

CMU DARPA Subterranean Challenge Final Presentation

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► Meet our client

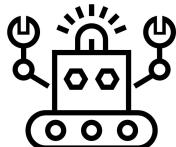


Team Explorer is comprised of 20+ graduate students and full-time faculty members in the **CMU Robotics Institute** and **Oregon State University's** Robotic Decision Making Lab.

► Key terms



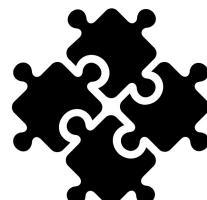
Defense Advanced Research
Projects Agency (DARPA)



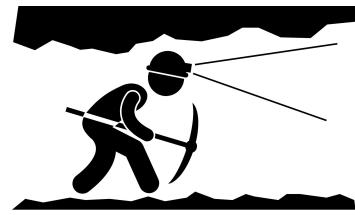
Rocky



Base Station Operator
(BSO)



STIX



Subterranean



Communication
nodes

► DARPA Subterranean Challenge



A multi-year robotics competition that seeks new approaches to **rapidly map, navigate and search** underground environments using semi-autonomous robots.

► Application

Support **emergency first responders** and **combat operators** in complex underground environments.



► Competition objective

Find all the artifacts that are located in a cave, as quickly and as accurately as possible.

There are **5 artifact categories:**

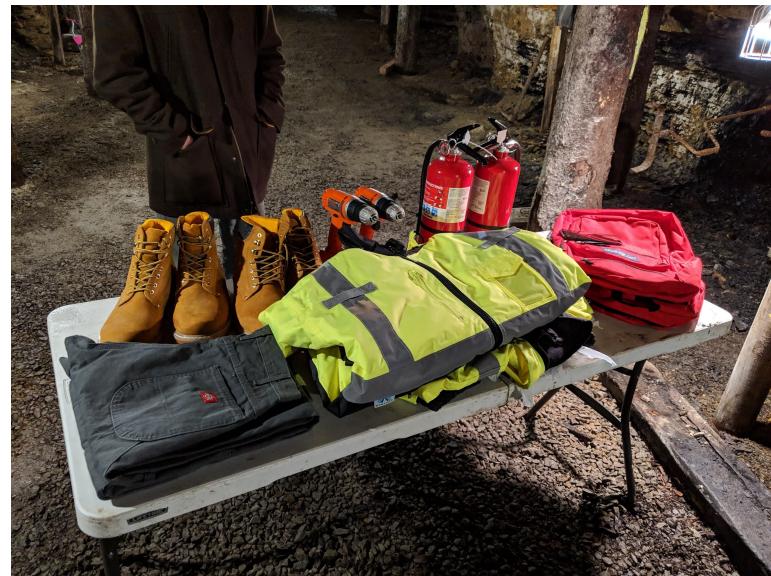
 **Drill**

 **Red Backpack**

 **Survivor**

Fire Extinguisher

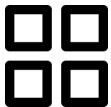
Cell Phone



► How to win



Accurate location reporting



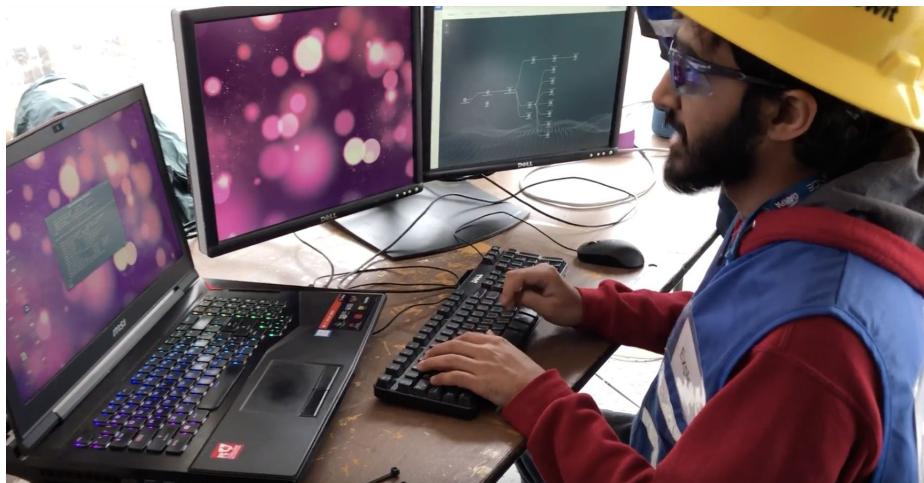
Accurate object category



Faster submissions to DARPA

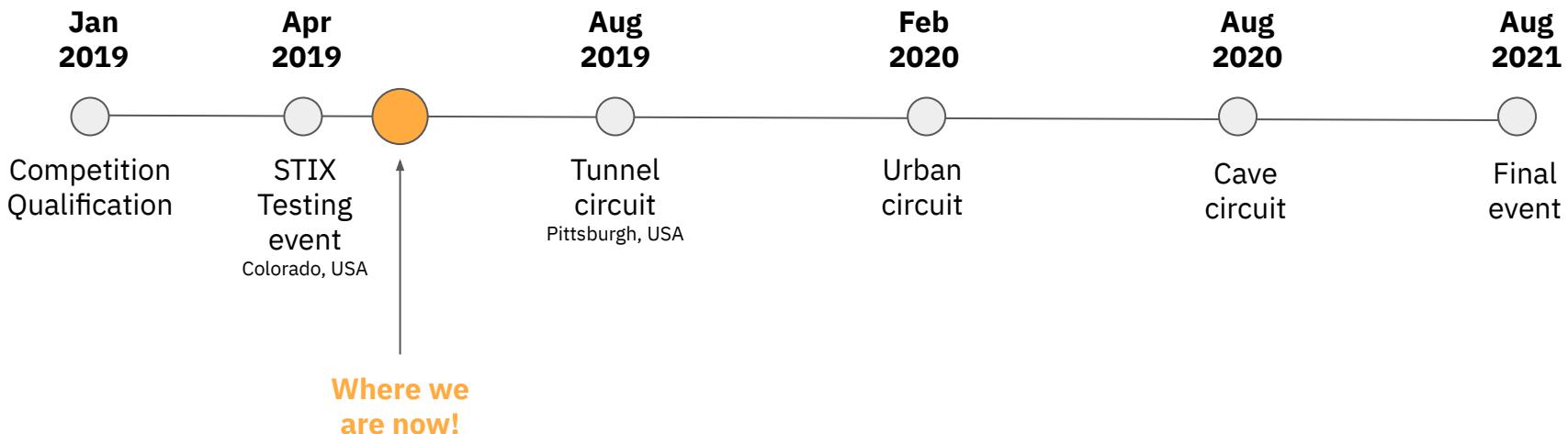
► Capstone objective

Design a **base station interface** to increase efficiency and reduce cognitive load for the base station operator as they **monitor multiple air and ground robots**.

