University of Colorado
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ASEN 4018: Senior Projects

Concept Definition Document (CDD)

Range Extending System to Complement Underground Exploration (RESCUE)

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1 Information

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1.3 Nomenclature

Acronym	Definition
CFAT	Continuous-flex-and-twist robotics cable
ClearPath Husky	The ground robot used by MARBLE, on which the project's sensor system will be supporting
DARPA	The Defense Advanced Research Projects Agency. The agency organizing the Subterranean (SubT) Challenge.
FC	Functional category
FOV	Field of View.
FR	Functional requirement
IDE	Integrated development environment. This often describes a software application that provides comprehensive facilities to programmers for software development.
MARBLE	CU's team competing in the DARPA Subterranean Challenge, stands for Multi-agent Autonomy with Radar-Based Localization for Exploration
NASA	National Aeronautics and Space Administration
NFC	Nested Firing Command. Explained in section 1.4.
RESCUE **TDR**	Range Extending System to Complement Underground Exploration Technical Design Requirement
UGV	Unmanned Ground Vehicle, most often used to refer to the ClearPath Husky in this document.

1.4 Definitions

Due to the unique nature of this project, this section is intended to define terms appearing throughout the document with specific meanings to ensure mutual understanding.

- **Activation Command:** A command sent from the MARBLE team to the sensing system to transition from a standby state to an active state.
- **Active State:** The sensor system state after an activation command, where the system is ready to receive a firing command. For example, a drone sensor system in an active state would be unattached to the Husky and ready to take off as soon as a firing command was recieved.
- **Artifacts:** Set of objects with distinct characteristics confirmed by DARPA to be found in undisclosed locations within the cave. Points are awarded to competitors in the DARPA SubT challenge for locating and identifying artifacts accurately [1]. The exact details on each artifact are listed in appendix section A.
- **Customer acceptance test:** A validation method. Ensuing that the costumer is satisfied with the product and meets their expectations.
- **Deactivation Command:** A signal sent from the MARBLE rover to the sensing system to terminate its current activity and return to it standby state.
- **Deployment:** The process of the sensor system going from its active state to an operational state in a location or set of locations commanded by the MARBLE team with a firing command or a nested firing command.
- **Detect:** Recognizing an artifact from sensed data.

- **Final Competition Environment:** The physical environment the team's system is expected to be used in. The Final Competition course is selected by DARPA as an underground, enclosed environment including human-made tunnel networks, urban and municipal underground infrastructure, and natural cave networks [1]. Throughout this document, the words **"Cave"** and **"Final Competition Course"** generalize this environment.

- **Firing Command:** A signal sent from the MARBLE team to the sensor system to deploy to a specific location relative to the ground robot inside the sensor system's physical reach.

- **Nested Firing Command:** A command that comes after the main firing command to order the system to deploy to another location relative to the current location of the sensing system. Nested Firing Commands (NFCs) could be repeated as many times as the operator wants, however, in practical competition the NFCs effectiveness is limited by the sensor system's physical and sensing reach capabilities and competition time.

- **Obstruction:** Any terrain or object that can block the travel of the Husky or a sensor apparatus it deploys. For example, a partially blocked doorway in the urban portion of the completion environment would be considered an obstruction.

- **Operational Conditions:** Term used to indicate the terrain and ambient conditions expected in the final competition environment. According to DARPA's documentation, these conditions typically include hazards or obstacles such as darkness, dust, fog, mist, smoke, sudden changes in terrain elevation, confined or low ceiling clearance spaces, and water puddles [1].

- **Operational State:** The sensor system state when the system is deployed and sensing. This includes the process of deployment, gathering data, transmitting data, and returning to the standby state again.

- **Physical Reach:** How far the sensing system can move its sensors from where they are stowed on the Husky. For example, the physical reach of a drone would be the locations it could fly to after launching off the Husky.

- **Reusability:** The sensor system's ability to receive multiple firing commands to the system after the course of the mission. Each deployment is process has its own unique firing command. For example, a sensor system using a set of launched projectiles containing sensors is reusable if multiple sensor projectiles can be launched over the course of MARBLE's mission.

- **Sense:** To collect data from the environment a given sensor is operating within. The sensed data will change from sensor to sensor, for example a visual signature sensor might collect still images or color video.

- **Sensing Reach:** How far the sensing system can sense. For example, a robotic arm with an attached camera would have a physical reach only as far as the arm could extend from the Husky, but the sensing reach would be determined by how far the attached camera could sense artifacts successfully.

- **Sensor Apparatus:** The component of the sensor system moving a sensor into position, the sensor being the component that is actually sensing artifact signatures. For example, if the sensor system was a drone carrying a camera on a gimbal, the drone and gimbal would be sensor apparatus while the camera would be the sensor.

- **Standby State:** The state in which the sensor system is powered on and ready to receive firing commands from the MARBLE team, but is not currently being used and is in a stowed position where the MARBLE Husky can go about its regular mission.

- **Unobstructed:** Defined relative to sensor system mobility requirements. Unobstructed indicates a straight line radius from a mounting point on the MARBLE team's ground robot that is not physically blocked by impassible terrain, such a solid ground surface that cannot be maneuvered around, or components of the Clearpath Husky that cannot be traveled through.

- **Usability Test:** A validation method. A technique used in user-centered interaction design to evaluate a product by testing it on users. This can be seen as an irreplaceable usability practice, since it gives direct input on how real users interact with the system.
- **Validation:** The assurance that a product, service, or system meets the needs of the customer and other identified stakeholders. It often involves acceptance and suitability with external customers [2].
- **Verification:** The evaluation of whether or not a product, service, or system complies with a regulation, requirement, specification, or imposed condition. It is often an internal process [2].

2 Project Description

2.1 Purpose

This project is centered around improving the performance of the University of Colorado's MARBLE team's entry in the DARPA Subterranean (SubT) challenge. Running since 2018 and currently scheduled to conclude in August 2021, the purpose of the challenge is to improve semi-autonomous robotic capabilities for military and emergency response organizations operating in underground environments [1]. The primary objective of this competition is to correctly identify and report "artifacts," such as survivors (represented by thermal dummies), cell phones, tools, ingress and egress points, and gas leaks. The existing MARBLE sensing suite is bound to the UGVs on which they reside, offering no sensing range beyond their immediate line of sight. As such, the purpose of Range Extending System to Complement Underground Exploration (RESCUE) is to extend the sensing range of the MARBLE team's UGV in order to identify artifacts in hard-to-reach locations.

The inability of ground based robots to sense environments blocked by hazards such as ledges, crevices, and holes is a weakness that this project will seek to overcome. Ground based robots have a much greater endurance than airborne drones, thus offering increased capability in long duration missions. When retrofitted with the RESCUE sensor system, ground based robots, such as the MARBLE team's Clearpath Husky, will have the capability of visually sensing the entire environment within 3 meters of the robot regardless of the obstacles that it faces. This capability will provide a ground based robot an edge over airborne drones in a vast majority of subterranean missions whether that be the DARPA Subterranean challenge or military and/or emergency applications.

2.2 Project Objectives

The objectives of this project are outlined in the table below and the success of each will be measured by three levels that build upon each other. Achieving level two or three will imply success in the lower level(s). Each level demonstrates increasing difficulty of achievement and increased capability of the sensor system.

Table 1: *Levels of Success*

	Level 1	**Level 2**	**Level 3**
Sensing Range	All sensors can be utilized to effectively sense their respective artifacts within 3 meters of MARBLE's Husky in any given accessible direction.	All sensors can be utilized to effectively sense their respective artifacts within 4 meters of MARBLE's Husky in any given accessible direction.	All sensors can be utilized to effectively sense their respective artifacts within 5 meters of MARBLE's Husky in any given accessible direction.
Physical Reach	Sensor apparatus has the ability to physically reach a location that is along an unobstructed radial path at least 1 m, but not more than 5m from its mounting location.	Sensor apparatus has the ability to make a directional change of $\geq 45°$ about at least one axis during deployment in order to reach a location that is not within a clear line of sight of its base on MARBLE's Husky.	Once the sensor apparatus is re-positioned, the mechanical mount for the visual artifact signature sensor shall be capable of rotating $\geq 90°$ about at least one axis.
Artifact Sensing	The sensor suite shall be able to visually sense the following brightly colored artifacts: human survivor, backpack, fire extinguisher, and rope.	The sensor suite shall be able to sense and detect CO_2 at approximately 2000 parts per million concentration.	
System Position and Orientation	Sensor apparatus able to determine and report its position relative to the Husky within 1 meter accuracy of its ground truth location.	Sensor apparatus is capable of reporting its orientation relative to the Husky with $\leq 5°$ accuracy.	
Response to commands	The total time to go from standby state to active state shall be $\leq 30[s]$.	The time of responding to firing commands should be instantaneous $\leq 1[s]$	The time between receiving deactivation commands returning to standby state shall be $\leq 120[s]$
Usage	The sensor apparatus can be deployed and utilized $\leq$5 times.	The sensor apparatus can be deployed and utilized $\leq$10 times.	The sensor apparatus can be deployed and utilized $\leq$15 times.
Endurance	Sensor system is able to maintain an active state where it is sensing for 25% of MARBLE average competition operation (30 minutes) and a standby state for 100% average competition operation and setup time (135 minutes).	Sensor system is able to maintain an active state where it is sensing for 50% of MARBLE average competition operation (60 minutes).	Sensor system is able to maintain an active state where it is sensing for 75% of MARBLE average competition operation (90 minutes).
Durability	Systemwide IEC IP43 rating or better [3].	Systemwide IEC IP44 rating or better [3].	System-wide IEC IP54 rating or better [3].
Communication	Communicate sensing data with MARBLE before next deployment. (1-Way)	Communicate sensing data with MARBLE upon request. (2-Way)	Communicate sensing data with MARBLE asynchronously as the sensor system operates. (2-Way continuous)

2.3 CONOPS

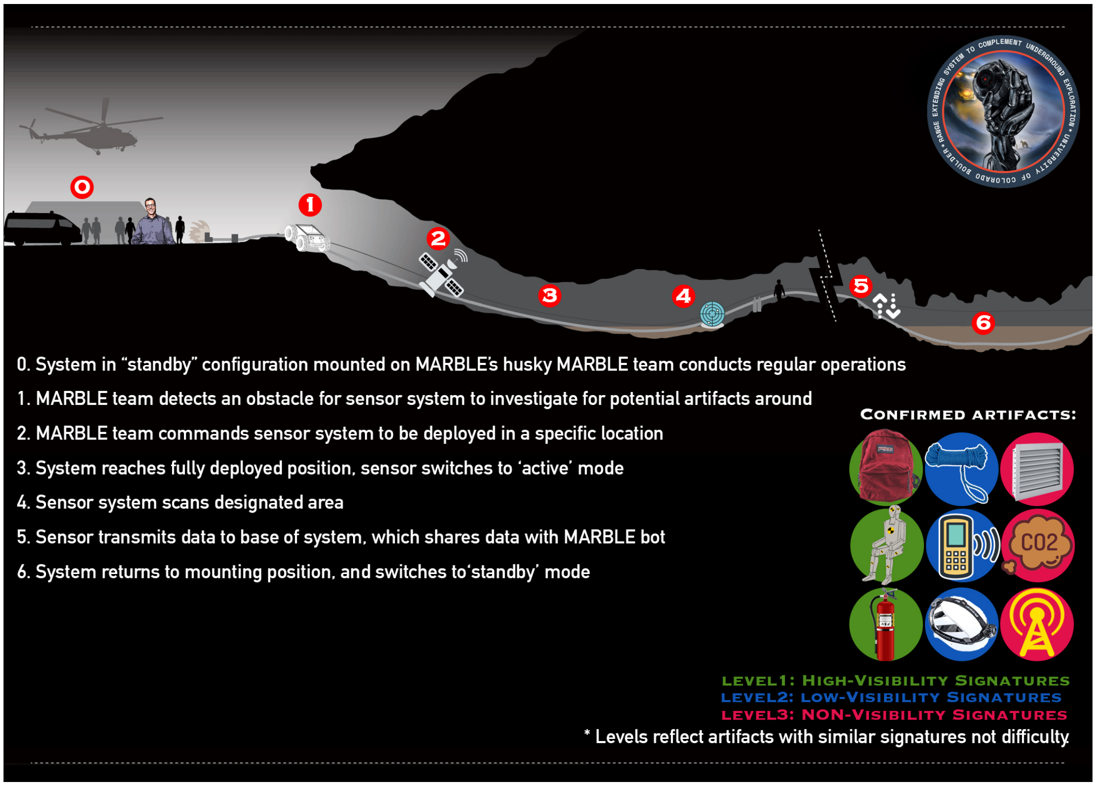

Figure 1: Concepts of Operations (CONOPS)

2.4 State Diagram

The following state diagram is a schematic representation of the typical states expected. The states are based on terminologies explained in Section 1.4.

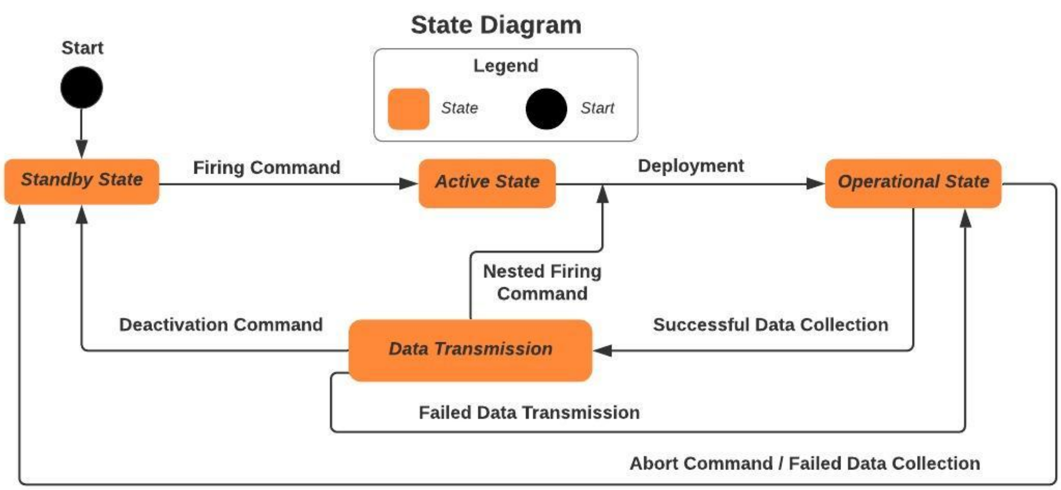

Figure 2: State diagram

2.5 Functional Block Diagram

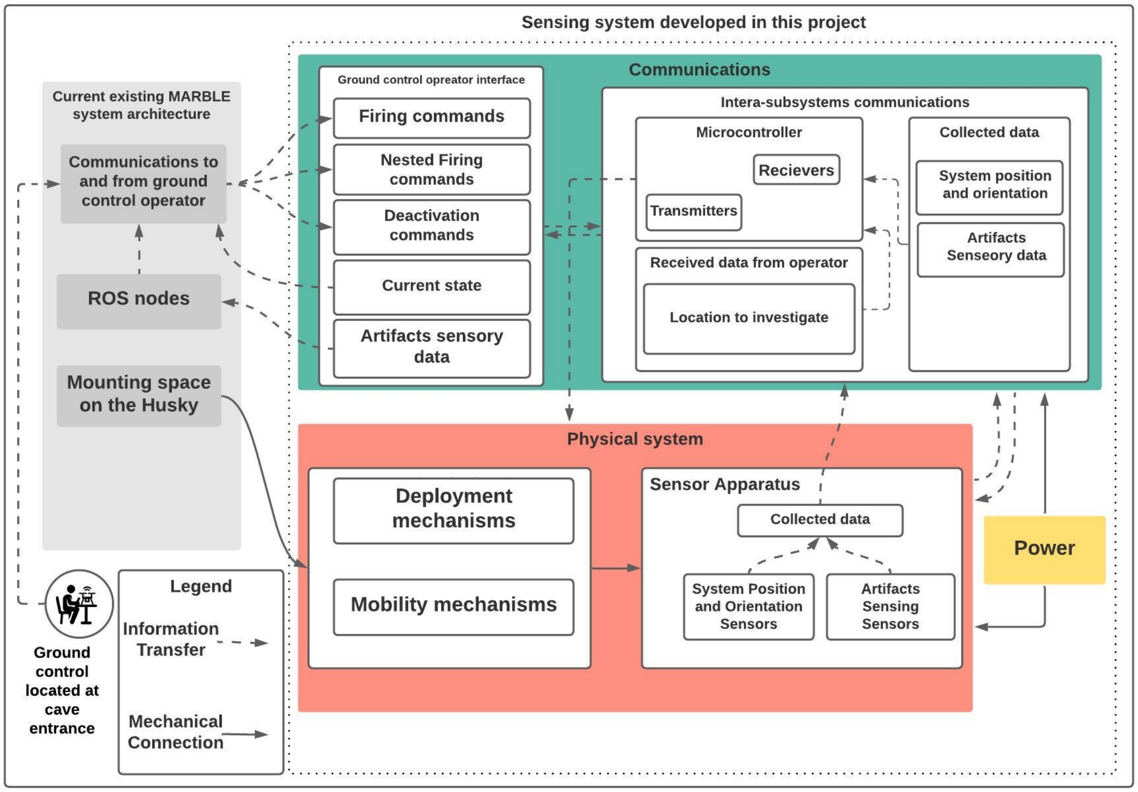

Figure 3: Functional Block diagram

2.6 Design Requirements Flow-down Diagram

The approach to develop the functional requirements (FRs) is to organize them into a higher functional categories (FCs). That will ensure that when meeting a set of FRs, a functional objective is met. Each FR is considered to be met if its constituent set of Technical Design Requirements (TDRs) is met. The TDRs are discussed further in Section 3, while the FRs are discussed in Section 2.7. This process of hierarchical dependency is shown in Figure 4.

