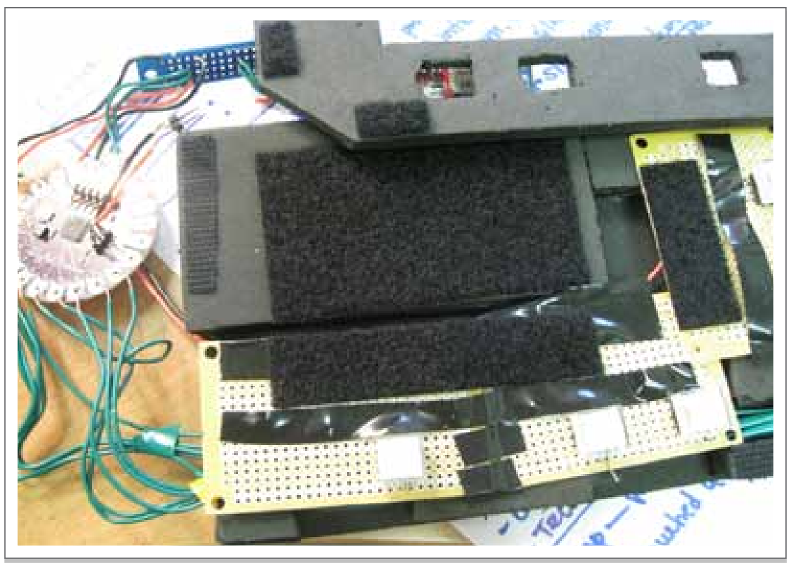
Exit zoom back out to go back to procedures

WEARABLE DEVELOPMENT

We built a custom foam core structure to house the Android tablet, circuit board, and external buttons. We then attached the foam core enclosure to the outside of the mount with velcro and elastic. We created a second fabric enclosure for the rest of the hardware components to shield the hardware during the mission simulation.

Our wearable, though not entirely robust, worked well for testing purposes because the individual components are removable. Everything stayed in securely and the participants did not complain about the admitted bulkiness of the prototype. Notably, this is a proof of concept, where a final design would have a more elegant connection to the spacesuit.

> *Our wearable worked well for testing purposes because the individual components are removable*



Layers of foam core with different cutouts, stacked together to house the hardware

The green pockets store the Arduino and Bluesmirf. Batteries are strapped on down below

OPERATIONAL READINESS TEST

Our last Operational Readiness Test was called Landing Day. We again recruited three participants, with one repeat participant to gauge expert performance. One of our participants is a NASA scientist with extensive field work experience in extreme environments.

To simulate the physical constraints, we asked the participants to don the full mock space suit plus helmet. We also purchased gloves for the participants to wear while operating the device.

One of the participants testing out the final prototype during the briefing

The majority of the participants were able to complete some backup activities, like making observations about the environment

The physical buttons provided tactile feedback even though the participants wore gloves

OPERATIONAL READINESS TEST: RESULTS

Every participant was able to finish the mission, some with minutes to spare. Most were also able to accomplish backup activities along the way. They had many good things to say about the interface and the remaining issues were largely out-of-scope or due to personal preferences.

We began synthesizing all the data we gathered in the ORT by going through the raw data (notes, observations, video) and noting any major findings. Along with each finding, we determined possible design implications.

TOP 5 ISSUES

FINDING	DESIGN IMPLICATION	SOURCE(s)
1. Traverse Information Not Shown on Time's Up Dialog	Show information for the last traverse in the dialog	U1: Had to compare notification of 4 minutes left to how long is the last traverse actually allocated to take
2. Traverse Map Was Not Used	Orient maps consistently, with North up	U1, U2, U3: "I didn't look at the map on the device." U2: Confused by the different orientations of the map view between paper and device
3. Confused About Which Activities Have Procedures	This could be marked with an icon or strengthening the dimmed procedure label	U2, U3: "I wasn't quite sure which activities had procedures."
4. Preparation of Plan Not Exactly Representative	Testing the device with more familiar plans and expert users might reveal different usability issues, which would be helpful for future tests on LuMo	U3: "I think the main weirdness was that we didn't get to spend enough time with the plan. Normally, you spend months and months on the plan so you know it really well."
5. Physical Prototype Buttons Too Far From Labels	Put the buttons closer to the labels when constructing the actual device	U3: "In an actual device, the buttons would be closer to the labels than they are now."
6. Based on Performance and Plan, Sometimes Mission Time Left Should Be Bigger	Based on the plan content or experience level of the astronaut, decide which should be more prominent: Mission Time Left or Segment Time Left	U2: "When I was ahead, I found the overall Time Left to be more useful." U3: "Each station's allocated 3-4 minutes. It's pretty similar so I found the overall Time Left to be more useful."
7. Shortcut For Procedure Browsing	Add more buttons to allow users to jump from procedure to procedure, tack on the next procedure when the end of a procedure is reached	U1: "Might be nice to go straight to the next activity once you reach the end of the procedure."