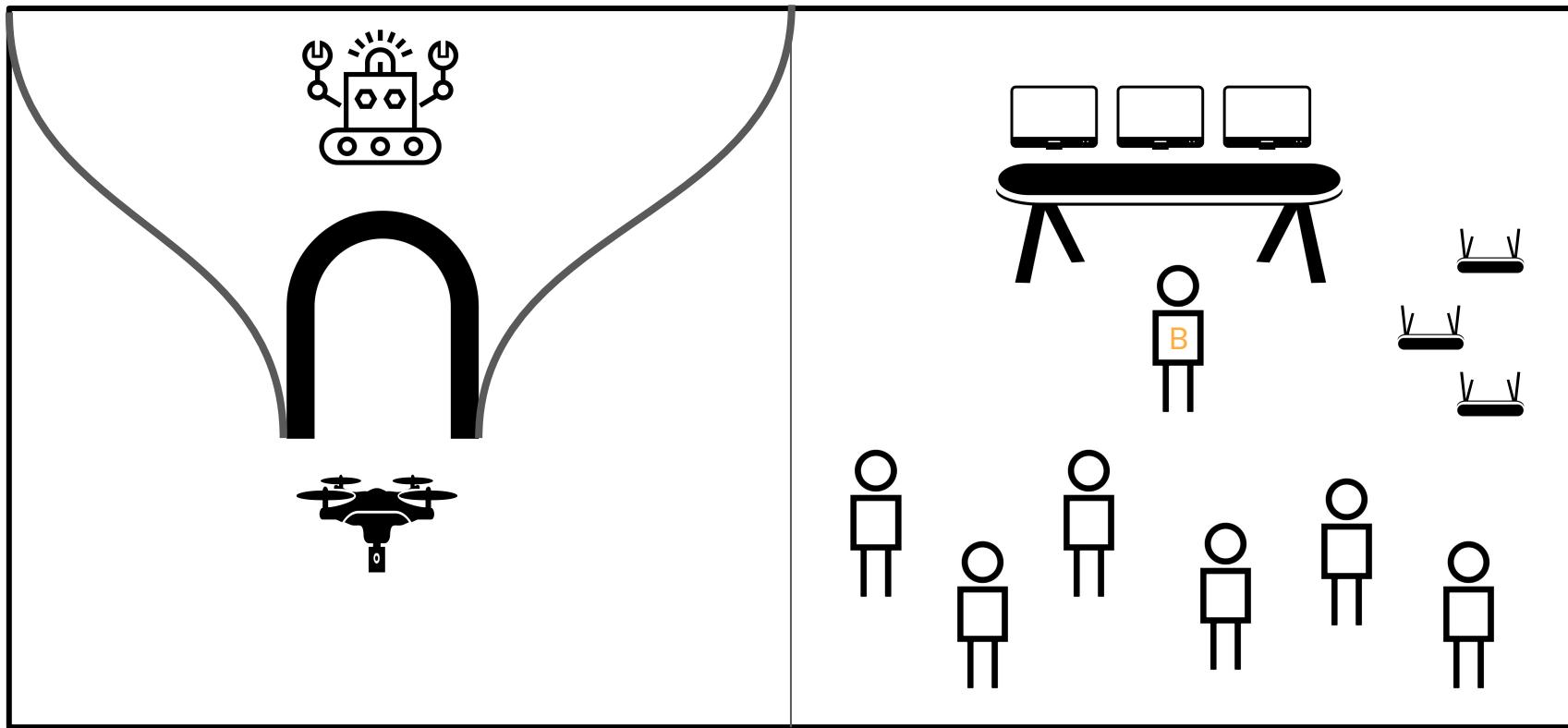


Vasu as the base station operator!

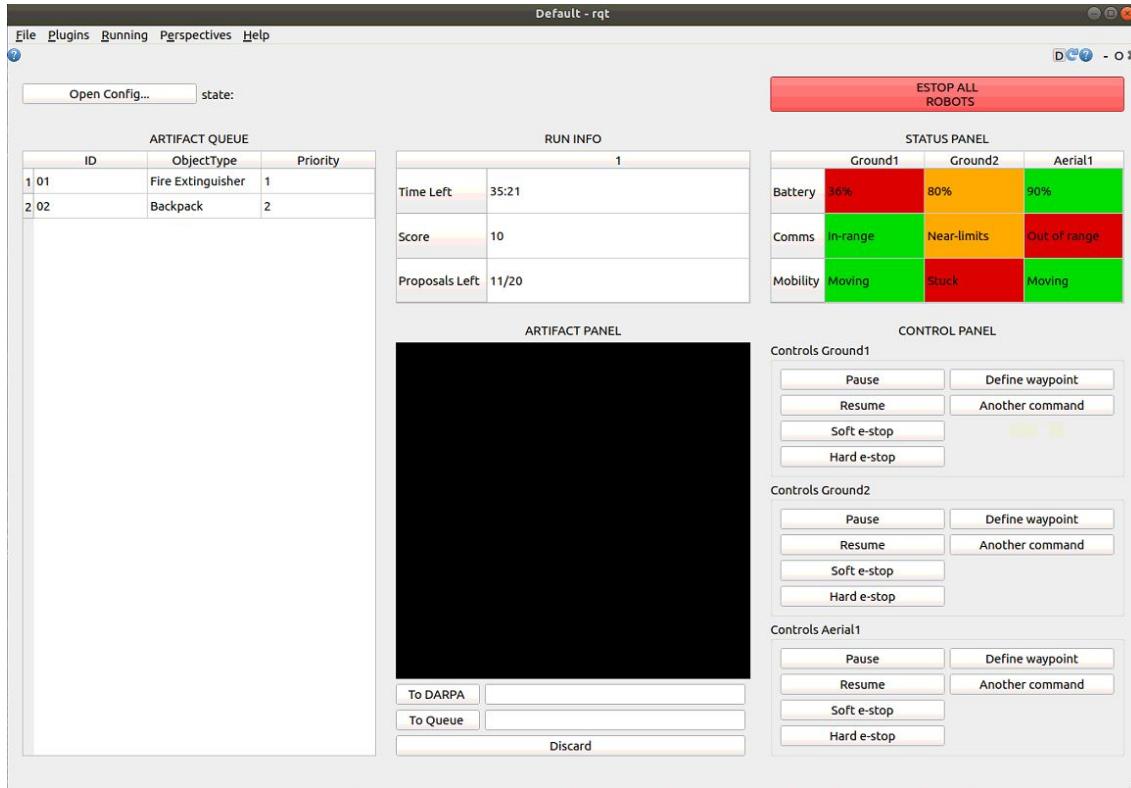
► Team Explorer timeline



► Base station setup



► Initial client GUI





Walkthrough + Demo

Action/Detection

The Action/Detection interface displays a list of artifacts identified by robots. The top bar shows '45/60' artifacts found. The 'Artifact Queue' section lists items in three categories: IDENTIFIED, SUBMITTED, and ARCHIVED. The 'Detail Pane' shows a video feed of a person in a yellow vest, a 3D point cloud map, and identification details for 'BP-01'. A 'Category' section identifies items like Backpack, Survivor, Fire Extinguisher, Cell Phone, and Drill. A 'DETAIL' section provides timestamp, location, and identification count information.

Category	Item	Count	Timestamp
Backpack	BP-01	1	04:13:02
Survivor	SU-02	1	06:01:31
Fire Extinguisher	FE-01	1	52:01:31
Cell Phone	CP-01	1	02:01:31
Drill	FE-02	1	42:01:31
Drill	FE-03	1	12:01:31
Drill	FE-04	1	22:01:31

Monitoring

The Monitoring Toolkit interface shows a live video feed of a robot named 'Rocky' in a dark environment. The top right corner shows 'Rocky' is active and part of a fleet. The 'Health' section displays battery, connectivity, mobility, CPU, and disk space levels. The 'Controls' section includes buttons for defining waypoints, dropping communication nodes, returning home, and emergency stops. The 'Message Center' and 'Notification Center' sections show recent messages and notifications.

Robot Status: Active - 1st robot in fleet
2-Axle Wheeled Ground Vehicle

Health:

- Battery: 45 min remaining
- Connectivity: 108 m from node
- Mobility: 96% capacity
- CPU: 68% capacity
- Disk Space: 74% capacity

Controls:

- Define Waypoint
- Drop Comm Nodes
- Return Home
- Highlight Robot
- SOFT Emergency Stop
- HARD Emergency Stop

Message Center:

- [16:54:24] Rocky (02) has identified a new object.
- [16:49:16] Rocky (02) has 25 minutes of battery life remaining.
- [17:49:02] Rocky (02) has completed a new object.