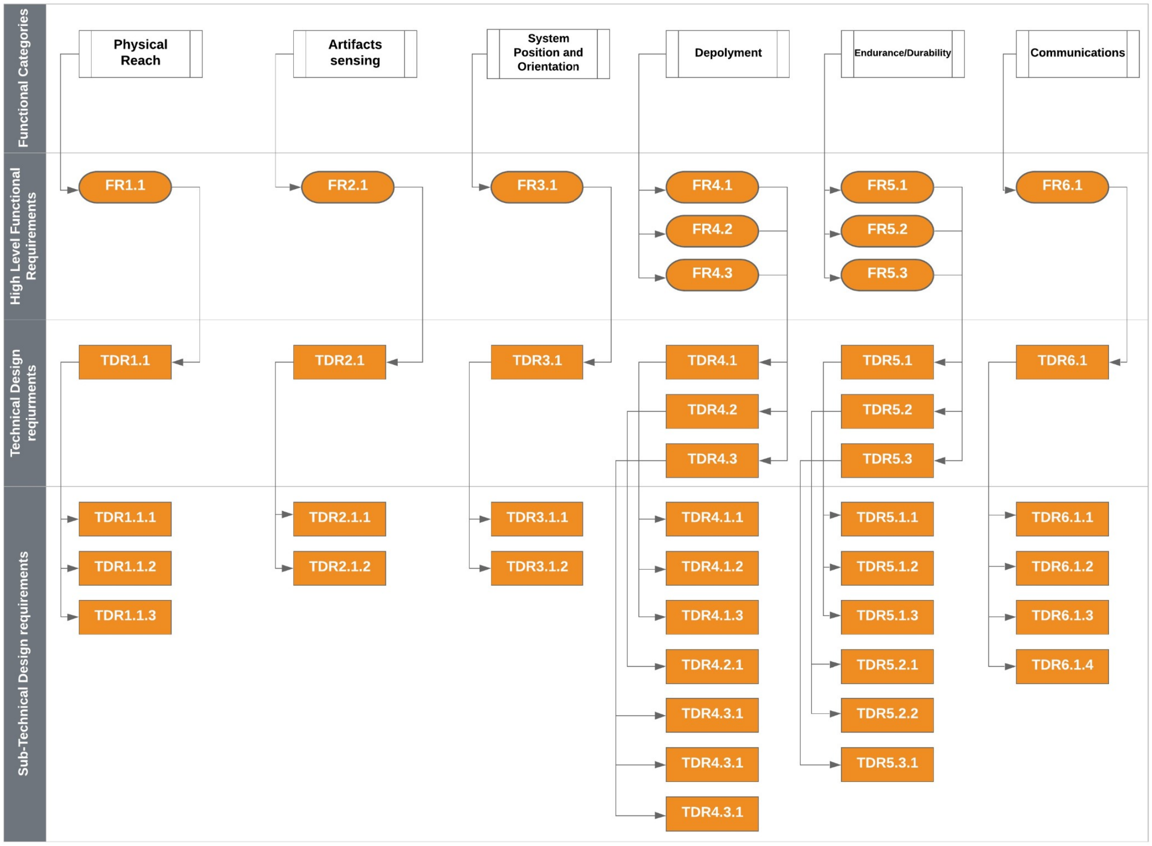

Figure 4: Requirements hierarchical view

2.7 Functional Requirements

Table 2: *Functional requirements table*

ID	Functional Requirement	Functional Category
FR1.1	At minimum, the sensor apparatus shall have the ability to physically reach a location that is at least 1 meter but not more than 5 meters from the apparatus' mounted position on the MARBLE Clearpath Husky.	Physical Reach
FR2.1	The sensing system shall be able to sense DARPA subterranean challenge competition artifacts.	Artifact Sensing
FR3.1	The sensor apparatus shall determine and report its location and orientation relative to the ground robot.	System Position and Orientation
FR4.1	When in its standby configuration, the system shall be compatible with the MARBLE team's Clearpath Husky.	Deployment: Constraints
FR4.2	When in operation, the system shall not interfere with the MARBLE team's Clearpath Husky's operations.	Deployment: Mechanical Interference
FR4.3	The system's deployment operations shall be rapid enough to incur a minimal time cost to MARBLE's total mission time.	Deployment: Time
FR5.1	The system shall operate despite the splash exposure to mud, water, and dust expected in the DARPA Subterranean Challenge circuit environment. The system shall withstand the thermal environment of the DARPA subterranean challenge.	Endurance: Environmental Hazard

FR5.2	The sensor apparatus shall have enough electrical power to maintain standby, active, and operational states fitting the MARBLE team's mission expectations.	Endurance: Time
FR5.3	The sensor apparatus shall withstand repeated deployments.	Reusability
FR6.1	The sensor system shall communicate its sensed data with MARBLE and this process shall not interfere with MARBLE's communication systems. The sensor system shall be able to receive firing commands, nested firing commands, and deactivation commands from MARBLE's team.	Communications

3 Technical Design Requirements

3.1 FR1.1 - Physical Reach Requirements

FR1.1: At minimum, the sensor apparatus shall have the ability to physically reach a location that is at least 1 meter but not more than 5 meters from the mounted position of the apparatus on the MARBLE Clearpath Husky.

TDR1.1.1: The sensor apparatus shall have the ability to physically reach a location that is at least 1 meter but not more than 5 meters along any unobstructed direction from the mounted position of the apparatus of the MARBLE ClearPath Husky.

Motivation: DARPA competition rules indicate that detected artifacts must be located to within 5 meters euclidean of their ground truth locations. The rules also indicate that several artifacts may be positioned on elevated surfaces, such as workbenches or ledges, or in potentially tight spaces where MARBLE's ClearPath Husky cannot currently reach [1]. The customer specifically requests the ability to place a sensor at least 1 meter from its standby position on the Husky to improve the team's chances of detecting artifacts.

Validation: Usability test. Defined in Section 1.4.

Verification: The apparatus will be set at an elevated starting location (400 mm), which will serve as a prop for the Husky robot. The apparatus will be extended and measured against a reference background to make sure it reaches within the 1-5 meter range.

TDR1.1.2: The sensor apparatus shall have the ability to make at least one directional change of 45° or more about at least one axis from the starting extended location to physically reach a location that is at least 1 meter but not more than 5 meters and not within a clear line of sight from the mounted position of the apparatus on the MARBLE Clearpath Husky.

Motivation: The competition environment dictates that MARBLE's Husky UGV may need to sense for artifacts in locations that are between 1m and 5m from its location but not along directions that are within "line of sight" from where the Husky is. For example, if the Husky is on the ground, the sensor system may need to change directions once deployed to look for artifacts on a ledge such a workbench. The sensor system's ability to reach unconventional locations that are not and cannot be in put in the Husky's line of sight provides signficant value to the customer.

Validation: Usability test. Defined in Section 1.4.

Verification: The apparatus will be set at an elevated starting location (400 mm), which will serve as a prop for the Husky robot. The apparatus will be extended and measured against a reference background to make sure it reaches within the 1-5 meter range. Then, the sensing apparatus will perform a directional change of 45° or more and measured against a reference background.

TDR1.1.3: Once the sensor apparatus is re-positioned, the mechanical mount for the visual artifact signature sensor shall be capable of rotating at least 90° or more about at least one axis.

Motivation: Once the sensor apparatus is positioned above or below a ledge, crevice, hole, or other obstruction that it is tasked with sensing beyond, it may need to alter the visual artifact sensor's orientation in order to bring artifacts into the sensors field of view.

Validation: Usability test. Defined in Section 1.4.

Verification: Test - The apparatus will follow similar procedures to the verification of TDR1.1.2, except the testing angle will be 0° or more.

3.2 FR2.1 - Artifact Sensing Requirements

FR2.1: The sensing system shall be able to sense DARPA subterranean challenge competition artifacts.

TDR2.1.1: The sensing apparatus shall have the capability to **visually sense** the following brightly colored artifacts: human survivor, backpack, fire extinguisher, and rope. The visual sensing of these artifacts shall occur within the visual sensor's operational field of view.

Motivation: Most objects that can be sensed by a visual sensor, and the more artifacts the sensing apparatus can visually sense, the more useful it is to MARBLE.

Validation: Usability test. Defined in Section 1.4.

Verification: Demonstration - The sensing apparatus will capture visual data of various objects, distinct from their background, in various lighting conditions.

TDR2.1.2: The sensing apparatus shall be able to **sense** and **detect** carbon dioxide (CO_2) at 2000 parts per million concentration.

Motivation: Being able to sensing CO_2 makes the sensing apparatus more valuable to MARBLE.

Validation: Usability test. Defined in Section 1.4.

Verification: Demonstration - The sensing apparatus will be exposed to a concentration of CO_2 at an approximately 2000 parts per million concentration to ensure the sensor is working.

3.3 FR3.1 - System Position and Orientation Requirements

FR3.1: The sensor apparatus shall determine and report its location and orientation relative to the ground robot.

TDR3.1.1: The sensor apparatus shall be able to determine its position relative to the ClearPath Husky, within 1 meter accuracy of its ground truth location at all times.

Motivation: Recognizing the location of the sensor would better allow the MARBLE robot to move within 5 meters of artifacts sensed outside of this range. Achieving a 5 meter proximity would enable the MARBLE team to simply report the Husky's location and score a point for said artifact.

Validation: Usability Test. Defined in Section 1.4.

Verification: Test - The apparatus will run a physical test to compare its actual vs measured positions relative to the Husky robots or its prop.

TDR3.1.2: The sensor apparatus shall be able to determine its orientation to the ClearPath Husky within 5° accuracy of its ground truth orientation at all times.

Motivation: This design requirement augments the previously listed design requirement in that it assists the MARBLE team in determining the ground truth location of the artifact.

Validation: Usability Test. Defined in Section 1.4.

Verification: Test - The apparatus will run a physical test to compare its actual vs measured orientation relative to the Husky robot or its prop.

3.4 FR4.1 - Deployment: Constraints Requirements

FR4.1: When in its standby configuration, the sensing system shall be compatible with the MARBLE team's Clearpath Husky.

TDR:4.1.1 When in its standby configuration, the system shall not exceed a volume of 38 centimeters wide by 45 centimeters long by 22-30 centimeters tall.

Motivation: Fixed limit from customer on how much space the system can occupy when mounted to the Husky in its standby state.

Validation: Costumer Acceptance Test. Defined in Section 1.4.

Verification: Inspection - While in its standby configuration, the dimensions of the apparatus will be measured to fit into the required volume.

TDR:4.1.2 The system shall not exceed a total mass of 10 kilograms.

Motivation: Fixed mass restriction from customer.

Validation: Costumer Acceptance Test. Defined in Section 1.4.

Verification: Inspection - The sensing apparatus will be weighed.

TDR:4.1.3 If the system is directly connected to the Husky, power drawn from the Husky robot shall be less than or equal to 24-30 Volts at 25 Amps.

Motivation: Fixed power restrictions from customer. Not that the word "if" is used because some system designs require their own detachable power sources.

Validation: Costumer Acceptance Test. Defined in Section 1.4.

Verification: Demonstration - The electrical performance of the apparatus will be measured while it is turned on.

3.5 FR4.2 - Deployment: Mechanical Interference Requirements

FR4.2: When in operation, the system shall not interfere with the MARBLE team's Clearpath Husky's operations.

TDR:4.2.1 When the system is deploying, in its active state, or in its operational state, the sensing apparatus shall not apply a force or moment that can unintentionally alter the position of or damage the MARBLE Clearpath Husky.

Motivation: Damaging the Husky could jeopardize the mission, which is unacceptable. Likewise, the hazards of the operational environment, such as holes or ledges, could make unintentionally moving the Husky a direct cause of it being damaged if it is positioned near them when deploying the sensor system.

Validation:. Costumer Acceptance Test and Usability Test. Defined in Section 1.4.

Verification: Analysis - The team will calculate the torque applied by the sensing apparatus on the Husky robot.

3.6 FR4.3 - Deployment: Time Requirements

FR4.3: The system's deployment operations shall be rapid enough to incur a minimal time cost to MARBLE's total mission time.

TDR:4.3.1 Upon receiving an activation command from the MARBLE team when in standby configuration, the system shall reach an active state in 30 seconds or less.

Motivation: Customer mandated. Any time spent not sensing for artifact detracts from the limited productive time the MARBLE team has in the DARPA final competition course.

Validation: Costumer Acceptance Test and Usability Test. Defined in Section 1.4.

Verification: Test - A physical test will be conducted to measure the time it takes for the deployment of the apparatus.

TDR:4.3.2 Upon receiving a firing command from the MARBLE team when in its active configuration, the system shall respond in an operational state as soon as (< 1 second) the command is received.

Motivation: Customer mandated. Once the 30 seconds or less activation time is complete, the sensor system must not expend any additional time preparing to deploy.

Validation: Costumer Acceptance Test and Usability Test. Defined in Section 1.4.

Verification: Test - A physical test will be conducted to measure the time it takes to receive and process the deployment command.

TDR:4.3.3 Upon receiving an deactivation command from the MARBLE team while, the system shall return from its operational/active configuration to its standby configuration within 120 seconds.

Motivation: Customer mandated. This allotted time is greater than the time for the system to respond to an activation command because the sensor apparatus may need to return to the Husky and reattach to it from up to 5 meters away. This travel may also include navigating past obstructions the sensor apparatus is moved around or past during deployment.

Validation: Costumer Acceptance Test and Usability Test. Defined in Section 1.4.

Verification: Test - A physical test will be conducted to measure the time it takes for the concealment of the apparatus.

3.7 FR5.1- Endurance: Environmental Hazard Requirements

FR5.1: The system shall operate despite the splash exposure to mud, water, and dust expected in the DARPA Subterranean Challenge circuit environment. The system shall withstand the thermal environment of the DARPA subterranean challenge.

TDR:5.1.1 The sensing system's mechanical and electrical components shall meet at least IP43 water exposure tolerances.