FINDING	DESIGN IMPLICATION	SOURCE(s)
8. Color Helped Distinguish Activities vs. Procedures	This was a successful solution and should be considered in future prototypes	U1: Briefly struggled with the difference, but adjusted quickly U2: "I like the new display of procedures and activities. It's a great improvement from last time."
9. Equipment List On Device Worked Well	While we've heard this worked well, we would like to validate the equipment list with more expert users in the future	U1, U2, U3: No one forgot anything U2: "I like being able to see what I need the whole time."
10. Segment Time Left Was Easy To See And Useful	This was a successful solution and should be considered in future prototypes	U1: "8 minutes left! I think we have time for Station 4!"
11. Looking Ahead Was Helpful During Egress and Ingress	Our research of a mobile checklist being useful for last minute preparations during egress and ingress proved to be valuable	U1, U2, U3: Looked at activities during egress. U1: "I looked at the future activities during ingress."
12. Supports Real-time Replanning	Giving executors information about Activity steps and not constraining them to time supports the need to dynamically replan	U2: Did the backup activities first because he could do them while walking to and from the formation. U2: "Yeah, that's another 2 minutes lost (ingress and egress) so I'm not going to go do that (take picture)."
13. General Improvements	Repeat participants responded positively to our final interface. It's possible that further user tests might not have revealed much more, where future improvements would be best suited for new concepts rather than refinements	U2: "It was A LOT better than last time. I liked how the items were needed were always on the screen." U3: "Hm...this is hard because it is already really good." (when responding to question about interface problems)
14. Supports Novice and Expert Users	Hiding notes by default helps reduce clutter for experts	U2: "I didn't look at the notes for that one at that station because it was never needed."
15. Tailor Interface to Personal Preferences	Explore personalization based on each user's preferences	U2: "At this point, it's just my personal taste, not the overall usability. I think this is pretty great already." U3: "I would have wanted the equipment list to be bigger." U3: "It might be nice to have the zoom button be a check-off button."
16. Useful On Long Missions	Explore checking off activities	U3: Many times I don't need this, but I can see this being useful in a long mission where things change, you might forget things, and you want to check-off things you've done."

Our final ORT had the participants in full mock space suits to test the wearable and hardware with more realistic physical constraints like fatigue.