Notification Center:

Action/Detection

The screenshot displays the Action/Detection interface. At the top, a progress bar shows "45/60 Success Rate". Below it, the "Artifact Queue" section lists identified artifacts: BP-01 (04:13:02), SU-02 (06:01:31), FE-01 (52:01:31), and CP-01 (02:01:31). The "Submitted" section shows pending submissions: BP-01 (02:01:31), FE-02 (02:01:31), D-02 (42:01:31), FE-03 (12:01:31), and FE-03 (22:01:31). The "Archived" section contains entries for FE-01 (52:01:31) and FE-01 (52:01:31). The "Detail Pane" on the right shows a video feed of a person in a yellow vest, coordinates (X: 161.569448, Y: -58.781789, Z: 781.3674187), and a 3D point cloud visualization with a red line and crosshair.

The screenshot displays the Monitoring Toolkit interface. At the top, a progress bar shows "15/30 Posts Received" and "30:03 Time Remaining". The main area shows a 3D point cloud visualization of a vehicle. On the right, the "Rocky" vehicle status is shown: Active - Tax robot in Best 3-Axis Wheeled Ground Vehicle. The "Health" section includes battery (45 min remaining), connectivity (100 m from node), mobility (98% capacity), CPU (48%), and disk space (74% capacity). The "Controls" section includes buttons for Define Map/World, Stop Camera, Emergency Stop, and Auto Emergency Stop. The "Message Center" shows a message: "Rocky - Robot has been detected at location: 100.000000, 58.781789, 781.3674187. Robot has been detected at location: 100.000000, 58.781789, 781.3674187." The "Notification Center" is empty.

45/60

Guesses Used

15/30

Points Received

30:03

Time Remaining

Artifact Queue

IDENTIFIED

D-01 1 04:13:02

SU-03 1 00:01:31

SU-02 1 06:01:31

FE-01 1 52:01:31

CP-01 1 02:01:31

SUBMITTED

BP-01 1 02:01:31

FE-02 1 02:01:31

D-02 1 42:01:31

FE-03 1 12:01:31

FE-03 1 22:01:31

ARCHIVED

FE-01 1 52:01:31

FE-01 1 52:01:31

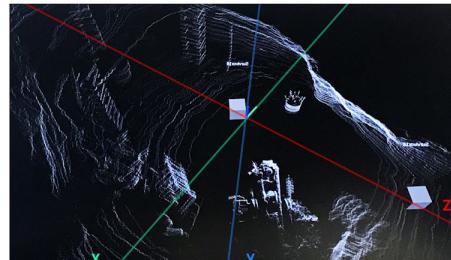
FE-01 1 52:01:31

Detail Pane

SU-03

1

04:13:02



X: 161.560448
Y: -58.7818789
Z: 781.3674187

Refine Point



Category

- Backpack
- Survivor
- Fire Extinguisher
- Cell Phone
- Drill

DETAILS

Timestamp: 02:01:31
 Identified By: GV1 (Rocky)
 Location: (161.560448, -58.7818789, 781.3674187)
 43 ft from Comm1
 # of Identifications: 01

Send to DCP

- ▶ **Scenario: An artifact is detected!**

45/60

Guesses Used

15/30

Points Received

30:03

Time Remaining

Artifact Queue

IDENTIFIED

D-01 1 04:13:02

SU-03 1 00:01:31

SU-02 1 06:01:31

FE-01 1 52:01:31

CP-01 1 02:01:31

SUBMITTED

BP-01 1 02:01:31

FE-02 1 02:01:31

D-02 1 42:01:31

FE-03 1 12:01:31

FE-03 1 22:01:31

ARCHIVED

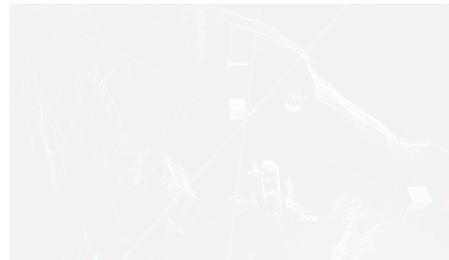
FE-01 1 52:01:31

FE-01 1 52:01:31

FE-01 1 52:01:31

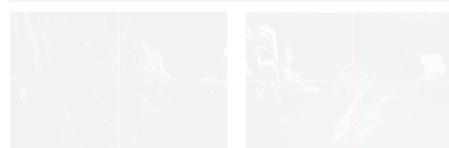
Detail Pane

SU-03 1 04:13:02



X: 161.568448
Y: -58.7818789
Z: 781.3674187

Refine Point

**Category**

Backpack

Fire Extinguisher

Drill

Survivor

Cell Phone

DETAILS

Timestamp: 02:01:31
 Identified By: GV1 (Rocky)
 Location: (161.568448, -58.7818789, 781.3674187)
 43 ft From Comm1
 # of Identifications: 81

Send to DCP

45/60

Guesses Used

15/30

Points Received

30:03

Time Remaining

Artifact Queue

IDENTIFIED

D-01 1 04:13:02

SU-03 1 00:01:31

SU-02 1 06:01:31

FE-01 1 52:01:31

CP-01 1 02:01:31

SUBMITTED

BP-01 1 02:01:31

FE-02 1 02:01:31

D-02 1 42:01:31

FE-03 1 12:01:31

FE-03 1 22:01:31

ARCHIVED

FE-01 1 52:01:31

FE-01 1 52:01:31

FE-01 1 52:01:31

Detail Pane

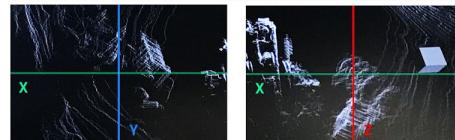
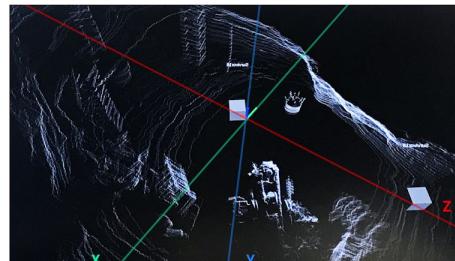


SU-03



1

04:13:02



Category

- Backpack
- Survivor
- Fire Extinguisher
- Cell Phone
- Drill

DETAILS

Timestamp: 02:01:31
Identified By: GV1 (Rocky)
Location: (161.560448, -58.7818789, 781.3674187)
 43 ft from Comm1
of Identifications: 01

Send to DCP

45/60

Guesses Used

15/30

Points Received

30:03

Time Remaining

Artifact Queue

IDENTIFIED

D-01 1 04:13:02

SU-03 1 00:01:31

SU-02 1 06:01:31

FE-01 1 52:01:31

CP-01 1 02:01:31

SUBMITTED

BP-01 1 02:01:31

FE-02 1 02:01:31

D-02 1 42:01:31

FE-03 1 12:01:31

FE-03 1 22:01:31

ARCHIVED

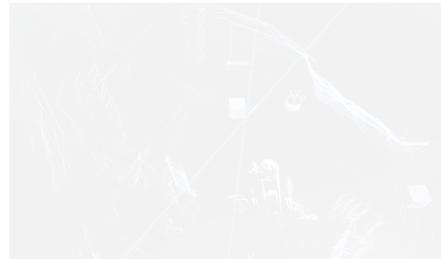
FE-01 1 52:01:31

FE-01 1 52:01:31

FE-01 1 52:01:31

Detail Pane

SU-03 1 04:13:02



X: -161.568448
Y: -58.7818789
Z: 781.3674187

Refine Point



Category

- Backpack
- Survivor
- Fire Extinguisher
- Cell Phone
- Drill

DETAILS

Timestamp: 02:01:31
Identified By: GV1 (Rocky)
Location: (-161.568448, -58.7818789, 781.3674187)
43 ft From Comm1
of Identifications: 81