Motivation: DARPA specifies that the competition environment can include water hazards typical to cave environments, including puddles and water dripping from ceilings [1]. The customer requests resistance from these kinds of hazards, especially splashing type water exposure. The system is expected to be carried on MARBLE's Husky UGV, which possibly could create splashing by driving though a puddle during competition. Using International Electrotechnical Commission's ingress protection (IP) codes allows for clearly defined water resistance testing [3].

Validation: Usability Test. Defined in Section 1.4.

Verification: Test - The team shall verify that the system still functions after a IP level 3 water test: using a spray nozzle, the device shall be subjected to "1 minute per square meter for at least 5 minutes; Water volume: 10 liters per minute (0.037 impgal/s); Pressure: 50–150 kPa (7.3–21.8 psi)" [3].

TDR:5.1.2 The sensing system's mechanical and electrical components shall meet at least IP43 dust exposure tolerances.

Motivation: Customer request: similar to the TDR5.1.1, having the system carried on the Husky, relatively low to the ground, creates environmental risk from dust and debris. IEC IP codes again allow for clearly defined standards.

Validation: Usability Test. Defined in Section 1.4.

Verification: Test - The dust exposure tolerances may be tested at an off-campus facility.

TDR:5.1.3 The system shall accomplish all other design requirements in an nominal thermal environment of 50-65° F.

Motivation: Temperatures underground below 10 meters stay approximately constant throughout the year. Since the tests will likely be conducted in Colorado, the average underground temperatures being used are those from Colorado. [4]

Validation: Usability Test. Defined in Section 1.4.

Verification: Analysis - Every part of the apparatus will have to be confirmed to operate in the ambient underground temperature.

3.8 FR5.2 - Endurance: Time Requirements

FR5.2: The sensor apparatus shall have enough electrical power to maintain standby, active, and operational states fitting the MARBLE team's mission performance expectations.

TDR:5.2.1 The system shall have enough electrical power to maintain a standby state for at least 135 minutes.

Motivation: Customer requirement. A SubT Challenge final competition run can last as long as 120 minutes, and our customer requests a 15 minute buffer time for when the Husky is preparing to start its competition run [1].

Validation: Usability Test. Defined in Section 1.4.

Verification: Analysis - The sensing apparatus power usage will be compared to the battery capacity to make sure it complies with the time requirement.

TDR:5.2.2 The system shall have enough electrical power to maintain an operational state for at least 30 minutes.

Motivation: Customer requirement. The customer requires the sensor to be capable of actively conducting sensing operations for at least 25% of a 120 minute maximum duration SubT challenge final course run [1].

Validation: Usability Test. Defined in Section 1.4.

Verification: Analysis - The sensing apparatus power usage will be compared to the battery capacity to make sure it complies with the time requirement.

3.9 FR5.3- Reusability Requirements

FR5.3: The sensor apparatus shall withstand repeated deployments.

TDR:5.3.1

Motivation: The MARBLE team requires the system be able to deploy at least 5 times during a competition run.

Validation: Usability Test. Defined in Section 1.4.

Verification: Test - The sensing apparatus will go from its standby state to its operational state and back multiple times in a row at different time intervals.

3.10 FR6.1 - Communication Requirements

FR6.1: The sensor system shall communicate its sensed data with MARBLE and this process shall not interfere with MARBLE's communication systems. The sensor system shall be able to receive firing commands, nested firing commands, and deactivation commands from MARBLE's team.

TDR6.1.1: The sensing system shall be capable of receiving firing commands from the ROS nodes in the existing MARBLE architecture.

Motivation: The ability to receive firing commands enables the system to deploy at appropriate times as designated by the MARBLE robot.

Validation: Usability Test. Defined in Section 1.4.

Verification: Demonstration - A test command will be sent to the testing apparatus to confirm it is able to receive commands.

TDR6.1.2: After deployment and retraction, the sensor system shall communicate sensing data with the MARBLE robot before its next deployment, or within approximately 60 seconds.

Motivation: The customer suggests that at minimum the sensor system should report its sensing data prior to the next deployment. This provides for each use of the sensing apparatus to be analyzed separately by the MARBLE team.

Validation: Costumer Acceptance Test and Usability Test. Defined in Section 1.4.

Verification: Test - The apparatus will take data and its communication time will be timed.

TDR6.1.3: The system shall transmit data to the MARBLE robot through a wired connection that will remain securely attached and functional throughout the duration of competition use.

Motivation: Data transmission via a direct, wired connection will be more stable and reliable than wireless communication. This measure will allow the team to focus on achieving communication at a higher data rate.

Validation: Usability Test. Defined in Section 1.4.

Verification: Demonstration - A test command will be sent to the MARBLE robot to confirm it is able to transmit data.

TDR6.1.4: The system shall deliver frequent status reports to the MARBLE robot regarding deployment status and data collection.

Motivation: Knowing the current status of the sensor apparatus will enable the MARBLE team to avoid sending premature firing commands to the system. It will also simplify identification of unsuccessful deployments (e.g. the apparatus getting stuck on an obstruction).

Validation: Usability Test. Defined in Section 1.4.

Verification: Demonstration - The system will show its ability to send updates of its state to the MARBLE robot.

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4 Key Design Options Considered

To explore the most technical design options, it must be acknowledged that some design options would span multiple FRs. Hence, When addressing these design options, they will be discussed in terms of what FRs a design solution could cover. FRs could be seen in Figure 4. The following list shows which FRs are combined into the same design option space.

- Physical Reach, Deployment and Endurance: **Combined design options to satisfy FRs**
- Artifacts sensing: **Unique design options for each FR**
- System Position and Orientation: **Unique design options for each FR**
- Communication: **Unique design options for each FR**

Moreover, some functional requirements require the consideration of multiple design options the together achieve the functional requirement. If the design option is one that requires a trade study, the driving requirements behind it are discussed in Section 5.

4.1 Physical Reach, Deployment, Durability Design Options

4.1.1 Robotic Sensor Arm

A robotic arm mounted to MARBLE's Clearpath Husky used to physically re-position a set of sensors would require three primary components, diagrammed in Figure 5:

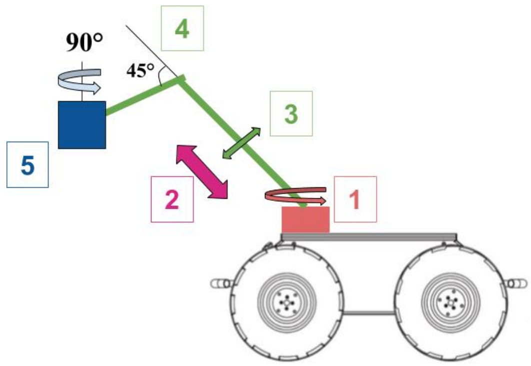


Figure 5: Robotic Sensor Arm Basic Element Breakdown

These elements are as follows:

1. **Mounting Plate:** Indicated as 1 in the diagram above, a robotic arm mounting plate would provide two critical functions. First, the plate must keep the arm attached to the Husky and keep the system stable when the arm extends (TDR 4.2.1). This includes supporting the arm in both its standby and fully extended configurations, as well as acting as a base station for all power and data physical connections between the arm and the Husky (FR 4.1). Secondly, the base must be able to rotate the arm in order to achieve TDRs 1.1.1 and 1.1.2.

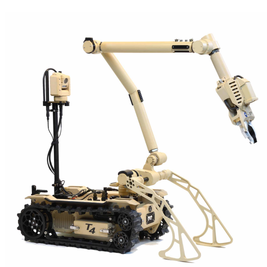
2. **The Robotic Arm Itself:** The robotic arm itself must be capable of being stowed when the system is in standby mode within the volume limits stated in TDR 4.1.1. This is indicated by 2 in the diagram. To meet TDR 1.1.1 the arm must have an angular range of motion about an axis perpendicular to the mounting plate's rotational axis. Finally, as indicated with 4 in figure 5, the arm must be capable of changing the angle to the sensor apparatus by at least 45° to achieve TDR 1.1.2.

3. **Sensor Package Mounting:** The sensor package mount, aside from supporting the mass and electrical connections for the sensors in it, must provide the mechanical capability to achieve TDR 1.1.3. In the diagram it is indicated as 5 with a representative axis aligned perpendicular to the Husky's ground plane.

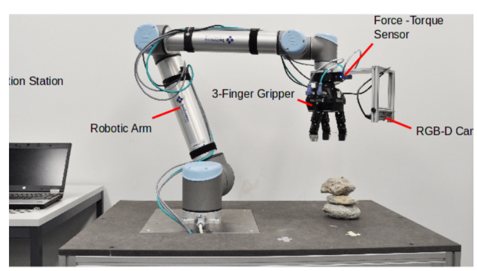
The following three subsections consider possible design options for each of these three key components:

Robotic Arm Mounting Plate Options

1) **Rotating base mount:** Rotating base mounts for robotic arms are extremely common in applications similar to this project. Such mounts work by having the arm attached to a base plate that is mechanically rotated using a motor. Figure 6 shows two applications of this kind of system:



(a) L3 Harris T4 UGV [5]



(b) ETH Zurich Robotic Reseach Arm [6]

Figure 6: Industry and Academic Examples of Robotic Arms Featuring Swivel Base Mounts

Figure 6a shows the L3 Harris T4 Unmanned Ground Vehicle (UGV) equipped with a robotic arm on a rotating base mount, while Figure 6b shows a high precision tabletop research robotic arm developed by ETH Zurich. A rotating arm mount in both cases provides key advantages that parallel several of the challenges in this CDD's project. The L3 Harris T4 in the configuration shown is used for military applications where moving the rest of the ground vehicle while the arm is operating may be undesirable or unsafe [5]. In the MARBLE project, the sensor apparatus may need to be deployed in situations where the Husky's movement is blocked or risky due to terrain such as holes, ledges, or water [1]. The ETH Zurich rock stacking arm project demonstrates another advantage of a swivel type arm base: precision [6]. For the MARBLE team, having precise control over where the sensors on the end of the arm are pointed would likely enable more successful artifact finding.

At an overview level, the swivel arm mount has the arm attached to a motorized base-plate that can rotate on command:

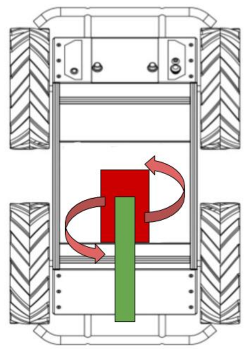
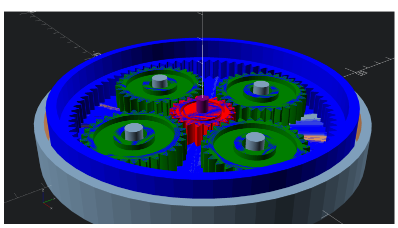
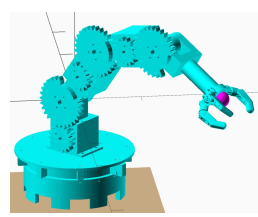


Figure 7: Basic Arm Swivel Mount Function

More specifically, nearly all swivel mount designs operate using a motor linked to a series of gears connected to a plate the robotic arm is actually mounted to. In Figure 8a; the red gear is directly attached to a motor's axle while the blue outer gear's flat edge would be mounted to a plate holding the robotic arm.



(a) Robotic Arm Swivel Mount Gearing Mechanism [7]



(b) Robotic Arm On Swivel Mount Mechanism in Cylindrical Casing [7]

Figure 8: Robotic Arm Swivel Mount: Diagram, Gearing and Casing Illustrations

The entire assembly is then contained in a sealed, cylindrical or rectangular casing (a cylindrical example is shown in Figure 8b). Aside from preventing gears becoming caught on obstructions, such a casing would be necessary on the MARBLE Husky to meet FR 5.1's TDRs.

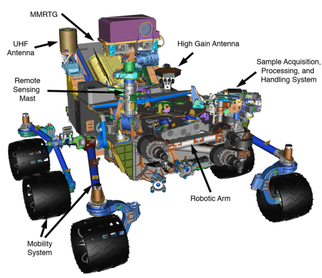
Such designs require the mechanical complexity of developing gearing system suited for a specific application. For example, the mass of the robotic arm often dictates the torque required to rotate it accuracy, which in turn drives the gear ratio and type of gears selected for the swivel mount. As an example, Fig. 8a originates from a lightweight, all 3D printed tabletop arm where thicker gears and a 4:1 gear ratio enable easy manufacturing and moderate torque [7]. Motor selection offers variety at a cost of complexity. Brushless DC stepper motors are often selected for their ease of electronic control but have to picked carefully to avoid incurring large project costs [8].

Table 3: *Robotic Arm Swivel Base Mount Pros and Cons*

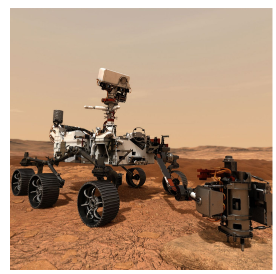
Robotic Arm Swivel Base Mount	
Pros	**Cons**
Swivel rotation mechanism can allow for more precise arm positioning (TDR 1.1.1).	Swivel rotation mechanism will likely require an appreciable amount of the allocated storage volume and mass in TDRs 4.1.1 and 4.1.2.
Swivel rotation mechanism does not place the Husky at additional risk due to rotating (FR4.1) if operated in terrain where the Husky cannot safely change its orientation.	Swivel rotation mechanism will require increased mechanical design and manufacturing complexity to develop a gear/motor selection suited to the attached arm design.
Swivel rotation mechanisms are commonly applied for similar projects, and research examples of successes are readily accessible.	Swivel rotation mechanism may require expensive brushless DC motors for precise control [6].

2) Static base mount:

A "static base mount" refers to a mount system where a robotic arm is connected to a ground vehicle without its own rotation mechanism. Instead, the vehicle itself provides the rotation necessary to reposition the robotic arm. Two examples of static base mounts are shown in Figures 9a, 9b, and 10:



(a) Curiosity Rover Robotic Arm: Folded [9]



(b) Curiosity Rover Robotic Arm: Extended [9]

Figure 9: Curiosity Rover Robotic Arm

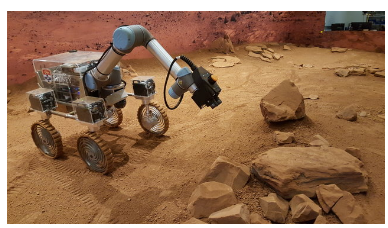


Figure 10: University of Sydney's Continuum Rover [10]

Figures 9a and 9b show NASA JPL's Curiosity Rover's arm in its folded and extended configurations, respectively. These images illustrate a key advantage for the MARBLE project: an arm without a base rotation mechanism takes up less space, which can potentially be used to store the arm in a more compact form factor when not in use.

Fig. 10 is of the University of Sydney's Continuum research rover, which uses a non-rotating mounted arm to support a high resolution rock examination camera [10]. Relative to the MARBLE project, this example illustrates how on the MARBLE project a static base arm could allow for supporting a heavier sensor package that would create challenges for swivel mount.

A static base mount would operate simply by attaching the robotic arm to the Clearpath Husky, which would provide the rotation to orient the robotic arm:

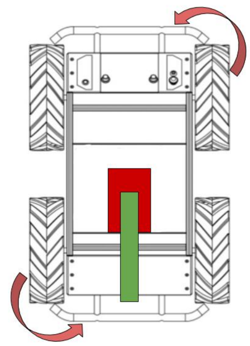


Figure 11: Static Base Mount Operation Diagram

Table 4: *Robotic Arm Static Base Mount Pros and Cons*

Robotic Arm Static Base Mount	
Pros	**Cons**
A static base arm requires less complicated mechanical development work than a swivel base mount.	Additional communications interface with the MARBLE Husky would be required to orient a static base arm.
A static base arm can likely support a heavier arm package; in relation to FR1.1 and this likely equates to a greater deployment reach with more mobility options.	Static base arm operation creates additional risk in relation to TDR 4.2.1 if the Husky must be rotated in place to orient the arm.
A static base mount allows more volume for arm storage in relation to TDR4.1.1.	Static base arm positioning may be imprecise due to its dependency on the MARBLE Husky for orientation.
A static base mount's lack of mechanical complication removes potential components to be impeded by water or dust in relation to FR 5.1.	