APPENDIX E

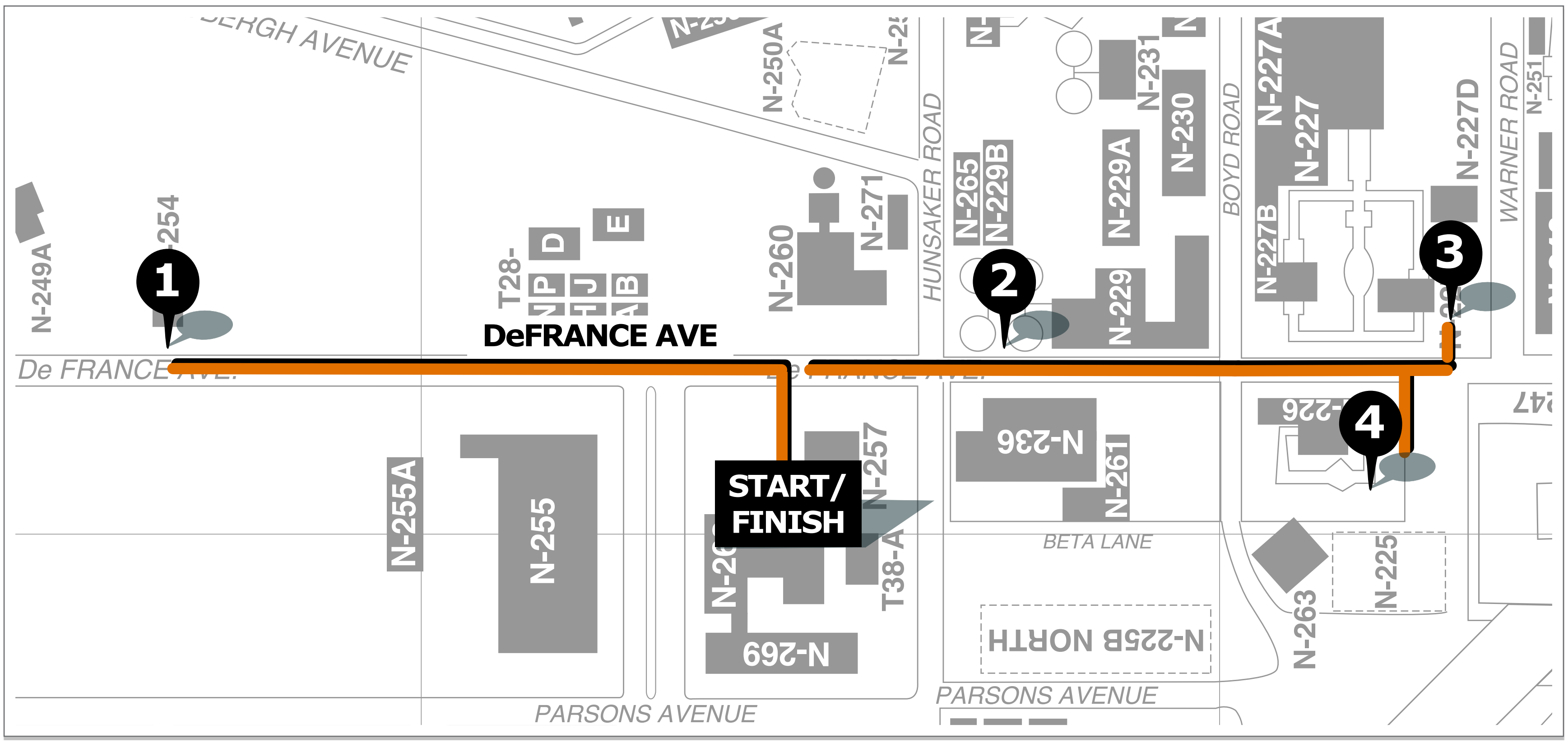
ORT MAP & PLAN

We first spent a lot of time trying to figure out what kind of activities to include in the mock mission: it must be analogous to geological activities, but must also employ a vocabulary readily understandable by the ORT participants, who are likely not trained geologists. We settled on creating "geological formations" out of colored foam blocks. Therefore, participants would only need to be aware of everyday words like color, shape, size, count, etc.

Second, we scouted out four locations around NASA Ames campus and placed a foam formation at each station. We strived to test a different kind activity at each station. For example, Station 1 was about making observations while Station 2 was about "fixing" a foam sensor according to a schematic.

MISSION MAP

We gave our participants a physical map to carry onboard the vehicle to help guide them through the traversals. Our plan specified four unique stations with activities like describing physical formations and collecting samples. Snippits of this map were also provided on LuMo to help remind them of their path while ingressing.



ORT PLAN

The following pages contain an exact transcription of the ORT plan. Its original form is a Microsoft Word document, which we formatted so that each page only shows one plan segment (Traverse or Station). We printed out two copies of this plan: one for the inside of the vehicle, and one for Ground Support sitting in the chase car.

This plan was also digitized for the LuMo prototype. Participants of the ORT used the paper version while inside the vehicle and used LuMo while outside of the vehicle. A copy of the map is also placed inside the vehicle.

Just like LuMo, this plan went through several iterations, mostly due to station changes and adjusted timings per station. The version included in this appendix is the one from the Final Iteration.