Send to DCP

Monitoring

45/60

Artifact Queue

BP-01 04/13/02

SU-02 06/01/31

FE-01 52/01/31

CP-01 02/01/31

BP-01 02/01/31

FE-02 02/01/31

D-02 42/01/31

FE-03 12/01/31

FE-03 22/01/31

FE-01 52/01/31

FE-01 52/01/31

FE-01 52/01/31

BP-01 04/13/02

15/30 30:03

Detail Pane

BP-01 04/13/02

SU-02 06/01/31

FE-01 52/01/31

CP-01 02/01/31

BP-01 02/01/31

FE-02 02/01/31

D-02 42/01/31

FE-03 12/01/31

FE-03 22/01/31

FE-01 52/01/31

FE-01 52/01/31

FE-01 52/01/31

BP-01 04/13/02

Category

- Backpack
- Survivor
- Fire Extinguisher
- Cell Phone
- Drill

Details

Timestamp: 04/13/21
Identified By: 001-00000000-00-00000000-000000000000
Location: 12345-00000000-00-00000000-000000000000
Altitude: 45.1 ft. from ground

No. of identifications: 41

Send to DCP

Monitoring Toolkit

Rocky

Active - 1st robot in fleet
2-Axle Wheeled Ground Vehicle

Health

- Battery: 45 min remaining
- Connectivity: 108 m from node
- Mobility: 96% capacity
- CPU: 68% capacity
- Disk Space: 74% capacity

Controls

- Define Waypoint
- Drop Comm Nodes
- Return Home
- Highlight Robot
- SDR Emergency Stop
- HARD Emergency Stop

Message Center

[16:54:24] Rocky (D2) has identified a new object.
[16:49:16] Rocky (D2) has 25 minutes of battery life remaining.
[17:49:02] Rocky (D2) has completed a new object.

Notification Center

Monitoring Toolkit

System Overlook

Rocky Magic Flighty Wall-E Lofty

View All

Rocky

Magic

Flighty

Wall-E

Lofty

Battery

Connectivity

Mobility

Layers

Vehicles
 Artifacts
 Communication Nodes

Point Cloud
 LIDAR
 Thermal Imaging
 Bluetooth Signal

+ -

Top View Perspective View

Notification Center 3

Monitoring Toolkit

The Monitoring Toolkit interface displays a central video feed of a robot navigating through a dark, cluttered environment. Below the main feed are five smaller camera feeds labeled: Point Cloud Map, Front Camera, Rear Camera, Right Camera, and Left Camera. To the right of the video feed are several monitoring panels:

- System Overlook**: Shows robot icons for Rocky, Magic, Flighty, and Wall-E.
- Rocky**: Active - 1st robot in fleet, 2-Axle Wheeled Ground Vehicle. Includes:
 - Health**: Battery (45 min remaining), Connectivity (108 m from node), Mobility (96% capacity), CPU (68% capacity), Disk Space (74% capacity).
 - Controls**: Define Waypoint, Drop Comm Node, Return Home, Highlight Robot, SOFT Emergency Stop (yellow button), HARD Emergency Stop (red button).
 - Message Center**: [16:04:24] Rocky (GV) has identified a new object. [16:49:19] Rocky (GV) has 25 minutes of battery life remaining. [17:54:03] Rocky (GV) has identified a new object.
 - Notification Center**: A red circle with the number 3 indicates three notifications.

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Monitoring Toolkit



Point Cloud Map Front Camera Rear Camera Right Camera Left Camera

System Overlook Rocky Magic Flighty Wall-E

Rocky

Active - 1st robot in fleet
2-Axle Wheeled Ground Vehicle

Health

Battery	45 min remaining
Connectivity	108 m from node
Mobility	96% capacity
CPU	68% capacity
Disk Space	74% capacity

Controls

Define Waypoint	Drop Comm Node
Return Home	Highlight Robot
Emergency Stop	HARD Emergency Stop

Message Center

[INFO] - Rocky has been assigned to new owner.
[INFO] - Rocky has 10 minutes of battery remaining.
[INFO] - Rocky has received a new object.

Notification Center

24

The screenshot displays the Monitoring Toolkit interface for managing a fleet of robots. At the top, a navigation bar includes links for System Overlook, Rocky, Magic, Fligthy, and Wall-E, along with a Lofty icon. The main area focuses on the "Rocky" robot, identified as the "Active - 1st robot in fleet" and a "2-Axle Wheeled Ground Vehicle".

Health (with + Expand button):

Battery	45 min remaining
Connectivity	108 m from node
Mobility	96% capacity
CPU	68% capacity
Disk Space	74% capacity

Controls (with + Expand button):

II	Define Waypoint	Drop Comm Node
	Return Home	Highlight Robot
▶	SOFT Emergency Stop	HARD Emergency Stop

Message Center (with + Expand button):

[16:04:24] Rocky (GV) has identified a new object.
[16:49:19] Rocky (GV) has 25 minutes of battery life remaining.
[17:54:03] Rocky (GV) has identified a new object.

At the bottom, camera feeds are shown: Point Cloud Map, Front Camera, Rear Camera, Right Camera, and Left Camera. A Notification Center icon is also present.



System Overlook Rocky Magic Flighty Wall-E

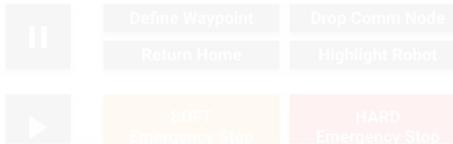
Rocky

Active - 1st robot in fleet
2-Axle Wheeled Ground Vehicle

Health

Battery		45 min remaining
Connectivity		108 m from node
Mobility		98% capacity
CPU		68% capacity
Disk Space		74% capacity

Controls



Notification Center

All Hardware Software

Magic is beginning to lose connectivity. If connectivity worsens, the robot may not be able to transmit data.
[Inspect robot](#) 00:21:10:43

Magic failed to drop a communication node at Location (x,y,z).
[See terminal output](#) [Try again](#) 00:23:18:01

Flighty has decreased mobility due to an incorrect detection of dust as an obstructive barrier.
[Inspect robot](#) 00:18:43:08

Point Cloud Map

Front Camera

Rear Camera

Right Camera

Left Camera

Monitoring Toolkit



System Overview [Sony](#) [Magic](#) [Flight](#) [Wait](#)

Magic

Alerts - Dell robot in their Aerial Track around Whole

Health

Accuracy	95%
Communication	90%
Drone	98%
Flight	99%
Robot Health	92%

⚠ Connectivity Critically Low

The connectivity level is dropping to critical low. Different flying power options, communication enhancement, flight safety, and the robot connection will be used.

[Flight Control Mode](#) [Emergency Stop](#)

Message Center

Robot Connection Alert

Robot Connection Alert

Notification Center



Research & Prototyping

► Lab research

System walkthroughs

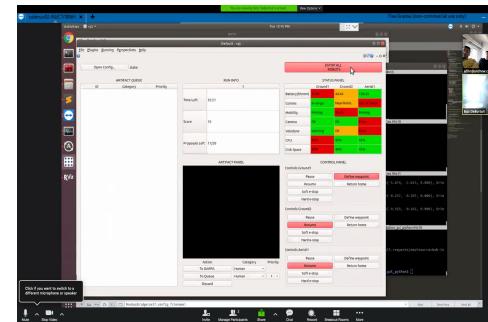
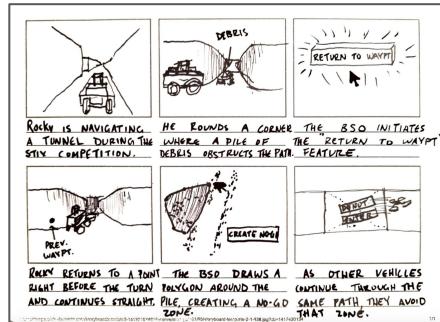


Literature review

Storyboarding

Dynamic prototyping

Affinity diagramming



► Field research



Mine observational
studies

Expert shadowing

Retrospective interviews

► Field research: Testing in Colorado





► Field interview methods

- Coming up with initial questions
- Observing test runs
- Revamping questions based on failures/issues during runs
- Learning new terminology and writing up any new questions
- Interview Vasu!