Robotic Arm Options

1) Folding Arm: A common design category for robotic arms is arms is using connected linear segments jointed with controlled motors. Such designs allow for significant mobility, and in some cases enable the arm to fold into a smaller profile when not in use. The figure below shows a patent diagram of a system using this kind of mechanism:

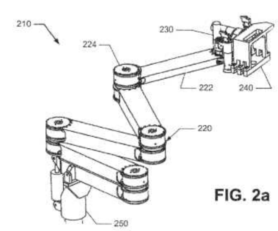
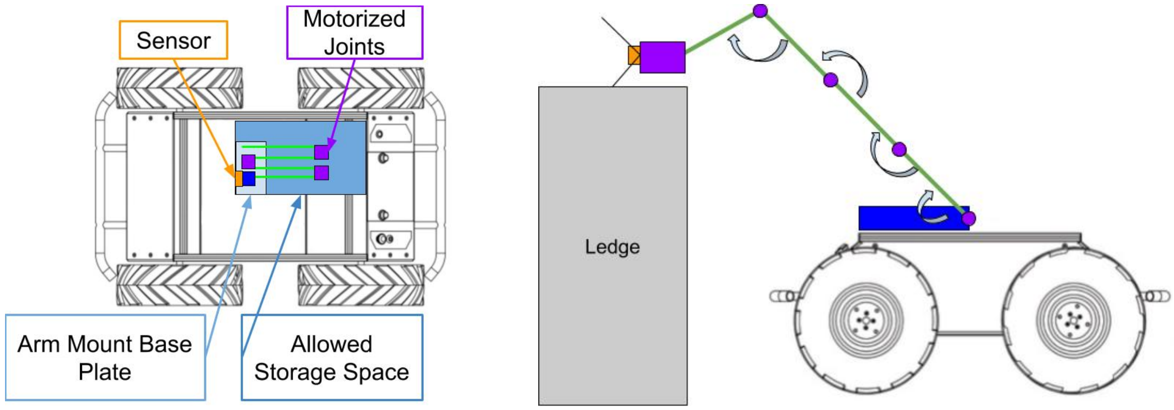


Figure 12: Example Folding Robotic Arm Mechanism [11]

Deploying a robotic arm using the same type of mechanism would operate as follows on the MARBLE Husky, the example figure shows an arm with four jointed segments in its standby and deployed configurations:



(a) Folding Robotic Arm: Standby Configuration (b) Folding Robotic Arm: Operational Configuration

Figure 13: Folding Robotic Arm: Operation Diagram

The folding arm option's potentially small volume while stowed improves its performance relative to FR4.1, while a jointed configuration likely facilitates achieving TDR1.1.2 more effectively. Research of existing designs support the conclusion that accomplishing TDR1.1.2 and FR4.1 well while extending such a device to at least 1m to meet TDR1.1.1 is achievable. Aside from the design shown in Figure 12, the team found numerous examples of arm systems with strong resemblances to desired characteristics for this project. These included the arm on the Aselsan KAPLAN Explosive disposal robot and an arm system for the iRobot UGV. In an extreme jointed arm case, the Suzumori Endo Robotics Laboratory used a jointed arm consisting of inflatable sections that could reach up to 20 meters from its base with a small camera [12] [13] [14].

Aside from showing promise to meet mobility requirements, introductory investigation indicates that a folding arm type system could fit FR5.2's criteria as well. Because the arm only requires electrical power when it is moving and is attached to the Husky, it does not require continuous power draw and can use heavier power sources or simply be connected to the Husky's electrical system.

FR5.1 could likely be achieved: servo motors required for such an arm's joints are available relatively inexpensively with complete sealing against water and debris [15]. Finally, for FR5.3, a folding arm not becoming detached from the UGV could be repeatedly deployed as long as sufficient electrical power was available.

Table 5: *Folding Robotic Arm Pros and Cons*

Folding Robotic Arm	
Pros	**Cons**
Folding mechanism allows long full extension length relative to required standby configuration storage space (TDR1.1.1, TRD4.1.1)	Multiple motorized joints require additional motors, which increases project cost and arm mass (TDR4.1.2)
Jointed arm segments can be controlled to meet TDR 1.1.2 extremely well	Fully extended arm could create a torque risk for mounting on the Husky without additional support (TDR 4.2.1)
Folding mechanical arms are common in similar applications, and design inspiration is plentiful	Folding mechanism is mechanically complicated, and would require extensive design research
Wired connections between the sensor package on the end of the arm and the Husky are possible, which improve power and communications performance	A longer folding arm would require lightweight components, which would increase cost
FR 5.1 - 5.3 appear highly achievable based on design space review	

2) Telescoping Arm: Another consideration for a robotic arm is using a telescoping arm that will allow the sensor mount reach the required distance. It is an easy solution for an accurate distance reach; it is structure allows to reach any distance within its range. The arm is mounted on two rotating bases, one of which allows it to change its direction of orientation (around z-axis) while the other rotating base allows to reach for higher targets (rotating around the y-axis). Figure 14 shows a possible configuration on the MARBLE's robot.

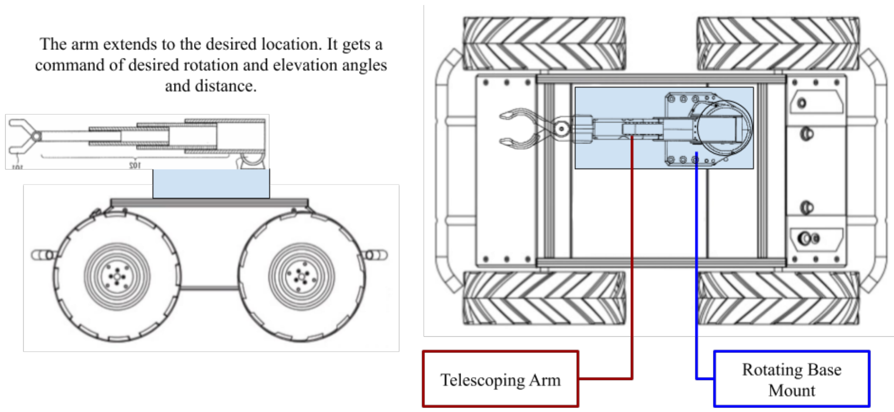


Figure 14: Example Telescoping Robotic Arm Mechanism

The telescoping arm option potentially increases the accuracy of the location of the arm, but it is storage volume may quickly become a significant issue when trying to comply with FR4.2. The table below provides a list of pros and cons of the telescoping arm option.

Table 6: *Telescoping Robotic Arm Pros and Cons*

Telescoping Robotic Arm	
Pros	**Cons**
A telescoping robotic arm is capable of reaching any distances within its range. Its structural nature allows to reach an accurate distance specified by the team	A telescoping arm would mean an increasing torque with the increasing distance of the arm. Choosing to use a telescoping arm would mean a more careful approach to getting lightweight sensors
A telescoping arm has a quick start and return of operation times. It is easily deployed and stowed when necessary	While its start and return of operation times are short, the amount of time it would require a telescoping arm to reach the required position is much longer. Multiple adjustments of position or a complicated control system might be necessary
This method does not require a lot of power, which makes it appealing to use. Moreover, its endurance is not only electrical, but physical as well - water droplets and dust cannot penetrate the structure	A telescoping arm is more susceptible to jamming and general mechanical issues. Most of them are not easily predictable or avoidable
	The storage volume of a telescoping arm is significantly bigger than of the other options available. Even though an arm can fold into itself, the mechanisms required to support the arm in operation may take up more space

Sensor Package Mounting Options

1) Single Rotation Axis Sensor Package Mount: The simplest version of a sensor mount capable of achieving TDR1.1.3 is a motorized, single rotation axis platform. Figure 20 shows a simple top-down view of how such a mount would operate:

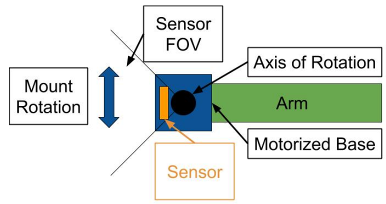


Figure 15: Single Rotation Axis Sensor Package Mount, top down diagram

The primary benefit of this design is that it achieves TDR1.1.3 as simply as possible. A single axis motorized mount requires less mass to be supported at the end of the robotic arm, fewer mechanical complexities, and less power draw if only one motor is powered. Finally, the motors required for such an application are readily available and cheaper, less precise options such as brushed servo motors have been shown to be effective in similar applications [16].

Table 7: *Single Rotation Axis Sensor Package Mount Pros and Cons*

Single Rotation Axis Sensor Package Mount	
Pros	**Cons**
Simplest design option possible to achieve TDR1.1.3.	Only offers single-axis rotation for sensor package, which limits artifact finding effectiveness.
Requires less mechanical design complexity, which in turn presents fewer moving components to be damaged by dust, mud, or water.	
Possible with inexpensive servo motors [16].	
Reduces the mass the end of the robotic arm has to support; limits risk of applying adequate torque to tip the Husky.	

2) Dual Rotation Axis Mount

Functionally a dual rotation axis sensor package mount works the same as the single axis mount other than incorporating an additional controlled motor to adjust the sensor package's angle about a second axis. Figure 16 indicates how a dual axis mount would operate:

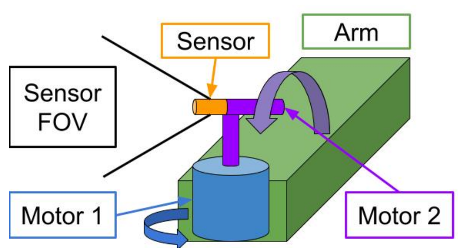


Figure 16: Dual Rotation Axis Sensor Package Mount Functional Diagram

Aside from the clear advantage of adding a second rotational axis for the sensor package, which would dramatically improve the performance of a camera-based visual signature sensor relative to FR2.1, a dual rotation axis type mount could potentially be purchased relatively inexpensively. The proliferation of miniaturized action cameras such as GoPros has created a demand for economic, off-the-shelf gimbal mounts would meet and exceed TDR 1.1.3 without requiring significant modifications [17].

Table 8: *Dual Rotation Axis Sensor Package Mount Pros and Cons*

Dual Rotation Axis Sensor Package Mount	
Pros	**Cons**
Adding a rotational axis would significantly improve the sensor system's potential for locating artifacts behind line of sight obstructions (TDR 1.1.2 and 1.1.3).	Commercial options may not be available for the team's ultimate choice of visual artifact sensor.
Dual axis sensor package mounts are available commercially at low prices with the ability to be programmed to the team's application [17].	Moving a visual artifact sensor about an additional axis creates added risk for damaging the sensor or having the mount mechanically fail.
Dual axis sensor package mounts are extremely common in small drone applications; as such many small and lightweight designs are published and avaiable as development inspirations.	Adding a second motor to rotate about another axis likely will add mass that must be supported by the robotic arm in addition to the sensor package the mount is rotating.

Robotic Arm: Summary Pro Con Analysis Considering all three robotic arm solution areas combined allows for developing a summary list of pros and cons for the robotic arm as a combined sensor deployment solution:

Table 9: *Robotic Arm Summary Pros and Cons*

Robotic Arm Summary	
Pros	**Cons**
Jointed or telescoping mechanism could likely reach and exceed 1m (TDR1.1.1)	Mechanically complicated solution
Jointed mechanism or telescoping mechanism combined with jointed mechanism could surpass TDR1.1.2	Moving parts must be protected against fouling from dirt or water
Arm sensor package mounts support TDR 1.1.3 well	Slightly elevated risk of applying a torque endangering the UGV compared to other solution categories.
Research examples of robotic arms applied successfully on similar projects	Achieving FR1.1 while fitting within the TDR4.1.1 volume constraints may be difficult
Arm solution could support wired sensor equipment	
Electrical power and mission duration concerns minimized based on introductory research of design space (FR5.2)	
Arm solution does not detach from UGV during deployment (FR5.2)	
Reusability is only limited by electrical power (FR5.3)	

4.1.2 Drone

Another deployment design option for the sensor package is via a drone. Drones are becoming very common for sensing and gathering data in missions similar to this, and they should definitely be considered as a design solution.

The drone would need a method to deal with potential collisions inside the cave. This could either be an active collision avoidance system, or some sort of protective padding on the drone. (either a spherical cage that surrounds the drone, or bumpers that protect protruding surfaces and the rotors). Active collision avoidance would require dedicated sensors on the drone, and a good bit of software to process the data of the drones surroundings and react accordingly. Even with collision avoidance software, it would be unwise to assume that the software is perfect and the drone will never contact anything, so some sort of protection would still be needed. A collision avoidance system is a great solution to operate in an environment with random obstacles, however it has requires a dedicated sensors and software that will likely require a significant amount work.

The other option for drone protection is some sort of protective padding, either a spherical cage-like structure or bumpers around the rotors and protruding surfaces. Both of these would likely be custom made out of a rubber type of material, something with the right amount of give. The maximum speed for the drone would be known, so the right material with the right properties to absorb the impact could be determined (not too stiff so the drone is not basically still hitting a wall, but stiff enough to stop the impact from occurring). The material also would ideally not exert a large restorative force on the drone, which could cause instability in it is flight and a possible crash. The cage would need to be tight enough so that pointy surfaces on the walls of the cave could not penetrate through and get to the drone. The sphere could be able to freely rotate along a couple different axes, which would help a lot with collisions so any moments are not just translated straight to the drone. Flyability partnered with a team from Zermatt Mountain Rescue to build a great example of this structure [18]. Their drone is used to explore the crevasses of the Zermatt Glacier and help with search and rescue missions. The drone is able to successfully navigate the glacier with excellent stability while bumping into walls constantly. There is likely some sort of gimbal system that allows the cage to spin and absorb moments without making the drone's flight unstable. Pictured below is a capture from video footage on the drone, where you can see the protective cage and the type of environment that the drone can explore.

Figure 17: Protective Cage Around Drone, Camera's Perspective [18]

Listed below are some pros and cons for the sphere and for the bumpers.

Table 10: *Spherical Cage Pros and Cons*

Speherical Cage	
Pros	**Cons**
Protective coverage against collisions in all 3 dimensions.	Takes up a lot of space, so mounting on the Husky could be difficult.
	Keeps the drone from fitting in tighter spaces.

Table 11: *Bumpers Pros and Cons*

Bumpers	
Pros	**Cons**
Likely uses less material than the spherical cage, meaning it is lighter.	Incomplete protective coverage.
Does not take up very much space so a larger drone could be used.	

Another option for the drone is whether it is tethered to the Husky or completely wireless. A tether could supply power to the drone, as well as serve as a communications line between the sensors and the Husky. It would eliminate the need to carry batteries on the drone, as well as the need to wirelessly transmit the data wirelessly communicate with the drone and send/receive positioning commands. Two of the main problems with drones of any kind are battery power and signal loss, so having it tethered would eliminate these two issues. Wireless would let you go farther from the ground robot, but that is not really needed for this application since there is maximum physical reach. The tether could just be made as long as we need. There is a concern of possible tangling of the tether, whether getting tangled on itself or getting caught on a cave wall. As for wireless, there would not be any concern of getting tangled, but sending data and communicating with the Husky would be much harder. Also, battery life becomes a big issue with being wireless. Charging while docked on the Husky could be a possibility, but it would have to be a very accurate landing system, probably impossibly accurate. All of these points are listed below in a pros vs cons list for wireless and wired approaches.

Table 12: *Wired (Tethered) Drone Pros and Cons*

Wired (Tethered) Drone	
Pros	**Cons**
Wired communication is much easier and more robust.	There is a potential for the tether to get tangled or caught up on the Husky or cave walls.
Power could be sent directly to the drone at all times.	

Table 13: *Wireless Drone Pros and Cons*

Wireless Drone	
Pros	**Cons**
More maneuverability and freedom.	Battery life becomes an issue. The drone would either need to carry extra batteries (more weight), or the docking and charging process becomes very complicated.
	Harder to transmit data and communicate with the Husky.