Participant looking at the paper plan during a Traverse onboard

Participant using LuMo, which contains a digital version of the plan

TRAVERSE 1 0:00-2:00 (2MIN)

Activity: Drive to Station 1

1. Turn North on De France Avenue out of parking lot.
2. Drive North on De France Avenue to large orange structure.

3. Find closest available parking for LER.

Activity: Note any woodland creatures in the field to the East

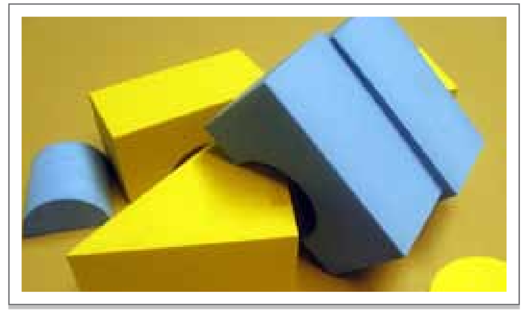
Activity: Egress

STATION 1 2:00-6:00 (4MIN)

Equipment: Ruler, Camera

Activity: Locate Formation

1. Search for blue and yellow formation at the base of the fence.
   NOTE: Sample from blue and yellow formation



Activity: Describe Formation

1. How tall is the highest point?
   NOTE: Use the ruler to measure in inches.
2. Estimate the number of blue blocks.
3. What is the most common shape?
   NOTE: Shapes might include cylinder, triangle, rectangular block, or arch.
4. Identify any anomalies.

Activity: Take Pictures

1. Take a picture from all four sides of the formation.
2. Take a close up picture of the tallest part of formation.

BACKUP ACTIVITIES

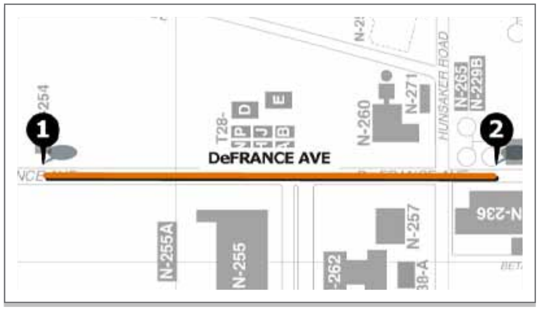
Activity: Describe Orange Structure (1 min)

1. Estimate the height of the orange structure in feet.
2. Estimate the width of the orange structure in feet.

TRAVERSE 2 6:00-10:00 (4MIN)

Activity: Ingress

Activity: Drive to Station 2



1. Go South on De France Avenue.
2. Drive South on De France Avenue to large metallic spherical structures.

3. Find a shaded parking location for LER.

Activity: Count the number of cars and pedestrians you pass on the drive.

Activity: Egress

STATION 2 10:00-14:00 (4MIN) *PRIORITY*

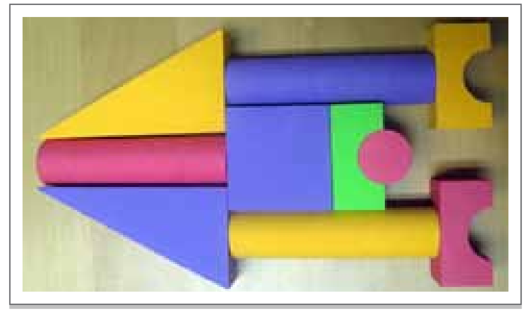
Equipment: Camera, Bag of Spare Parts

Activity: Locate Broken Sensor *PRIORITY*

1. Search for broken sensor device underneath the most southern tree.

Activity: Repair Broken Sensor *PRIORITY*

1. Take a picture of broken sensor device before disturbing.
2. Reconstruct sensor device to match specification (see Notes).



NOTE: Sensor Device Specification

3. Collect any broken parts and replace with spares.
4. Take a picture of reconstructed sensor device.

BACKUP ACTIVITIES

Activity: Describe Spherical Structures (2 min)

1. Count the total number of spherical structures in the area.
2. Estimate the diameter of the spherical structure in feet.