Field Test Cards

SubT Integration Exercise Test Card		
Team Name:	Test #:	SubT Integration Exercise Test Card
Explorer	1	<p>Number and types of vehicles planned for deployment: 1, ground vehicle</p> <p>Requests for DARPA accommodations: Setup 3 comms nodes (n30m apart), based on RSSI</p> <p>What tests or types of tests do you plan to run, and what do you hope to learn? - drive the robot to manual waypoints - goal is to test the communication with comms nodes + bring it back manually / return home</p>
Explorer	0	<p>Number and types of vehicles planned for deployment: 1, ground vehicle</p> <p>Requests for DARPA accommodations: set up 3 comms nodes (n30m apart), based on RSSI</p> <p>What tests or types of tests do you plan to run, and what do you hope to learn? Goal: verify comms network parallel Setup → we setup total station and DARPA sets up comms nodes</p>
SubT Integration Exercise Test Card		
Team Name:	Test #:	SubT Integration Exercise Test Card
Explorer	3	<p>Number and types of vehicles planned for deployment: 1, aerial vehicle</p> <p>Requests for DARPA accommodations: Setup 3-4 Comms nodes based on RSSI values - If the drone starts to function improperly, the drone may need to be taken out of the mine</p> <p>What tests or types of tests do you plan to run, and what do you hope to learn? - drop comms nodes based on distance (n350-400m) - once we've missed one of the times to drop a comms node, we can bring in the aerial vehicle</p>
Explorer	3	<p>Number and types of vehicles planned for deployment: 1, aerial vehicle</p> <p>Requests for DARPA accommodations: Setup 3-4 Comms nodes based on RSSI values - If the drone starts to function improperly the drone may need to be taken out of the mine</p> <p>What tests or types of tests do you plan to run, and what do you hope to learn? - send the drone / aerial vehicle in - go upto the given comms range - end the test in 10-15 mins - drone returns home and then we will conduct calibration</p>



Research insights

Research insight #1

Being able to override algorithms is necessary so the operator can always remain in control.

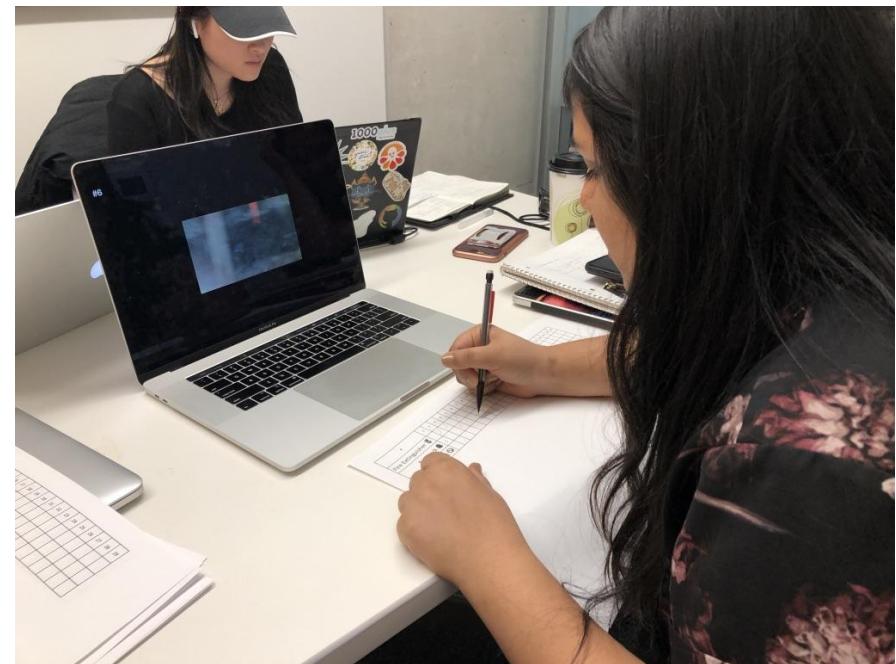


► Dynamic prototype: Manual Image recognition test

We tested people's **ability to recognize objects under time pressure.**

- Avg. Score of 27/29 correct recognitions

This makes us confident operators can be a reliable fallback when autonomous detection fails.



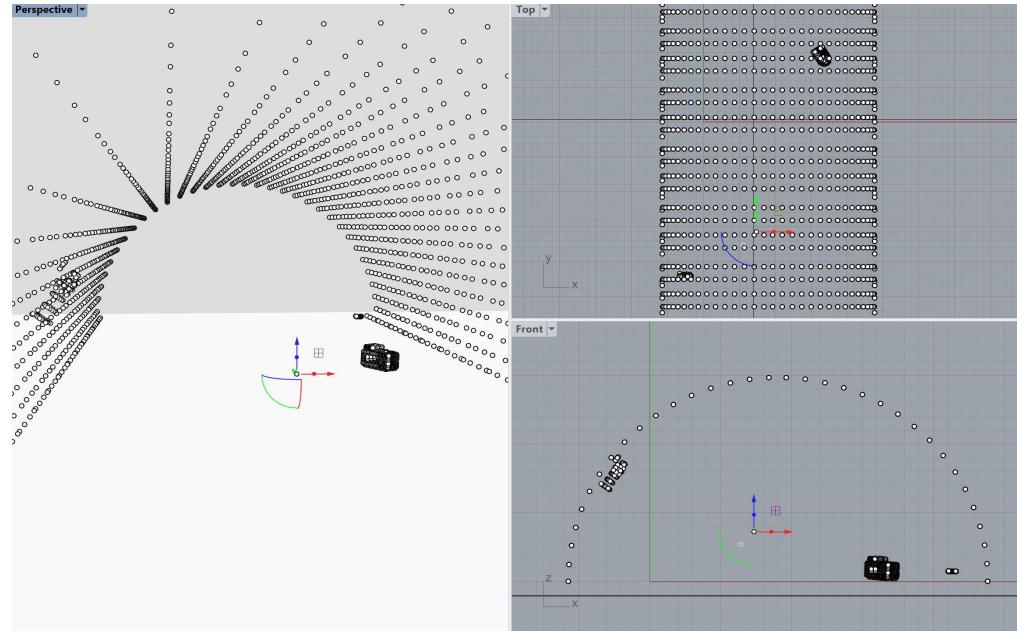
► Dynamic prototype: location refinement