Drone: Summary Pro Con Analysis

Table 14: *Drone Pros and Cons*

Drone	
Pros	**Cons**
FR1.1 - Easy physical reach. 5 meter reach is not an issue, positioning and changes in direction are also not a concern.	TDR4.1.1 - Deployment constraints. Mounting on the Husky may be a dimensional issue if its protective system takes up a lot of space. It would have to be a relatively small quadcopter.
FR4.2- Mechanical Interference. The drone will not be tipping the Husky over and will not interfere in any other way.	FR5.1- Environmental hazards. Having the drone itself and all of its components waterproof and dustproof might be difficult.
TDR4.3.1 and TDR4.3.2 - Deployment time. The drone turns on and can lift off of the Husky with electric motors pretty much instantly.	FR5.2- Endurance time requirements. This is a con if a wireless drone is picked or there is not a way to provide power over a tether.

The reusability is both a pro and a con for the drone. It is in no way a single use system, but landing on the Husky could present some issues. The landing area would be tight and the team cannot rely on it being flat all of the time.

4.1.3 Projectile Launcher

A projectile launching system mounted to the MARBLE Clearpath Husky used to launch a sensor cluster to a desired location requiring three primary elements, diagrammed below in Figure 18. The sensor system being used will be in the form of a sphere. This is due to the sphere being a simple shape to integrate into the launch system and it is able to be adjusted to fit the sensors required in any orientation desired. The sensors in use shall be determined by the sensor team and the deployable vehicle will be designed to accommodate there needs.

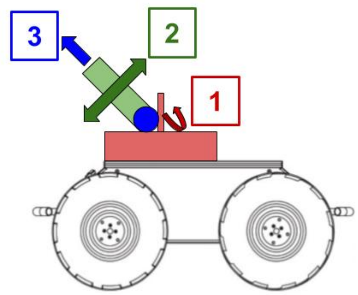


Figure 18: Projectile Launch Basic Element Breakdown

Theses elements are as follows:

1. Base Plate: Indicated as 1 in the diagram above, the base plate would provide two critical functions. First, the plate must keep the launcher attached to the Husky and stable during firing (TDR 4.2.1). This includes supporting the cannon in both it is standby state and its deployed state, and acting as the base link for power and data connections to the Husky (FR4.1). Second, the base will rotate and incline the launch system to achieve TDRs 1.1.1 and 1.1.2.

2. Launch Mechanism: Indicated as 2 in the diagram above. The launch mechanism includes the system to launch the sensor cluster to the target to achieve TDR 1.1.1. as well as reset the mechanism to be ready for another deployment to satisfy FR5.3.

3. Rearm Mechanism, Reusable vs. Single use Indicated as 3 in the diagram above. This includes either a retrievable and reusable sensor on a tether or a storage space housing discard-able sensor cluster to be used. This reload system will reset the deployable sensor cluster to be ready for another deployment to satisfy FR5.3.

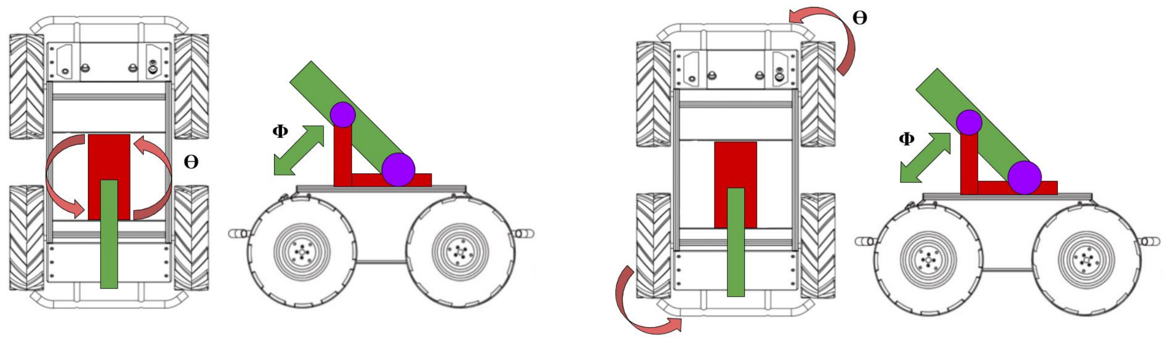
In the next three subsections possible design solutions are considered for each design element:

Projectile Launch Base Plate

1) Rotational Base Plate:

Rotating base mounts are common in projectile launching systems such as navel turrets and air defense systems like anti-aircraft guns. These systems have motors that rotate they base as well as change the inclination of the barrel to achieve the desired firing arc. This project would use a similar system on a smaller scale.

The mechanical approach to rotating the base is similar to the process the robotic arm from before utilizes. The system is attached to a motorized base plate and is rotated on command using a motor connected to a series of gears that swivel the plate to the desired direction. The inclination, at a basic level, is handled by placing an axis through some point along the barrel and applying a rotation to that axis to set the inclination. This and be done by many methods such as sets of gears and motors, or servos directly places onto the axis. Below in Figure 19a the axes are labeled as θ and ϕ for base rotation and inclination respectively. The system would be encased in a cover to avoid any obstructions to the moving components to meet FR 5.1 while mounted to the MARBLE Husky rover.



(a) Projectile Launch Rotational Axis

(b) Projectile Launch Rotational Axis, Static Mount

Figure 19: Projectile Launcher Rotational Methods

Designs, such as this, have a high mechanical complexity owing to the need to develop a rotation and inclination system using gears and motors able to function under the mass of the system and achieve a high degree of accuracy to ensure that the projectile is launched to the desired location.

Table 15: *Rotational Base Plate Pros and Cons*

Rotational Base Plate	
Pros	**Cons**
Allows for orientations that would be unachievable by the Husky when operating in restrictive environments	Increased mechanical complexity to develop, manufacture, and test
High accuracy to orient at target location	Increased attitude determination and controls system to be developed and tested
Regularly used mechanism with large amounts of examples research from	

2) Static Base Plate:

Static base mounts are similar to statically mounted arms on robots. The inclination would still be controlled in a similar way as the rotational base mount while the rotation would be controlled by rotating the rover to the desired orientation. This is very similar to a fixed robotic arm system such as the University of Sydney's Continuum Rover from before. In Figure 19b an example is shown of the rotational axis for this case.

Having a static base required more communication with the MARBLE rover to deploy in the correct direction. However, this simplification reduces the mechanical complexity of the system reducing the locations where error or failure could occur.

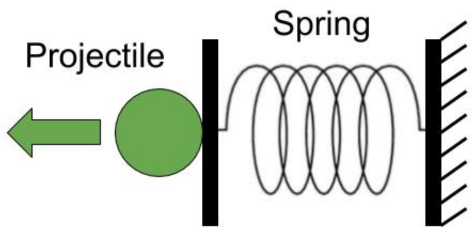
Table 16: *Static Base Plate Pros and Cons*

Static Base Plate	
Pros	**Cons**
Static mount required less complex mechanical development	Requires additional communication with the rover to be able to point in desired direction
Know single source of forces that could result in destabilizing the MARBLE rover in relation to FR4.2	Decrease in ability to target a location dependent on the ability of MARBLE to position itself
Removes potential components that could be impeded by dust and water in relation to FR5.1	

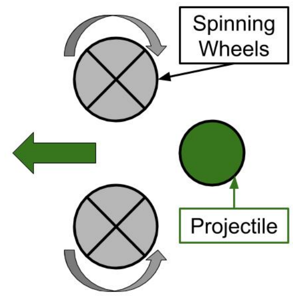
Launch Mechanism

1) **Spring Loaded:** A simple system that is used in many other applications to launch projectiles, like nerf guns. A spring is compress behind the projectile, when released the projectile is pushed forward. Systems like this are able to produce consistent forces that can be easily modeled for projectile motion using the spring force equation below Equation 1, where F is force, k is the spring constant, and x is the distance compressed. Also the force can be easily adjusted by adjusting the compression distance allowing for variations in the trajectory.

$$F = -k * x \tag{1}$$



(a) General Spring Loaded System



(b) General Spinning Wheels System

Figure 20: Launch Mechanisms

Above, in Figure 20a, is an example of the general configuration of a spring loaded projectile system. The complexity is increased by the need to be able to re-compress the spring to different distances depending on the desired trajectory. Once the spring is compressed the system can fire right away resulting in faster results. The spring will be re-compressed when the next target is determined.

Table 17: *Spring Loaded Mechanism Pros and Cons*

Spring Loaded Mechanism	
Pros	**Cons**
Springs produce a repeatable and model-able force for ballistic trajectories	Required a system to re-compress the spring for each reuse
Adjustable depending on the desired trajectory to achieve accurate results	Spring is easily able to be obstructed

2) **Spinning Wheel:** The spinning wheel system is similar to how tennis ball launching machines operate. Using two wheels that are spinning at the same rate projectiles that pass in between and contact the wheels are ejected along a trajectory. The trajectory is able to be adjusted by changing the spin rate of the wheels. Additionally the trajectory is able to be simulated using the kinetic energy transferred during contact. In Figure 20b, is an example of the general system to fire projectiles. Once launched the system will return to a standby state where the wheels are stationary.

This system reduces mechanical complexity by not requiring a rearm system, however there is increase complexity in keeping both wheels rotating at the same rate. Unbalanced rotation can lead to spin being imparted to the projectile and/or a misaligned trajectory resulting in missing the target.

Table 18: *Spinning Wheel Mechanism Pros and Cons*

Spinning Wheel Mechanism	
Pros	**Cons**
Trajectory is easily simulated and adjusted	Induce unknown spin on the sensor ball
No complex mechanism to reset the system	Required additional time to spin wheels up to desired configuration

Rearm Mechanism, Reusable vs. Single use

1) **Reusable Sensor:** The reusable sensor cluster shall be attached to the system using a cable tether that will also handle power and communications with MARBLE. The tether shall be on a spool, similar to a fishing reel, and retracted using a electric motor once the sensor scan is complete.

Table 19: *Reusable Sensor Cluster Pros and Cons*

Reusable Sensor Cluster	
Pros	**Cons**
Increase budget allowing for increased quality of sensors	Retrieval can be blocked by many obstacles
Reduced number of systems required to be contained by deployable	Hazardous objects could sever the tether

2) **Single Use Sensor:** The single use sensor cluster shall be deployed and not retrieved. This requires the cluster to have its own power and communications system to return data to the rover. A storage system shall be arranged connected to the launcher. When reset to standby configuration the storage system shall place another sensor cluster into the launcher using either gravity or mechanical movement.

Table 20: *Disposable Sensor Cluster Pros and Cons*

Disposable Sensor Cluster	
Pros	**Cons**
No need to retrieve deployed ball saving mission time	Extra storage space required to house at least five total deployables for FR5.3.
Lower cost per deployable	Increased systems, power and communications, required inside of the deployed ball

Projectile Launcher: Summary of Pros and Cons: Below is the cumulative summary of the pros and cons for using a projectile launcher for comparing to the other design solutions.

Table 21: *Projectile Launcher Pros and Cons*

Projectile Launcher	
Pros	**Cons**
Long physical reach satisfying FR1.1	Increased mechanical complexity can create issues satisfying FR5.1
Low chance of disturbing rover satisfying FR4.2	Increased software complexity to satisfy FR3.1
Highly controllable trajectories satisfying FR1.1	Requires projectile simulations to satisfy FR3.1
Rapid deployability satisfying FR4.3	Increase complexity and chance for failure to satisfy FR5.3
Low power draw in active and standby states satisfying FR5.2 and TDR4.1.3	Difficult to satisfy mass and volume for TDR's 4.1.1 and 4.1.2

4.2 Artifacts Sensing

There are multiple types of sensors that could be chosen to satisfy FR2.1 Artifact Sensing Requirements. The design is not limited to choosing one sensor and will require at least two sensors to meet both TDR2.1.1 and TDR2.1.2. While there are nine DARPA artifacts, the TDR is for FR2.1 only outlined the need for **visual sensing** and CO_2 **detecting**.

TDR2.1.1 Design options: To **visually sense** artifacts cameras, LiDAR and thermal lenses were considered. These all provide different levels of detail and accuracy when visually sensing their surrounding environments.

Cameras: The types of cameras considered include RGB-D and VR depth cameras. An RGB camera is a digital camera that produces color images. They mostly see in the visible light spectrum and therefore require a sufficient light source to produce a quality image. RGB-D cameras have the same capabilities as RGB cameras but augment the image with depth information. This allows for a more 3-dimensional perception of the environment. These cameras will be most useful for **visually sensing** the brightly colored artifacts. A VR or virtual reality camera is used to create single images encompassing a larger view, up to 360 degrees. These omnidirectional, panoramic style photos are useful when large visual fields need to be covered. VR images use multiple shots merged together to create a singular complete image which increases FOV but also takes longer to capture.

Table 22: *RGB-D Camera Pros and Cons*

RGB-D Camera	
Pros	**Cons**
Color Image	Needs Lighting
Depth Sensing	Limited FOV
Dedicated ROS library	Quantity of Images

Table 23: *VR Camera Pros and Cons*

VR Camera	
Pros	**Cons**
Color Image	Needs Lighting
Depth Sensing	High Time per Image
Wide FOV	
Fewer images needed	

Thermal Imaging: Thermal imaging lenses operate in the IR spectrum and visualise the environment through heat signatures. Thermal imaging can be added to an RGB camera with a thermal imaging lens which can reduce costs by not having to buy multiple cameras. Thermal imaging would be mostly be helpful for the artifacts that give off heat signatures, but also has potential to be useful for the other visual artifacts depending on the temperature and materials of the artifact is surroundings.

LiDAR: LiDAR, light and detection ranging, is a method of remote sensing that utilizes light pulses in the form of lasers to map the environment. LiDAR produces a very precise, 3-dimensional image, and while it does not require additional lighting, it cannot distinguish colors. This is a good option for visual artifacts, brightly colored or not. LiDAR is typically going to be a more expensive sensor.

TDR2.1.2 Design options: CO_2 sensors range in quality, price and size. Most sensors are fairly small and as they increase in price, the speed in which the sensor delivers results and sensing capabilities improve. There are not a lot of design options for CO_2 sensors besides brand. The only direct requirement for the sensor is that it needs to be able to **sense** and **detect** Carbon Dioxide at about 2000 PPM so smaller, lighter and cheaper sensors with this capability are more ideal. The two carbon dioxide sensors being considered are the SCD30 from Sensirion and the CCS811 Air Quality Breakout from SparkFun. Because these two sensors are very similar in terms of performance, it was determined that it would be more effective to do pros and cons of each rather than do a full trade study.

- *PPM Sensing Capability:* Both sensors have the ability to sense 400 ppm and greater which satisfies the 2000 ppm requirement. The difference is the accuracy of the measurements. The Sensirion SCD30 has an accuracy of $\pm(30ppm + 3\%)$ where the Sparkfun CCS811 does not have a determined accuracy.
- *Size:* The Sensirion SCD30 has dimensions of 35 mm x 23 mm x 7 mm. The Sparkfun CCS811 has dimensions of 4mm x 2.5 mm x 1mm. The smaller the sensor the better, as these decreases likelihood the sensors will limit mechanical design choices. This means that the Sparkfun CCS811 is better in this category.
- *Power Draw:* Both sensors require a very minimal amount of power which is advantageous. Because both their power draws are so small, this is no longer a good criteria to determine which is better. The Sensirion SCD30 uses about 400 mW and the Sparkfun CCS811 requires about 60 mW.
- *Cost:* The Sensirion SCD30 costs about $60.00 while the Sparkfun CCS811 costs about $20.00. The cheaper cost of the Sparkfun CCS811 makes it preferable.
- *Other Considerations:* While both sensors have a calibration period that ranges from hours to days, this can be performed prior to attaching the sensor to the final design. The Sparkfun CCS811 requires an additional 20 minute warm up when started in order to output valid data. This is a major con for the Sparkfun CCS811 because the sensor system is being designed to be used during a DARPA competition and to be complimentary to the MARBLE robot while constraining and affecting it minimally. If MARBLE is turned on right before the competition, the Sparkfun CCS811 would be useless for the first 20 minutes of the 60-90 minute long competition. This means the sensor could be useless for up to 33.3% of the competition.