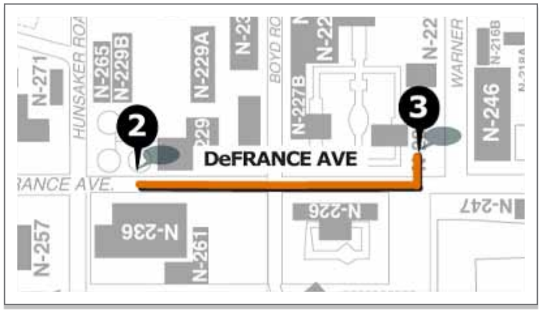
Activity: Describe Environment (1 min)

1. Count the total number of trees less than 10 feet away from the structures.

TRAVERSE 3 14:00-18:00 (4MIN)

Activity: Ingress

Activity: Drive to Station 3



1. Proceed South on De France Ave.
2. Drive towards the row of trees located on the left.

3. Park the LER in any available parking spot near the rows of trees.

Activity: Egress

STATION 3 18:00-21:00 (3MIN) *PRIORITY*

Equipment: Sample Collection Bag

Activity: Locate Formation *PRIORITY*

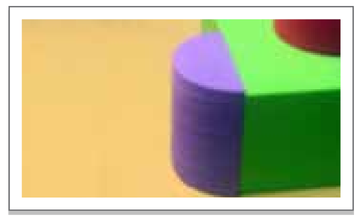
1. Search for formation at the base of one of the trees.

Activity: Describe Formation *PRIORITY*

1. How many vertical protrusions are there?

NOTE: Vertical Protrusion

2. How many horizontal protrusions are there?



NOTE: Horizontal Protrusion

3. How many distinct colors are there?
4. Identify any anomalies.

Activity: Collect Sample

1. Identify blue base with green protrusion.
2. Carefully lift green protrusion from blue base.
3. Place sample in Sample Collection Bag.

BACKUP ACTIVITIES

Activity: Describe Environment (2 min)

1. Count the total number of trees in the two rows.
2. Estimate the distance between the 2 rows of trees.

TRAVERSE 4 21:00-24:00 (3MIN)

Activity: Ingress

Activity: Drive to Station 4

1. Continue North on De France Avenue.
2. Make an immediate left in the next available drive-in lot.
3. Park LER in a reasonable location but not near the high voltage zone.

Activity: Egress

STATION 4 24:00-27:00 (3MIN)

Equipment: Ruler

Activity: Locate Formation

1. Search for triangular formation at the base of the plant formation.
   NOTE: Samples from the triangular formation.

Activity: Describe Formation

1. Estimate the number of blue triangles?
2. How tall is the tallest point?
   NOTE: Use the ruler to measure in inches.
3. Identify any anomalies.
4. Compare colors and shapes to observations at station 1.

NOTE: Station 1 formation

BACKUP ACTIVITIES

Activity Describe High-Voltage Structure (1 min)

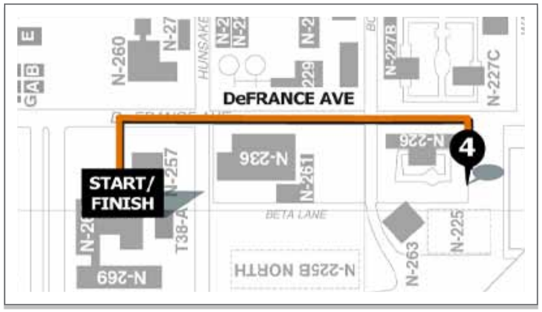
1. Estimate the height of the highest point of the high-voltage structure

Activity Describe Environment (1 min)

1. Estimate the distance from the shrub to the high voltage structure in feet.

TRAVERSE TO CAMP 27:00-30:00 (3MIN)

Activity: Drive to Basecamp



1. Turn out of the lot and head north on De France Ave
2. Continue on De France Avenue to Basecamp.
3. Find any available parking for the LER.


Station 2: Crater
Time Left: 0:36:30
Camera, Sample Collection Kit
Sample crater rim
Pan crater rim
Collect rock samples
BACKUP ACTIVITIES
Trench
ACTIVITIES
PROCEDURE
10min
< PREV
NEXT >
ARCHOS
5 internet tablet
NASA