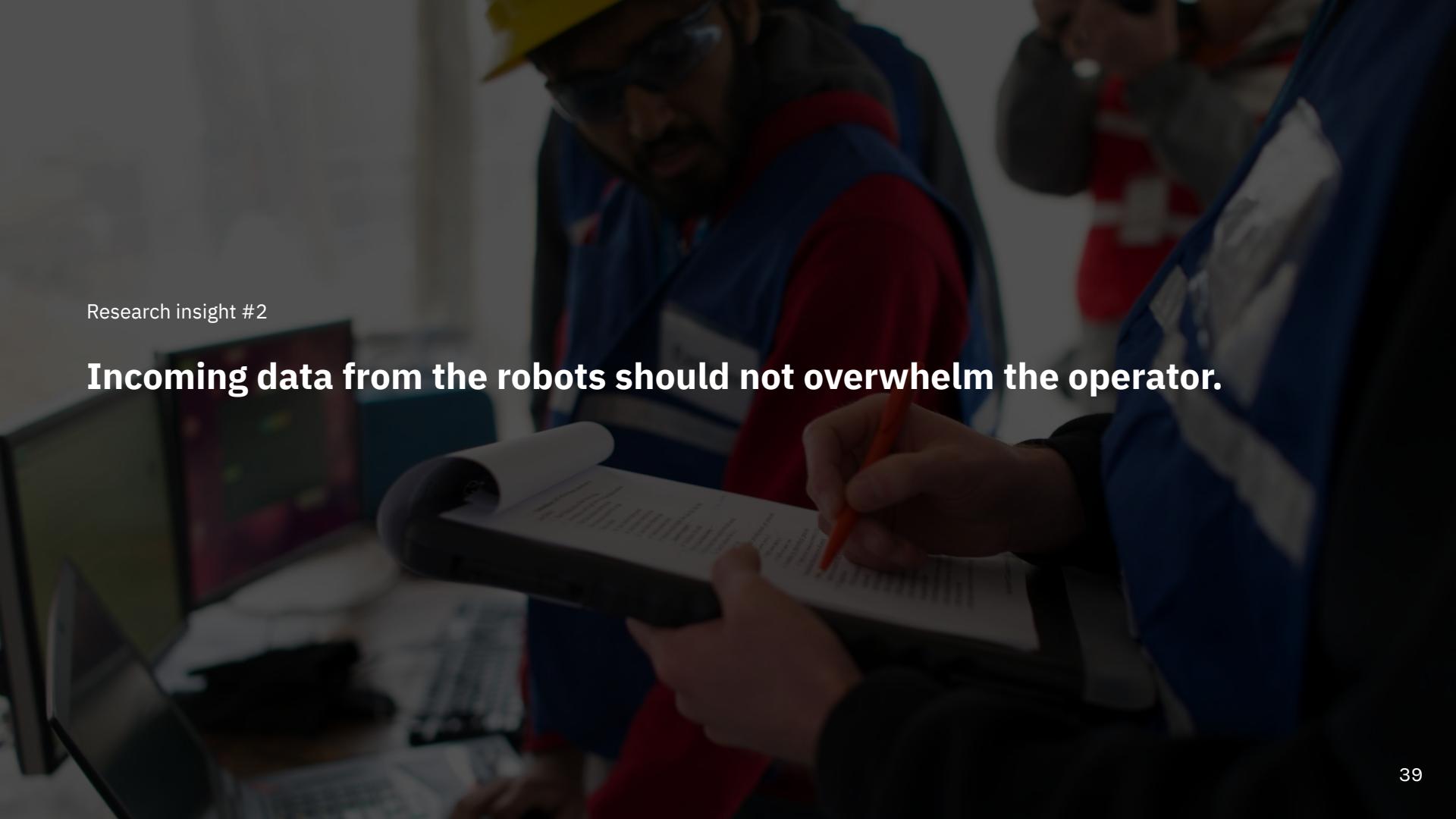
What?

Refining the XYZ-point
location of artifacts detected
by the robots

Why?

Existing method can cause
inaccuracies and delays



A photograph showing a man in a yellow hard hat and a blue and red safety vest. He is looking down at a computer monitor which displays a complex interface with multiple windows and data. In his left hand, he holds a white clipboard with a pen, appearing to take notes or review information. The background is slightly blurred, suggesting an industrial or office environment.

Research insight #2

Incoming data from the robots should not overwhelm the operator.

► Low-fi prototype: Artifact queue

The interface displays the following data:

- Artifacts Identified:** 4
- Artifacts in Queue:** 19
- Guesses Remaining:** 54
- Time Remaining:** 38:19

Detection History:

- Artifact 1:** Backpack - 2 detections
- Artifact 2:** Drill - 3 detections
- Artifact 6:** Fire Extinguisher - 2 detections
- Artifact 15:** Backpack - 2 detections
- Artifact 3:** Cell Phone - 1 detection
- Artifact 7:** Drill - 1 detection
- Artifact 11:** Backpack - 1 detection
- Artifact 12:** Cell Phone - 1 detection
- Artifact 13:** Drill - 1 detection
- Artifact 14:** Backpack - 1 detection
- Artifact 16:** Cell Phone - 1 detection
- Artifact 17:** Drill - 1 detection

Media Gallery: Intel RealSense Camera Robot 1 Rocky

Artifact Location:

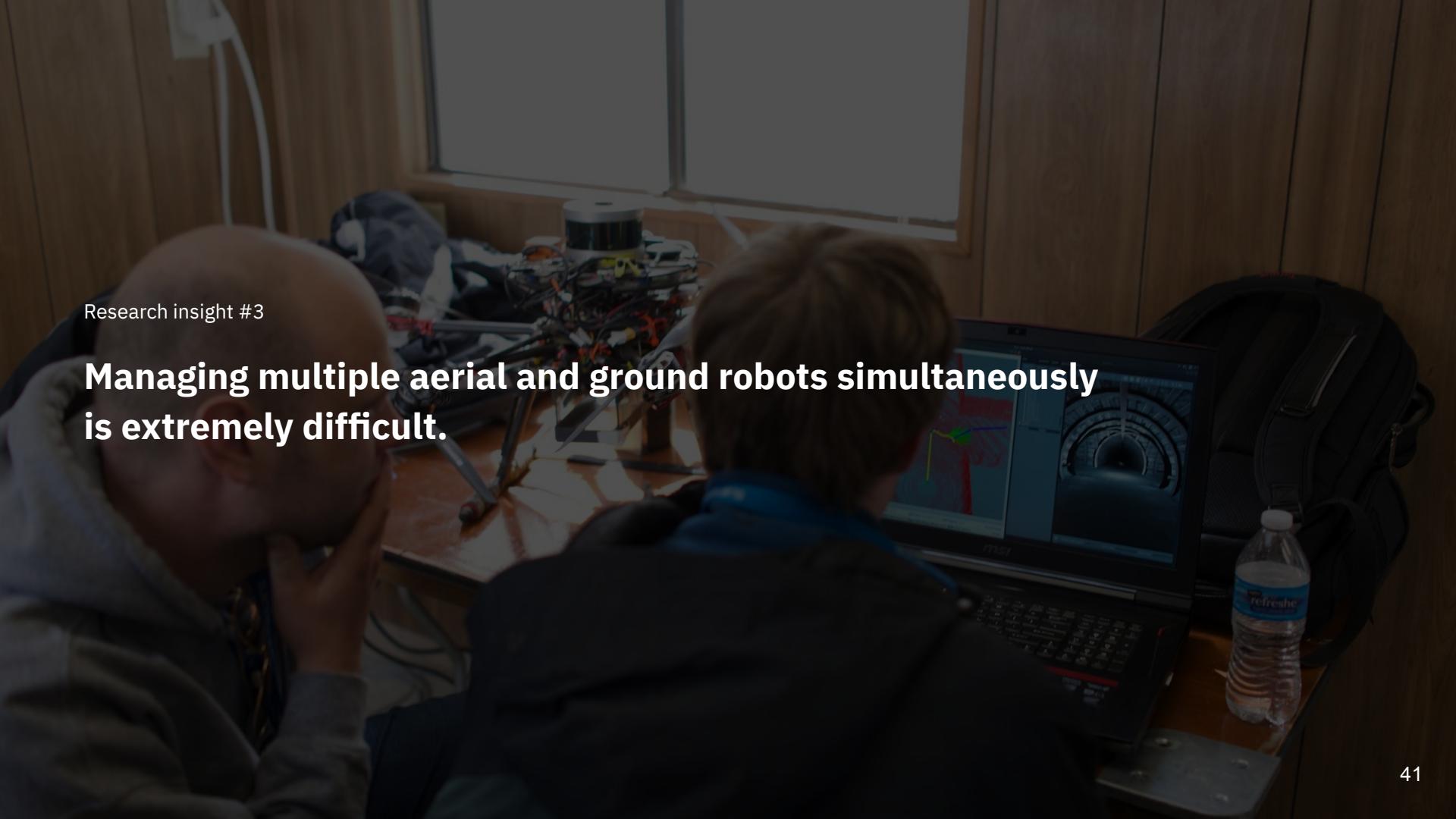
- Detection 1:** (132.2,236.5,593.0) - Robot 1, 05:01
- Detection 2:** (132.2,238.6,594.5) - Robot 2, 11:34
- Best Guess:** (132.2,237.6,593.8)