Due to the additional 20 minute warm up requirement for the Sparkfun CCS811 and lack of determined accuracy in parts per million measurements, the perception team has decided to eliminate the Sparkfun CCS811. Therefore, the only remaining CO_2 sensor is the Sensirion SCD30 which will be used as a component of the sensor suite.

4.3 System Position and Orientation

Determining system position and orientation is a key element in a project of this nature. Accurate position and orientation of the sensing system helps the MARBLE team to approximate the ground truth location of a sensed artifact. Moreover, it helps the sensor apparatus in performing its tasks efficiently, as the sensing system will do all of its tasks based on relative location provided by firing commands. Hence, accurate position and orientation readings are vital.

The task of determining attitude and position is typically performed by sensors of some form. Different sensors uses different methods to extract information regarding change in position and orientation. Most available attitude determination sensors rely on readings from gyroscopes, magnetometers, and accelerometers. The main differences stem from how the readings from these sensors are combined together to produce meaningful results, such as position and orientation, and how errors are handled.

Table 24: *Separate Sensors Pros and Cons*

Separate Sensors	
Pros	**Cons**
Independence	Less cost-effective
More control over quality	Data has to be processed separately
	Complexity of integration

In general, there are two solutions to FR3.1: employing independent sensors to satisfy TDR3.1.1 and TDR3.1.2 separately, or use one sensor to achieve both tasks. The pros and cons of each method is discussed in Tables 24 and 25. Typically, since sensor technologies can often be applied to determine changes in either position or orientation, a combined configuration is more frequently used.

Table 25: *Combined Sensors Pros and Cons*

Combined Sensors	
Pros	**Cons**
Simple integration	Cost
Accuracy	

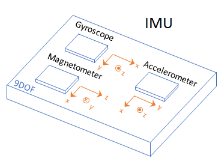
Such a shift towards dual-purpose sensor configurations has been enabled by sensor technologies decreasing in price and increasing in precision over time, especially in recent years. Separate-sensor arrangements are less common; they are rarely used unless a sensing task requires position and orientation measurements to be taken independently. These configurations offer more abstraction than combined sensors; if one sensor loses functionality, the system will still be able to report data from the other sensor. However, if a combined sensor fails, neither position nor orientation can be reported.

4.3.1 Position determination Design options

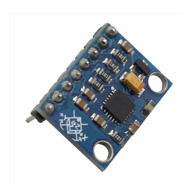
Table 26: *Pros and cons for using GPS to determine position*

GPS/GNSS	
Pros	**Cons**
Easy to use	Low-accuracy relative to the requirements
Direct measurements	Limited coverage in cave environment

There are three typical sensors that are used to determine positions. The first, and most widely known, option is the Global Positioning System (GPS)/Global Navigation Satellite System (GNSS). Such systems relay heavily on satellite communications to determine position and are used for a wide variety of applications, from cell phones to autonomous cars. One of the main challenges that comes with GPS/GNSS systems is reception. If a device using GPS/GNSS technology is in an environment where the signals could be blocked, GPS/GNSS systems tend to perform poorly. GPS/GNSS systems' pros and cons in the context of this project are compared in Table 26.



(a) Typical IMU schematic representation. Courtesy of MATHWORKS.



(b) Typical off-the-shelf IMU. Courtesy of Robotshop.

Figure 21: Inertial Measurement Unit (IMU)

Another option is Inertial Measurement Units (IMUs). IMUs are very popular in the field, and have been used for various distinguished missions, including NASA's Apollo program. Figures 21a and 21 show a typical IMU schematic and an off-the-shelf IMU sensor, respectively. IMU sensors are unique in that they use a combination of multiple sensors in conjunction. The readings of the sensors could be used to determine position (and orientation too, however, this has to be done by post-processing sensor data). IMUs are notorious for accumulating errors due to Gyroscope drifts and other issues, and small deviations could propagate and accumulate to make significantly erroneous readings. To determine position, usually acceleration data are integrated twice to estimate position, and hence small deviations in acceleration accumulate to large errors. Therefore, one would typically use filters and error-correcting mechanisms to account for this. The pros and cons of IMUs are listed in Table 27.

Table 27: *Pros and cons for using IMU to determine position*

IMU	
Pros	**Cons**
Relatively cheap	Needs external processing to determine position
Could satisfy both TDR3.1 and TDR3.2	Accumulated errors
Wide range of accuracies	Sensitive to thermal gradients
	Errors could be corrected using other methods at the cost of additional complexity

The final sensor considered was the Attitude and Heading Reference System (AHRS). AHRS sensors give very accurate readings for both position and orientation, and have been used more often in recent years because they have been developed in smaller sizes and more affordable options. AHRS sensors are far more accurate than IMUs because they contain filtering systems and complicated algorithms that use a technique called "sensor fusion" to eliminate errors from sensors and present accurate measurements by using multiple readings. These systems have on-board processing units, hence the readings of the sensors are converted into orientation readings on board. Position could be obtained from accelration data wich are filtered and calibrated by the AHRS. AHRS pros and cons are shown in Table 28.

Table 28: *Pros and cons for using AHRS to determine position*

AHRS	
Pros	**Cons**
Accurate	More expensive relative to IMU and GPS/GNSS
Could satisfy both TDR3.1 and TDR3.2	Complex integration
Internal processing to determine position and orientation	
Error correcting mechanisms	
Various outputs options	
Sensor fusion	

4.3.2 Orientation determination Design options

Though information from the same sensors (gyroscopes, magnetometers, and accelerometers) is typically used to determine both position and orientation, it is processed differently for each of the two measurements. As such, both IMUs and AHRS sensors are used to detemrine orientation, and both are discussed throughly in section 4.3.1.

Another option, the Vertical Reference Unit (VRU), measures roll, pitch, and yaw, and thus deals primarily with orientation. This is done primarily by using a gyroscope, accelerometer, and inclinometer. Table 29 discusses the pros and cons of the VRU.

Table 29: *Pros and cons for using VRU to satisfy orientation determination requirements*

VRU	
Pros	**Cons**
Relatively cheap	Gets only orientation and not position
Accurate	

4.3.3 Design choice

Based on the discussion in this section, a trade study on position and orientation is not an interesting one, and the most technical solution seems obvious from the pros and cons tables. An AHRS sensor is the most technical solution to determine orientation and position. Since AHRS sensors can be purchased off the shelf, any AHRS with sufficient accuracy will satisfy FR3.1. It is important however to remind as noted in Section 4.3.1 that the filtering varies from a sensor to another. Based on some conducted reasearches by the team, the AHRS sensors developed by YOSTLABS are a viable solution for this project. YOSTLABS manafcture sensors htat use various filtering algorithms and sensor fusion techniques, but more importantly, allows the user to access raw data, calibrated data, and final orientation readings. The position could be estimated by integrating the filtered and calibrated acceleration data. The exact sensor chosen is discussed in Section 6.

4.4 Communication & Data Transmission

4.4.1 Method of Communication

Several methods of communication were considered in order to satisfy FR6.1 Communication Requirements; these included docked data transfer and on-board data storage, as well as both wired and wireless transmission. On-board data storage did not involve frequent transmission, instead storing data on-board the sensor until the end of the mission. As this is not conducive to the mission purpose of frequently reporting artifacts, it was not considered in the trade study. Docked data transfer entails deploying a remote sensor apparatus, such as a drone, and storing data on-board the sensor until its return to the 'docked' position on the MARBLE UGV. However, the two most promising methods of communication and data transmission were wired and wireless communication, as elaborated on in Section 5.3.

Wired communication would likely entail a shielded continuous-flex, or continuous-flex-and-twist, cable. The cable would be shielded so as to avoid interference to or from MARBLE's other communications systems. The decision between continuous-flex and continuous-flex-and-twist relies heavily on the perceived motion of the appointed deployment system, specifically its rotation capabilities.

On the other hand, a wireless communication solution would be reliant on a dependable transmitter, such as an xBee Zigbee adapter board. Such a communication method could be configured for low-power and low-cost data transmission, but the team deliberated on doubts of transmission reliability with obstructions [19]. As the primary facet of this project involves sensing around obstructions, this complicates the implementation of a wireless communication solution.

4.4.2 Microcontroller

For effective data transmission, communication, and system control, a microcontroller will be crucial to the success of this project. In order to keep the system relatively lightweight, only small, single-board microcontrollers were considered. The units considered were the Raspberry Pi 4 Model B, Arduino Mega 2560 Rev. 3, BeagleBone Black Rev. C, and the Silicon Labs Pearl Gecko EFM32. These were all selected for consideration with ease of integration in mind; less time spent establishing a secure interface between the microcontroller and sensors allows more time for the team to focus on mechanical and other tasks.

4.5 Programming Language

For the purposes of communication, data transmission and controls, this team shall decide on a specific programming language to use to create software for our instrument. The software shall interface with MARBLE's main system. However, other languages could be used in conjunction with this team's primary programming language, depending on what functions this software shall have. As such, several programming languages were considered for the role of the primary language despite the fact that less favorable options may be employed for specific software tasks.

4.5.1 C++

Of the options listed in this section, C++ is the lowest-level programming language, generating relatively optimized machine code in the scope of the options considered. It is largely due to this that the language boasts quick run times; another factor is the fact that data management is handled manually in C++. This enables programmers to maintain responsive software with low storage requirements - however, this comes at the cost of added development complexity [20]. C++ also enables the use of pointer variables to reference memory addresses, which contributes to both the responsiveness and complexity described earlier. It is also one of the languages most often used to interface with ROS, the other being Python [21]. As a result, documentation for C++ in this purpose is extensive, as are supporting libraries.

Table 30: *Pros and cons for using C++ as the primary programming language*

C++	
Pros	**Cons**
Data management for low memory allocation	Higher programming complexity with data management
Lowest runtime - most responsive	No native IDE
Familiar language based on earlier coursework	
Extensive ROS documentation & libraries	

4.5.2 C#

Like C++, C# is derived from the widely used C programming language. However, the similarities between the two successors mostly end here. While C++ is an object-oriented language, C# is considered to be component-oriented, which lends itself to a more modular code. C# does not compile into machine code - rather, it compiles to CLR, which is interpreted by ASP .NET [20]. On this note, C# is a much higher-level language than its object-oriented counterpart. It is also standardized, but is rarely used outside of Windows environments, thus its applications are limited [20]. In addition, all messages that a C#-based ROS package can possibly used are wrapped, leading to long compilation times [21].

Table 31: *Pros and cons for using C# as the primary programming language*

C#	
Pros	**Cons**
Modular in nature	High-level, less responsive
Standardized	Limited scope of applications
Lower complexity with automated data management	Higher memory allocation decreases responsiveness
	Cannot create standalone applications
	Long compilation time with ROS packages
	No native IDE

4.5.3 Python

Python is a widely accessible programming language, as it is developed under an open-source license. It is widely regarded for its numerous open source package libraries, whose contents rival (and sometimes surpass) those of programming goliaths such as MATLAB. Python is a high-level language which, like C# and MATLAB, offers automated data management; the advantages and disadvantages of this are described in Section 4.5.1. However, Python is a very versatile language due to its accessibility and the extensive nature of its supplementing libraries. Though it was not created as a primarily computational language, Python is sometimes referred to as a resemblance of an "open source MATLAB." Python syntax is also generally much more simple than other programming languages [22].

Table 32: *Pros and cons for using Python as the primary programming language*

Python	
Pros	**Cons**
Automated data management	Larger memory allocation required
Extensive libraries & relevant documentation	Higher level, less responsive
Simple syntax	No native IDE
Open source, no cost	

4.5.4 MATLAB

MATLAB, short for 'Matrix Laboratory', was developed primarily as a computational tool for matrix operations. However, it quickly evolved into one of the most widely used applications in scientific research and industry, with numerous supporting software features and toolboxes of varying specialties. One such of the latter, the Robotic System Toolbox, can be used to interface with ROS [21]. MATLAB is a very high-level programming language and as such is not very fast when executing code compared to low-level programming languages (e.g. Java, C++). However, it has extensive documentation provided by its parent company, SimuLink, and this team is quite familiar with its use and syntax from previous experience in ASEN courses within the University of Colorado Aerospace Department. MATLAB is also an expensive application, but this is not an immediate problem for the team, given that all members at this time possess an academic license. However, this would likely come into consideration for other users down the line.

Table 33: *Pros and cons for using MATLAB as the primary programming language*

MATLAB	
Pros	**Cons**
Very familiar to team	Primarily used for computations
Extensive, reliable documentation	High-level, slow
Native IDE already installed by all teammates	Expensive
Numerous toolboxes available under academic license	

5 Trade Study Process and Results

To conduct the trade studies for this document, NASA's System Engineering handbook guideline were followed [9]. In addition, NASA's Trade Studies Module for Space Systems Engineering approach was also taken [23] to develop the trade studies. In particular, the trade studies were designed such that they started from the high level requirements in order to accomplish "pruning unattractive early alternatives" in what is sometimes known as doing "killer trades." [9]. This allows for secondary trades to dive deeper into the most promising solutions. Secondly, as a practice to make the trade studies more rigorous, uncertainty estimation was included in some the trade study matrices to favor solutions the team was more confident of being able to design. This practice highly recommended by NASA's Handbook [9]. Furthermore, to support the decision making process and ensure that the most acceptable technical solution emerges, the trade studies criteria was chosen to cover both Measures Of Performance (MOP) and Measures Of Effectiveness (MOE). A MOE is "A measure of how well mission objectives are achieved.", while a MOP is "a quantitative measure that, when met by the design solution, will help ensure that an MOE for a product or system will be satisfied." [23]. Hence, every criteria chosen for any trade study in this document will be either a MOP or MOE, and it would be obvious from the criteria itself whether it is a MOP or MOE.

All trade studies used a value scale from 1 to 5 for assessing criteria.

5.1 Physical Reach, Deployment, Durability

Following the Systems Engineering handbook guidelines, for deployment and mobility solutions the team started with a trade between the three general categories of mobility solutions researched. Conducting a trade between the robotic arm, a drone, and a sensor launcher prevented needing to perform unnecessary trades within solution spaces that were not going to be chosen for the final design.

Design effects for this initial trade study were directly based on the FRs and TDRs that a sensor system mobility system would have to accomplish. These effects were labeled and selected as follows:

1. **Maneuverability and Reach** FR1.1, including all three of its TDRs, was selected to encompass all of the design effects important to how the system could actually move a sensor package around in the competition environment. The group determined that not all solutions considered had the same chances of achieving unobstructed reach, directional changes, and being able to rotate the sensors attached to them; therefore this effect was included into the trade as a quick way of ruling out solution spaces without a balance of all three factors.

2. **Communications and Sensing Interface** The point of a sensor deployment system is to physically re-position a sensor. Therefore, "communications and sensing interface" was selected as an important design effect where the team could evaluate how well a mobility system could support large and/or heavy sensor options, as well as if the mobility system could support wired and/or wireless sensor systems. The group noted that 80g, 56250mm^3 was a rough mass and size benchmark for the smallest sensor combination considered.

3. **Weight/Size** FR4.1's weight and size limitations for the overall system were chosen as a broad design effect to assess how well mobility solutions could fit the volume and mass limits set by the customer. These effects were chosen given that the team expects the vast majority of the project's allocated mass and volume to be taken up by the mobility system.

4. **TDR4.2.1** TDR4.2.1 was selected as a design effect because all mobility solution spaces involved moving parts attached to the UGV. Therefore, the risk the selected mobility solution created for tipping or otherwise damaging the UGV needed to be evaluated.

5. **FR4.3** As with FR1.1 and FR4.1, FR4.3 was evaluated a design effect category including all of its TDRs. Any mobility solution worth selecting would need to perform within the rigorous time constraints the customer requested.

6. **FR5.1** FR5.1 was evaluated as a design effect important to mobility solutions because water and dust damage could result in a inadequately protected mobility solution being rendered inoperable and therefore a liability to the MARBLE mission. FR5.1's temperature TDR, although clearly achievable for all solution spaces, was included in the trade for completion.

7. **FR5.2** FR5.2 was evaluated as a mobility design effect given that not all solution considered had the same operational speed, and faster deployment and return to standby make the project more useful the MARBLE's mission.

8. **Design Complexity** The team noted that the mobility solutions had noticeable variations in how likely the team could design and construct them effectively within the time-span of the senior projects course. Therefore, design complexity was marked as an important effect: a mobility system prohibitively difficult to produce on time would fail by default.

9. **TDR5.3.1** Any mobility solution selected would have to meet the repeat deployment requirement of TDR5.3.1; a solution more preferable to MARBLE would need to exceed the minimum five deployments according the the customer's comments.

The criteria were then assigned percent weights as follows:

Table 34: *Rationale for criteria of sensor type trade study.*

Criteria	Weight	Rationale
Maneuverability and Reach	20%	Sensor system mobility was given the heaviest criteria weight given that the primary objective of the project is to expand the MARBLE team's sensing range: all other requirements enable this objective.
Comms. and Sensing Interface	15%	The ability to support the specific sensors selected for the system, both in terms of size/weight and connections, was heavily weighted. If the mobility solution cannot support the selected sensors, it is pointless.
Weight/Size	10%	While important to mission success, the TDRs under FR4.1 were given only a 10% weight because the team's research indicated that all considered mobility solutions could be designed to meet all three TDRs.
TDR4.2.1	5%	The team decided to give this criteria a low weight of 5% since it has a high chance of being met by all 3 solution options. It is unlikely that any of the solution options would tip over the Husky or cause damage to it during the competition, so it does not make sense to give this criteria a large weight and have it be the deciding factor.
FR4.3	10%	The team decided to give this criteria an average weight of 10%. The deployment times are important and should be considered when trading solution options, but they are not a very limiting factor. The mission goal could still be accomplished given slightly longer deployment times. This is also a criteria where all three solution options will likely meet the requirements.
FR5.1	10%	The environmental hazard requirements were given an average weight of 10%. If the system gets damage due to environmental elements and cannot function properly, the mission is a failure. However, the team feels confident that the system can endure any environmental hazards that will realistically be present in the cave.
FR5.2	10%	The longer the system is able to remain in a standby state increases the usability over the course of the mission. The longer the system can remain in the active state increase the amount of potential artifact locations that could be scanned. For these reasons this category was given a weight of 10%.
Design Complexity	10%	This was given a weight of 10%. If the system is too complex or not feasibly to manufacture then there is no reason to pursue it.
TDR5.3.1	10%	This criteria was implemented to ensure customer requirements are met. For this reason the category was given a weight of 10%.

The value assigning approach for this trade was arranged on a 1-5 scale.

Table 35: *Deployment and Mobility Solutions: Solution Categories Trade Study Values Scale*

Criteria	1	2	3	4	5
Maneuverability and Reach	The reach apparatus has < three degrees of freedom and < 0.5 meters of reach.	[...] at most four degrees of freedom and at least 1 meter of reach.	[...] at most five degrees of freedom and at least 1.5 meters of reach.	[...] at most six degrees of freedom and at least 2 meters of reach.	[...] more than six degrees of freedom and definitely more than 2 meters of reach.
Sensing and Comms. Interface	Does not meet included FRs/TDRs	Supports only wireless or only wired sensors; supports less than the 80g, 56250mm^3 sensor package minimum set by sensing subteam	[...] wired and wireless sensors; up to 80g, 56250mm^3	[...] wired and wireless sensors; sensor package in excess of of 80g 56250mm^3	[...] wired and wireless sensors; minimal concern over sensor package mass/size
Weight/Size	Research suggests the reach apparatus has a footprint larger than 110% of the 51300cm^3 max volume and/or weighs more than 15kg in standby state	[...] larger than 105 percent of the 51300cm^3 max. vol. or weighs more than 15kg in standby state	[...] 51300cm^3 max. vol. and weighs 10kg max. in standby state	[...] 95 percent of 51300cm^3 max. vol. in standby state and weighs 10kg max.	[...] 90 percent of the 51300cm^3 maximum volume in standby state and weighs 10kg max. in standby state
TDR4.2.1	Certain that system will damage or alter the position of the Husky	Highly likely [...]	Likely [...]	Unlikely [...]	Nearly impossible [...]
FR4.3	Meets none of the FR4.3 requirements	Reaches active state in over 30s, returns from operating to standby configuration in longer than 120s. Firing commands require greater than 10s response.	Reaches active state in 30s, respond to a firing command as soon as received, returns from operating to standby configuration in longer 120s	Reaches active state in 30s, respond to a firing command as soon as received, returns from operating to standby configuration in 120s	Reaches active state in under 30s, responds to firing command as soon as received, returns from operating to standby configuration in under 120s
FR5.1	Meets none of the FR5.1 requirements	System can operate in 50-60 deg. F ambient temperature, neither mechanical nor electrical components meet IP43 standards.	System can operate in 50-60 deg. F ambient temperature, either mechanical or electrical components meet IP43 standards.	System can operate in 50-60 deg. F ambient temperature, mechanical and electrical components meet IP43 standards.	System can operate in 50-60 deg. F ambient temperature, mechanical and electrical components exceed IP43 standards.
FR5.2	Standby time of less that 60 min., active time of less than 15 min.	75 min. standby, 15 min. active	105 min. standby, 23 min. active	135 min. standby, 30 min. active	Standby > 135 min. and/or active time > 30 min.
Design Complexity	Solution is unachievably difficult based on consideration of mechanical, software, and manufacturing development efforts required relative to project timeline and team skills	Solution is extremely difficult [...]	Solution is difficult [...]	Solution is achievable [...]	Solution is highly achievable [...]
TDR5.3.1	The system cannot be deployed	The system can be deployed 1-2 times	[...] 3-4 times	[...] 5 times	[...] > 5 times

This resulted in a trade study where the group concluded that the robotic arm was the best mobility option to pursue:

Table 36: *Deployment and Mobility Solutions: Solution Categories Trade Study*

Criteria	1	2	3	4	5	6	7	8	9	Weighted Score		
Criteria Description	Maneuver-ability and Reach	Comms. & Sensor Interface	Weight & Size	TDR 4.2.1	FR 4.3	FR 5.1	FR 5.2	Design Com-plexity	TDR 5.3.1			
Weight	20%	15%	10%	5%	10%	10%	10%	10%	10%	100%		
OPTIONS										Certainty	Numerical Score	Percentage Score
Robotic Arm	3	4	3	4	4	4	4	3	5	1.00	3.70	74%
Drone	4	3	5	5	3	3	3	2	3	1.00	3.40	68%
Sensor Projectile Launcher	2	2	3	4	4	3	5	3	3	1.00	3.10	62%

Within the arm design space, the group evaluated the three subcategories considered and concluded that an additional trade on the arm being either telescoping or folding in its extension design was critical. Given that research indicated some existing designs used hybrids of the two types, the hybrid approach was also considered [12]. The static base arm mount was ruled out without a trade given the risks it created by requiring the UGV to move to re-position the arm. The dual rotation axis sensor package mount was shown to be a commonly implemented design that could significantly improve a visual sensor's use to the MARBLE team without being dramatically more complicated, heavy or expensive; therefore the single axis sensor package mount was also eliminated.

The group determined the following design elements critical to comparing folding, telescoping, and hybrid arm solutions:

1. **Length Extension** The group determined that given any arm's primary purpose of extending the physical distance a sensor package can be operated from a standby position on the UGV, different arm's extension abilities needed to be compared in light of the different solutions showing a range of performance in this effect.

2. **Sensor Bearing Capacity** The group's research suggested that different arm types in existing designs varied in how much mass and size they could support. This was determined to be an important criteria: for example, if an arm could extend dramatically but not support sensors, it would not meet its mission goal.

3. **Availability of Successful Application Research** The group considered access to design inspiration, especially in industry and academic projects with similar goals, an effect worth considering. All arm solutions appeared likely to require significant amounts of new design work from the team rather than simply combining off the shelf components, and having places to start design work concepts would be important.

4. **Mechanical Complexity** This design effect was considered given that the arms researched varied significantly in their level of complication. The group observed that simply choosing the highest performing arm without evaluating how difficult it would be to develop could create budgetary and lead time issues later in the project.

These effects were then weighted:

Table 37: *Weighting Determination for Robotic Arm Type Trade Study*

Criteria	Weight	Rationale
Length Extension	30%	An arm's ability to extend was given the highest weight considered because the customer emphasized that greater sensor reach than the 1m minimum was highly desirable.

Sensor Bearing Capacity	25%	An arm design's ability to support a large and heavy sensor package, ideally larger and heavier than the benchmark minimum sent by the sensing subteam, was considered important but not more important than sensing reach. The team made a research based conclusion that while it might require more expensive materials and components depending on the design, all three arm types could potentially be improved to support more mass and space consuming sensor packages.
Availability of Successful Application Research	25%	The ability to find successful applications of an arm design in similar projects was given an average level weight: being able to find high quality design inspiration is important, but should not outweigh performance requirements.
Mechanical Complexity	20%	Mechanical complexity, while important, was given a slightly lower weight because the group did not want to allow better performing but more difficult to design arm concepts from being eliminated simply because they might require more design work to function properly.

The following value system was used to assess the trade study:

Table 38: *Robotic Arm Type Trade Study: Value System*

Criteria	**1**	**2**	**3**
Length Extension	At least 1 meter extension length feasible	Extension past 1 meter possible, but mechanically difficult	Extension past 1 meter is possible and mechanically demonstrated in existing projects
Sensor Bearing Capacity	Research suggests system can support up to an 80g, 56250mm^3 sensing system	Research Suggests system can support a sensor package in excess of 80g and 56250mm^3	N/A
Availability of Successful Application Research	Found minimal examples of successful applications in similar projects	Found some examples of successful applications in similar projects	Found multiple examples of successful applications in similar projects
Mechanical Complexity	Extremely mechanically complex	Moderately mechanical complex	Comparatively mechanically simple

Finally, the trade was conducted:

Table 39: *Robotic Arm Type Trade Study*

Criteria	1	2	3	4	**Weighted Score**		
Criteria Description	Extension Length	Sensor Bearing Capacity	Availability of Successful Application Research	Mechanical Complexity			
Weight	30%	25%	25%	20%	100%		
OPTIONS					**Certainty**	**Numerical Score**	**Percentage Score**
Telescoping Arm	3	1	1	3	1.00	2.00	67%
Folding Arm	3	2	3	2	1.00	2.55	85%
Hybrid	3	1	1	1	1.00	1.60	53%

5.2 Sensing

5.2.1 Visual Sensor Type Trade Study

The sensor apparatus is an extremely critical component to the overall system design. The visual sensor component specifically provides the system with the capability to sense the DARPA artifacts. It can act as an avenue for the apparatus to localize itself within the global map that MARBLE builds. Therefore, it is important to conduct a trade study to first determine which category of visual sensor we should use. From there, we will be able to conduct another trade on specific sensors within these visual sensing categories.

Table 40: *Rationale for criteria of sensor type trade study.*

Criteria	**Weight**	**Rationale**
Different Artifact Capabilities	30%	This criteria describes how well the visual sensor is able to sense different artifacts. A visual sensor that is able to sense more artifacts has the ability to earn team MARBLE more points according to the DARPA rules. Therefore, this criteria was assigned the majority of the weighting as it essentially measures how useful our sensor suite is to the customer.
Weight and Size	18%	The visual sensor will be placed on the carrying apparatus and must be not interfere with it is operation or place an unnecessary burden on the structure. Although most visual sensors intended for robotics applications are small we decided that the size could severely limit our carrying apparatus design choices and thus should be assigned a weight of 18%.
Compatibility with MARBLE's Sensing & Comms	16%	This criteria was created to ensure the chosen visual sensor data was usable by team MARBLE. More specifically, the sensor data must be able to be processed by the object detection algorithm YOLOv3. However, we recognized that we can train a YOLOv3 model on the chosen visual sensors data, giving it a weight of 16%.
Cost	21%	The total budget is $5000 and visual sensors for robotics can range from $100 to $1000 dollars. Given that we are constructing the carrying apparatus ourselves we need to ensure that there is financial leeway. Therefore, we decided to weight cost at 21% to ensure the visual sensor does not place an unnecessary financial burden on the project.
Versatility of Application	15%	This criteria was designed to capture the additional benefits that a visual sensor could provide. These added benefits are the ability for some visual sensors to provide the pose of the apparatus which eliminates the need for an added attitude sensor. However, because this is not the primary goal of the visual sensor it was assigned a weight of 15 %.

Table 41: *Table showing the criteria and their respective numeric breakdown.*

Criteria	1	2	3	4	5
Different Artifact Sensing Capability	The sensor type is not capable of sensing any of the brightly colored artifacts.	The sensor type is able to sense one of the brightly colored artifacts.	The sensor type is able to sense two of the brightly colored artifacts.	The sensor type is able to sense three of the brightly colored artifacts.	The sensor type is able to sense all four brightly colored artifacts.
Weight & Size	<1kg	0.75 - 1 kg	0.5 - 0.75 kg	0.1 - 0.5 kg	< 0.1 kg
Compatibility with MARBLE Sensing & Comms	YOLOv3 has not been applied to the visual sensor type's data.	N/A	N/A	N/A	YOLOv3 has been applied to the visual sensor type's data.
Cost	>$1000	$500 - $1000	$100 - $500	$50 - $100	<$50
Versatility (i.e. Controls)	No onboard capability for detection of position and orientation.	N/A	N/A	N/A	Onboard capability for detection of position and orientation.

To score each visual sensor type our perception team developed a 1-5 scale for each criteria. The different artifact sensing capability criteria was graded on the visual sensor types ability to sense different numbers of brightly colored objects, as seen in Table 44. Scaling based on the capability for the visual sensors to detect the brightly colored artifacts ensures that any sensor type that is capable of fulfilling FDR2.1 will get selected for a more in depth trade. The weight and size category was developed after extensive research on industry standard visual sensors. The heaviest visual sensor found was 1.6 kilograms, which lead to the lowest numeric score being any visual sensor that was heavier than 1 kilogram. For the compatibility with MARBLE sensing criteria we created a binary scale to quantify if MARBLE would be able to apply their object detection algorithm to the output data from each visual sensor. This essentially quantifies if the visual sensors data is usable by team MARBLE for artifact detection or not. The cost criteria was divided into the numeric categories based on fractions of the $5,000 budget. The perception team decided that the visual sensor should not cost more than 20% of the final budget, which was used to establish the lowest category. For the final criteria, versatility, we decided to establish another binary categorization system that quantifies whether or not the visual sensor type has on board capability for position and orientation determination.