Artifact Category:

- Backpack** (selected)
- Best guess based on 3 detections**
- Other Categories:** Fire Extinguisher, Drill, Cell Phone, Survivor

Categorization: Backpack
Location: (132.2,237.6,593.8)
ERROR: Formatting issue in location entry
Send to DCP

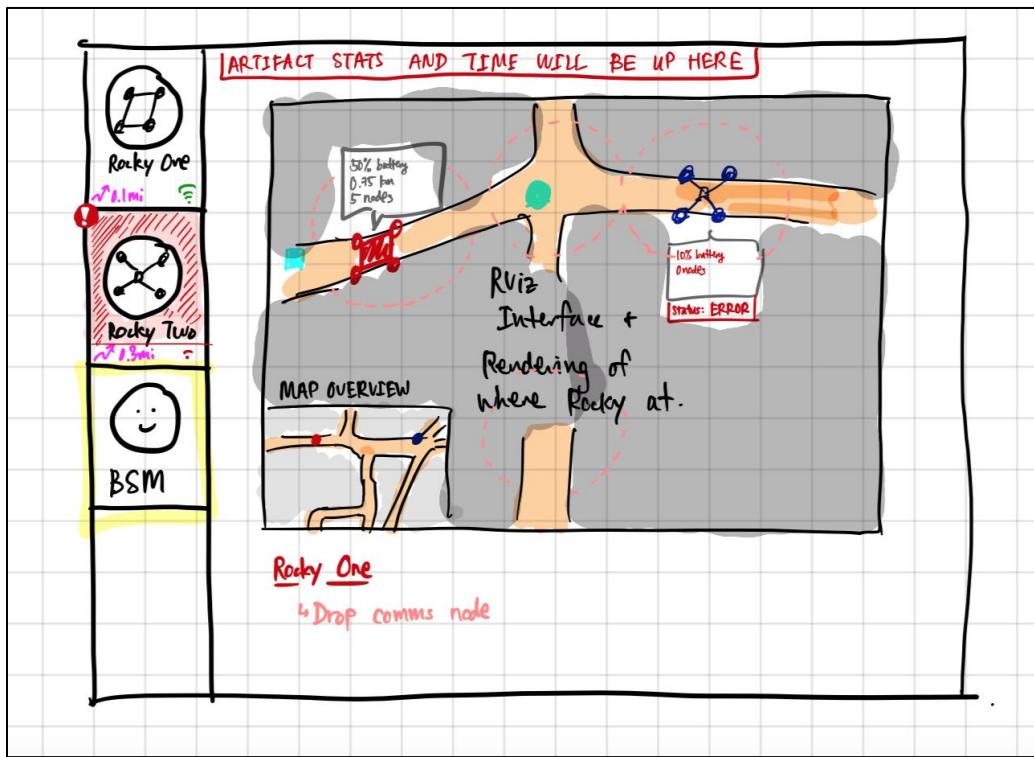
The artifact queue allows the base station manager to be able to **prioritize detections**, make changes, and optimize a **strategy for sending to DARPA**.

A photograph showing a person from behind, wearing a blue hoodie, sitting at a desk and working on a laptop. In the background, another person is visible working on a robotic arm mounted on a table. The scene is set in a room with wooden paneling and a window. A water bottle is on the desk next to the laptop.

Research insight #3

**Managing multiple aerial and ground robots simultaneously
is extremely difficult.**

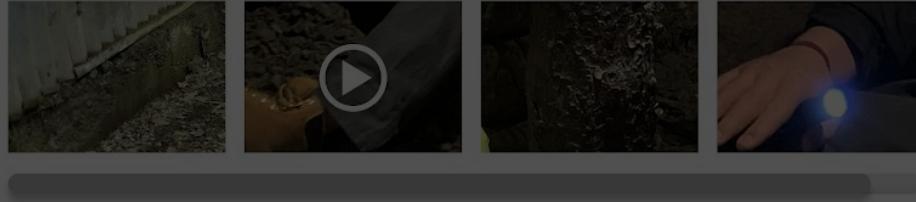
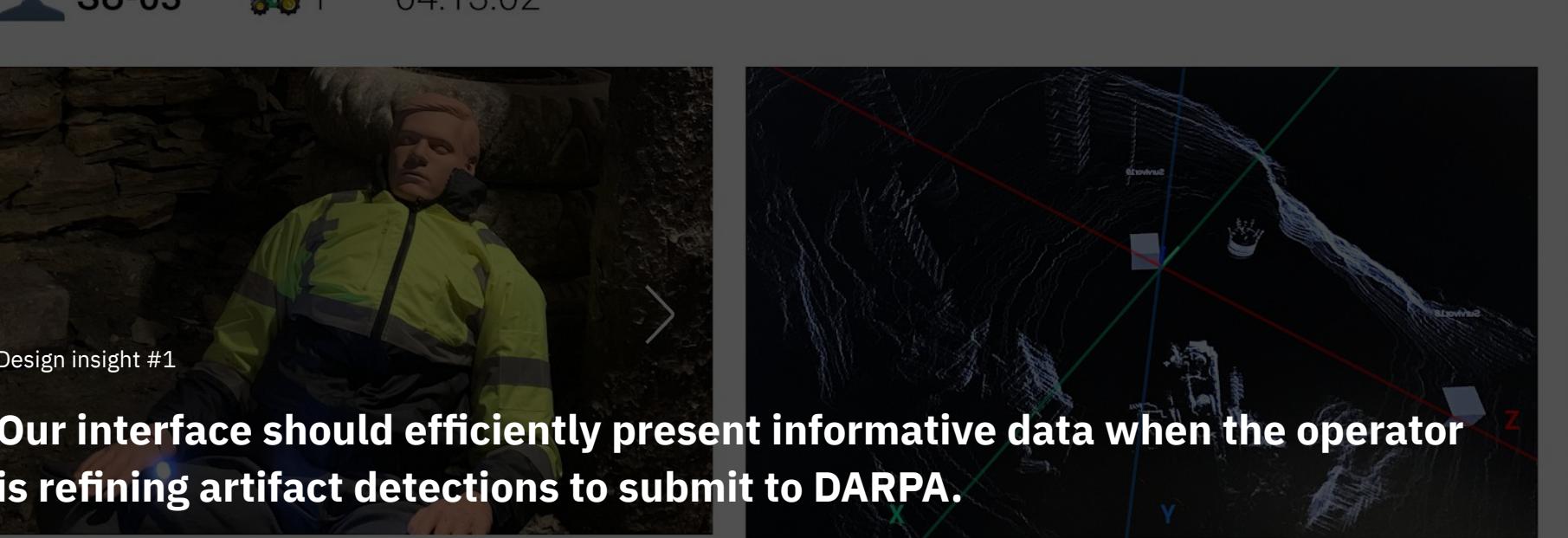
► Low-fi prototype: Scalability



Features a **tabbed sidebar** that shows a preview of all deployed robots



Design insights



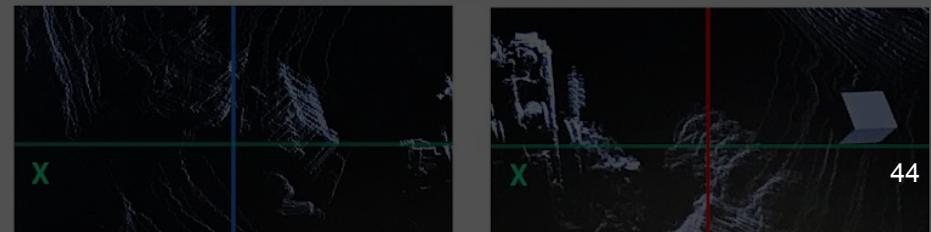
Category

Backpack

Survivor

Fire Extinguisher

Cell Phone



45/60

Guesses Used

15/30

Points Received

30:03

Time Remaining

Artifact Queue**IDENTIFIED**

D-01 1 04:13:02

SU-03 1 00:01:31

SU-02 1 06:01:31

FE-01 1 52:01:31

CP-01 1 02:01:31

SUBMITTED

BP-01 1 02:01:31

FE-02 1 02:01:31

D-02 1 42:01:31

FE-03 1 12:01:31

FE-03 1 22:01:31

ARCHIVED

FE-01 1 52:01:31

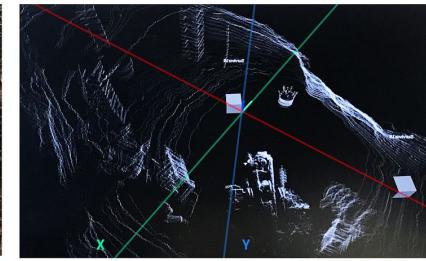
FE-01 1 52:01:31

FE-01 1 52:01:31

Detail Pane**SU-03**

1

04:13:02



X 161.560448
Y -58.7818789
Z 781.3674187

Refine Point

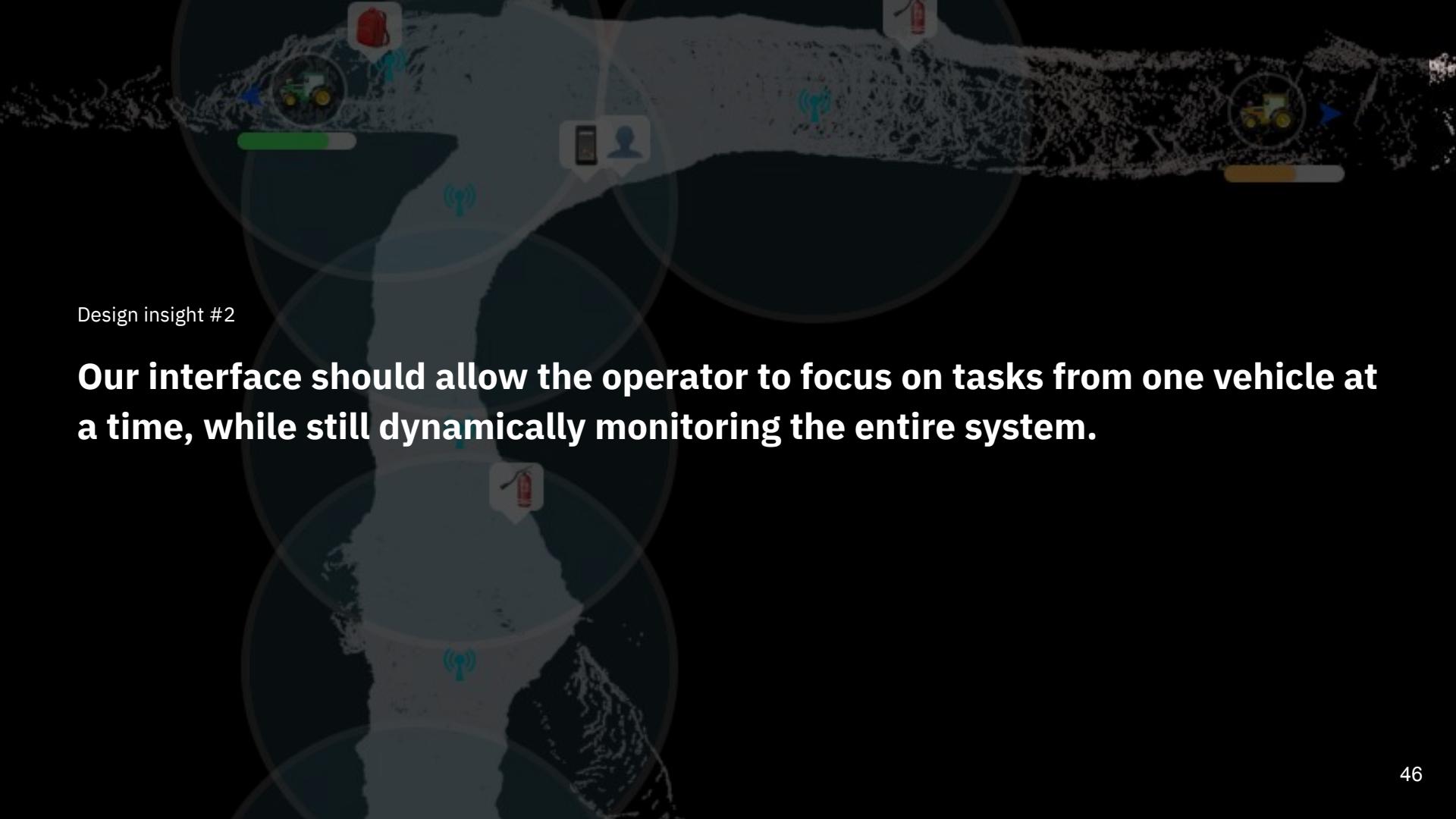
**Category**

- Backpack
- Survivor
- Fire Extinguisher
- Cell Phone
- Drill

DETAILS

Timestamp: 02:01:31
 Identified By: GV1 (Rocky)
 Location: (161.560448, -58.7818789, 781.3674187)
 43 ft from Comm1
 # of Identifications: 01

Send to DCP



Design insight #2

Our interface should allow the operator to focus on tasks from one vehicle at a time, while still dynamically monitoring the entire system.

Monitoring Toolkit

System Overlook

Rocky

Magic

Flighty

Wall-E

Lofty



View All



Rocky



Magic



Flighty



Wall-E



Lofty



Notification Center

Monitoring Toolkit

The screenshot displays the Monitoring Toolkit interface, featuring a 3D map of a terrain with several robots and their status information.

Top Bar:

- System Overlook
- Rocky
- Magic
- Flighty
- Wall-E
- Lofty

Left Sidebar:

- View All
- Rocky
- Magic** (selected)
- Flighty
- Wall-E
- Lofty

Map Area:

- A 3D point cloud map of a terrain.
- Robot icons: Rocky (blue tractor), Magic (yellow tractor), Flighty (drone), Wall-E (red tractor), and Lofty (purple tractor).
- Communication nodes represented by blue signal icons.
- Artifacts represented by red fire hydrant icons.
- A circular callout for the Magic robot provides detailed status information.

Middle Callout (Magic Robot Status):

Magic
Active - 2nd robot in fleet
4-Axle Track Ground Vehicle

Resource	Status	Details
Battery	Low	58 min remaining
Connectivity	Low	218 m from node
Memory	Medium	54% capacity
Mobility	Medium	44% capacity
CPU	Low	20% capacity

Disk Space
The following features are currently limited:
Front Camera Video Feed, Back Camera Video Feed

Bottom Callout (Status Indicators):

- Battery: Green circle (high)
- Connectivity: Red circle (low)
- Mobility: Orange circle (medium)

Layers:

- Vehicles
- Artifacts
- Communication Nodes
- Point Cloud
- LIDAR
- Thermal Imaging
- Bluetooth Signal

View Options:

- Top View
- Perspective View

Notification Center:

- 3 notifications



Conclusion

Despite some small feature updates,
the team was **impressed** by GUI
prototypes and can foresee them
being **instrumental to their success**
in the future competition.



► Handoffs

- Design documentation and recommendations that will guide them throughout future states of the competition
- Detailed breakdown of the components of the Action and Monitoring screens
- A report of our insights from our observations of the test runs in Colorado

► Future Vision

- Using the GUI we designed, the team is able to **successfully manage a full fleet of robots** through the rest of the competition.
- As new challenges arise throughout the course of the competition, the team is able to the **use design principles** we've introduced to solve them.

CMU DARPA Subterranean Challenge Final Presentation

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