Table 42: *Trade matrix for the visual sensor type.*

Criteria	1	2	3	4	5	**Weighted Score**		
Criteria Description	Artifact Sensing Capability	Weight Size	Compatibility with MARBLE Sensing & Comms	Cost	Versatility (i.e. Controls)			
Weight	30%	18%	16%	21%	15%	100%		
OPTIONS						**Certainty**	**Numerical Score**	**Percentage Score**
Camera	5	5	5	3	5	1.00	4.58	92%
Thermal	2	3	5	1	1	1.00	2.30	46%
LIDAR	5	2	5	1	5	1.00	3.62	72%

5.2.2 Camera Trade Study

Table 43: *Rationale for criteria of camera trade study.*

Criteria	Weight	Rationale
Field of View	18%	The larger the field of view the camera has the more coverage it will have. This translates into the ability for the camera to identify artifacts or even multiple artifacts at once. Therefore, this criteria was given a weighting of 18%.
Weight and Size	25%	The camera will be placed on the carrying apparatus and must be not interfere with its operation or place an unnecessary burden on the structure. Although most cameras intended for robotics applications are small we decided that the size could severely limit our carrying apparatus design choices and thus should be assigned a weight of 25%.
Perception Capability	21%	This criteria was designed to capture the cameras ability to work cohesively with the object detection algorithm that team MARBLE uses, YOLOv3. It is imperative that the camera data is usable by team MARBLE for the intended purpose of detecting artifacts. Due to these considerations we assigned a weight of 21%.
Cost	21%	The total budget is $5000 and cameras for robotics can range from $100 to $1000 dollars. Given that we are constructing the carrying apparatus ourselves we need to ensure that there is financial leeway. Therefore, we decided to weight cost at 21% to ensure the visual sensor does not place an unnecessary financial burden on the project.
Resolution	15%	Following the same line of reasoning as field of view, a higher resolution will allow us to take images with a higher coverage area. Furthermore, a camera with a wider range of possible resolutions reduces the burden of image processing prior to passing the data to MARBLE because the images will be in a resolution they expect. Because most robotics cameras will be capable of a wide array of resolutions we gave resolution the lowest weight at 15%.

Table 44: *Table showing the criteria and their respective numeric breakdown.*

Criteria	1	2	3	4	5
FOV	Horizontal 40 degrees. Vertical 40 degrees. Diagonal 40 degrees.	Horizontal between 40 and 70 degrees. Vertical between 40 and 70 degrees. Diagonal between 40 and 70 degrees.	Horizontal between 70 and 100 degrees. Vertical between 70 and 100 degrees. Diagonal between 70 and 100 degrees.	Horizontal between 100 and 150 degrees. Vertical between 100 and 150 degrees. Diagonal between 100 and 150 degrees.	Horizontal 150 degrees. Vertical 150 degrees. Diagonal 150 degrees.
Weight/Size	>1kg	0.75 - 1 kg	0.5 - 0.75 kg	0.1 - 0.5 kg	<0.1 kg
Perception Capability	YOLOv3 has not been applied to the cameras data.	N/A	N/A	N/A	YOLOv3 has been applied to the cameras data.
Cost	>$1000	$500 - $1000	$200 - $500	$100 - $200	<$100
Resolution	**424 x 240** is the highest resolution capable.	**480 x 270** is the highest resolution capable.	**640 x 360** is the highest resolution capable.	**848 x 480** is the highest resolution capable.	**1280 x 720** or higher resolution is capable.

To score each camera our perception team developed a 1-5 scale for each criteria.The scaling for the field of view criteria was developed based on the angular view of the cameras. The numeric conditions for each scale were determined based on research on computer vision industry standard cameras. Through this research the perception team did not find a camera with an angular view lower than a 40 degree horizontal, vertical, and diagonal angle of view. Therefore, we decided to set this as the lowest scaling of the field of view category and the largest angle of view we discovered as the largest scaling. The weight and size category was developed after extensive research on industry standard robotics cameras. The heaviest camera found was an ultrasonic camera that weighed 1.6 kilograms, which lead to the lowest numeric score being any visual sensor that was heavier than 1 kilogram. For the perception capability criteria we created a binary scale to quantify if MARBLE would be able to apply their object detection algorithm to the output data from each camera. This essentially quantifies if the cameras data is usable by team MARBLE for artifact detection or not. The cost criteria was divided into the numeric categories based on fractions of the $5,000 budget. The perception team decided that the visual sensor should not cost more than 20% of the final budget, which was used to establish the lowest category. The numeric scaling for the final category, resolution, was determined based on research into industry standard robotics cameras. The largest and smallest scaling categories were based on the largest and smallest resolutions we encountered through research.

Table 45: *Camera type trade study.*

Criteria	1	2	3	4	5	**Weighted Score**		
Criteria Description	FOV	Weight Size	Perception Capability	Cost	Reso-lution			
Weight	30%	18%	16%	21%	15%	100%		
OPTIONS						**Certainty**	**Numerical Score**	**Percentage Score**
Intel RealSense Depth Camera D435i (RGBD)	3	5	5	4	5	1.00	4.43	89%
ZED Mini (Depth)	3	3	5	3	5	1.00	3.72	74%
FLIR FireFly DL (IR)	3	5	5	3	5	0.90	3.80	76%
Imperium AcoustoCam i700 (Ultrasonic)	5	1	1	1	1	0.80	1.38	28%

5.3 Communication & Data Transmission

The communications and data transmission from the sensor suite to MARBLE is a crucial part of meeting the set requirements for success. Communications need to occur not only between the sensor suite when deployed and its base, but also from the base to MARBLE. It is important to do trade studies to determine the most effective yet efficient way to transmit useful data. There will be one trade study for the method of communication between the sensor suite and its base and another trade study for communication with MARBLE.

Table 46: *Rationale for trade study criteria of communication and data transmission from sensor suite to its base.*

Criteria	**Weight**	**Rationale**
Reliability	32%	This criteria is ranked highest because it determines the likelihood a signal can be transmitted. If a signal cannot transmit then it does not matter at what rate it would have transmitted.
Transmission Rate/Resolution	26%	This criteria is designed to ensure the chosen method for communication and data transfer is capable of transmitting usable data that MARBLE can utilize. The data transmitted needs to be sent quickly enough and with enough resolution that MARBLE is able to process it.
Power Consumption	22%	The power consumption that is needed contributes to the overall power draw of the sensor suite. While this can be a limiting factor for a design, the power budget set is not too restricting.

Cost	20%	Cost is a limiting factor for the entire project but relative to the other criteria listed being weighed, it is not the most limiting criteria. Being able to transmit any gathered data is crucial to the success of the project and therefore the cost should not be the determining design factor.

Table 47: *Communications and Data Transfer Criteria for Trade Study*

Criteria	1	2	3	4	5
Reliability	Signal can easily be blocked by obstruction	Signal could possibly be blocked by an obstruction	Signal can be lost due to mechanical failure but not blocked	Signal is not likely to be lost or blocked	Signal is almost never obstructed or lost
Transmission Rate & Resolution	<5 GB/s	5 GB/s	11 GB/s	100 GB/s	$\geq$ 330 GB/s
Power Consumption	>2.5 W	2.49W - 2W	1.99W - 1.5W	1.49W - 1W	<1W
Cost	>$200.00	$141.00 - $200.00	$81.00 - $140.00	$21.00 - $80.00	<$20.00

Each criteria for the communication and data transfer trade study was divided into levels from 1 to 5. Reliability was not set on a numerical scale but rather based on the ability of the communication method to physically transfer data. Because of this, the wireless transmitter was ranked as the lowest given of it is potential to drop its connection when physically blocked. The wired options were all more reliable with the continuous-flex-and-twist cable being the most reliable due to its ability to withstand the most physical motion. To set the ranges for transmission rates and resolutions, the team researched the various options to understand what ranges were typical and which were optimal. The continuous-flex and continuous flex-and-twist cables had the fastest data transfer capabilities at the highest resolution. The power consumption was hard to definitively rank because the maximum for the wired connections was higher than would ever be needed for the amount of data transfer this project will require. Because of this, we ranked both the continuous-flex and continuous flex-and-twist cables at a 5 for power consumption. Lastly the cost of all the options was considered and the continuous flex-cable was the cheapest option at $1-$5 per foot, depending on wire gage and number of wires within the cable. Considering the weights of each criteria as shown in Table 46 and the numerical scores given in Table 48, the best option was the continuous flex-and-twist cable.

Table 48: *Communications and Data Transfer Trade Study*

Criteria	1	2	3	4	**Weighted Score**		
Criteria Description	Reliability	Transmission Rate & Resolution	Power Consumption	Cost			
Weight	32%	26%	22%	20%	100%		
OPTIONS					**Certainty**	**Numerical Score**	**Percentage Score**
Wireless transmitter	1	4	2	3	1.00	2.40	48%
Continuous-flex cable	4	5	4	4	1.00	4.26	85%
Continuous-flex-and-twist cable	5	5	4	3	1.00	4.38	88%
Data transfer while docked (Wired)	3	2	2	3	1.00	2.52	50%

5.4 Microcontroller

A trade study was performed to determine which microcontroller to use as an interface with MARBLE as well as for communications, data transfer and sensor interface. The criteria used to evaluate the microcontrollers is outlined in Table 50. Because the microcontroller is tied to so many subsystems of the project, it is critical to choose a quality brand that can handle all the requirements but also stay within the various budgets set.

Table 49: *Microcontroller Trade Study Criteria*

Criteria	Weight	Rationale
Software Integration	15%	Being able to complete the project in a timely manner is important given the short duration of the course. A microcontroller that uses a language that is already known by the team will cut out time spent learning the language and leaves more time to ensure the system is working properly and to improve the design.
Hardware Integration	15%	This criteria was considered because it is crucial to ensure the microcontroller will be able to physically interface with MARBLE.
Power Consumption	25%	Power consumption is important given the power budget and the fact that communications, data transfer, the microcontroller and the sensors will all be using power.
Processing Speed	25%	This criteria is important because the microcontroller needs to be capable of handling data transfer, commands from MARBLE, and controls.
Cost	20%	Given the budget, cost is important to consider but is not the most important criteria for this trade because microcontrollers tend to not be prohibitively expensive.

Table 50: *Microcontroller Criteria for Trade Study*

Criteria	1	2	3	4	5
Software Integration	Unique, unknown language	Familiar to one or two teammates, easy to learn	Familiar to some teammates, easy to learn	Familiar to most teammates	Widely familiar, easily interpreted language
Hardware Integration	No port compatibility	Limited port compatibility	Some port compatibility	Good port compatibility	Very compatable
Power Consumptio	> 15 W	11 - 15 W	6 - 10 W	1 - 5 W	< 1 W
Processing Speed	<10 MHz	10 - 50 MHz	51 - 200 MHz	201 MHz - 1 GHz	> 1 GHz
Cost	>$200.00	$151.00 - $200.00	$101.00 - $150.00	$51.00 - $100.00	<$50.00

The criteria for the microcontroller trade study, explained in Table 50, were divided into five levels to help determine the best microcontroller option. The software integration levels were based on how familiar the team is with the language required to operate each microcontroller. Because of this both the Raspberry Pi and the BeagleBone options were ranked the highest. Hardware Integration was ranked based on the microcontrollers ability to interface with MARBLE. The Raspberry Pi was the most compatible, while the Arduino has no compatibility which all but eliminated it from contention. The power consumption of the microcontroller options ranged from 12 watts to less than 1 watt making the Silicon Labs Pearl Gecko the highest ranked. The processing speeds of the were all fairly high except for the Arduino which makes sense because the Arduino is also the cheapest option. With the criteria weights and the rankings considered, the Raspberry Pi 4 Model B was the best option for this project's microcontroller.

Table 51: *Microcontroller Trade Study*

Criteria	1	2	3	4	5	**Weighted Score**		
Criteria Description	Software Integration	Hardware Integration	Power Consumption	Processing Speed	Cost			
Weight	15%	15%	25%	25%	20%	100%		
OPTIONS						**Certainty**	**Numerical Score**	**Percentage Score**
Raspberry Pi 4 Model B	5	5	2	5	5	1.00	3.00	60%
Arduino Mega 2560 Rev 3	3	1	4	2	5	1.00	2.60	52%
BeagleBone Black - Rev C	5	3	3	5	4	0.98	2.70	54%
Silicon Labs Pearl Gecko EFM32	4	2	5	4	3	0.95	2.61	52%

5.5 Programming Language

Table 52 depicts all five criteria used in deciding the principal programming language for this project and the rationale behind them. After deliberation, it was decided that the run-time of the programming language was the most important criteria, followed closely by external resources and prior knowledge. These were heavily weighted because they evaluate the amount of online support available for development issues and the team's existing expertise in different languages. Higher scores in these categories will surely provide a smooth and quick software developmental experience over the course of this project.

Table 52: *Rationale for criteria of programming language trade study.*

Criteria	Weight	Rationale
Speed/ Runtime	30%	Softare runtime will be a primary influence on the bandwidth possible on data transmission, as well as the time interval used for the control loop. As such, a high-speed programming language can significantly increase the precision of communication and control systems.
External Resources	25%	This criteria concerns external libraries available for purposes of the project and documentation on said libraries and the language in itself. Using a language with well-developed libraries fitting project requirements would lower the overall difficulty of software-related tasks, and thorough documentation is extremely helpful in overcoming obstacles in software development.
Integration	10%	ROS integration can be performed with the simultaneous use of multiple languages; for this reason, it is important that the language selected as the primary vessel for the project's software functions should be compatible with other programming language options. This criterion bears the lowest weight because these languages are all compatible with each other to some degree.
Prior Knowledge	20%	A user's prior knowledge in a programming language can be described as inversely proportional to the amount of time and research invested in successful implementation. Choosing a language in which the team has experience can reduce the amount of team members necessary to work on the software aspect of the project, leaving more teammate hours available for other facets.
Ease of Use	15%	The ease of use of a programming language plays a key part in the amount of time the software team will spend programming. However, its effects will primarily take place at the beginning of the development process, meaning it has less impact on development time than prior knowledge or external resources.

As with the rest of the trade studies performed for this project, each criteria was set on a scale of 1 to 5. They were all ranked on qualitative descriptions, though quantitative research was used to influence decision-making. This is especially present in the speed/runtime criteria, which ranks C++ as the language with the lowest runtime, followed by C and Python; the criteria itself was not made quantitative as benchmark testing cited did not evaluate MATLAB [24].

Table 53: *Criteria for programming language trade study*

Criteria	1	2	3	4	5
Speed/Runtime	Unusably slow	High-level language, high runtime cost	Mid-to-high level language, moderate runtime cost	Low-to-mid level language, low runtime cost	Low-level language, minimal runtime cost
External Sources	No documentation	Minimal documentation and online community	Some documentation, minimal online community	Well documented, small online community	Thoroughly documented, extensive online community
Integration	Incompatible with other options	Compatible with other options, at the cost of complexity	Compatible with other options, with limited complexity	Simple to integrate with other options	Fully integrated with other options
Prior Knowledge	1 or fewer teammates have prior experience	2-3 teammates have prior experience	Only software team is familiar with the language	Most of the team is familiar (to some degree) with the language	Everyone on the team has extensive experience in the language
Ease of Use	Most to all teammates will struggle to set up an IDE	IDE can be established for all teammates, but doing so will be tedious	IDE can be established for all teammates if some time is invested	IDE is accessible and simple for everyone on the team	Everyone on the team already has the IDE established

Upon evaluation, it was found that C++ would be the best fit for the primary programming language used for this project. Given that Matlab and Python scored only slightly lower and had very little score difference between each other, they will both be considered for tasks in which C++ is deemed less than ideal.

Table 54: *Programming language trade study*

Criteria	1	2	3	4	5	Weighted Score		
Criteria Description	Speed/Runtime	External Resources	Integration	Prior Knowledge	Ease of Use			
Weight	30%	25%	10%	20%	15%	100%		
OPTIONS						Certainty	Numerical Score	Percentage Score
C++	5	4	4	4	3	1.00	4.15	83%
Python	3	4	4	4.5	4	1.00	3.80	76%
MATLAB	2	5	3	5	5	1.00	2.90	78%
C#	4	4	3	2	2	0.90	2.88	58%

6 Selection of Baseline Design

The first crucial trade to narrow down the design of the system was between three deployment options: a robotic arm, a drone, and a sensor projectile launcher. The trade resulted in the highest score for the robotic arm. The key areas that separated the arm from the other two options were the communications/sensor interface and reusability. The arm presents the most technical solution support the weight of the sensor system. The arm can also confidently be deployed and reused the required number of times. With the drone, there is concern of landing back on the small area on the Husky, which is further complicated if it is not level. The launcher presents a reusability concern because the sensor projectiles must either be tethered, in which case the tether could get caught on the ground, or they can be single-use, in which case several projectiles would have to be made. All things considered, the robotic arm had the highest score of 74%, while the drone and sensor projectile launcher scored 68% and 62% respectively, so the robotic arm is the winner of this design trade study.

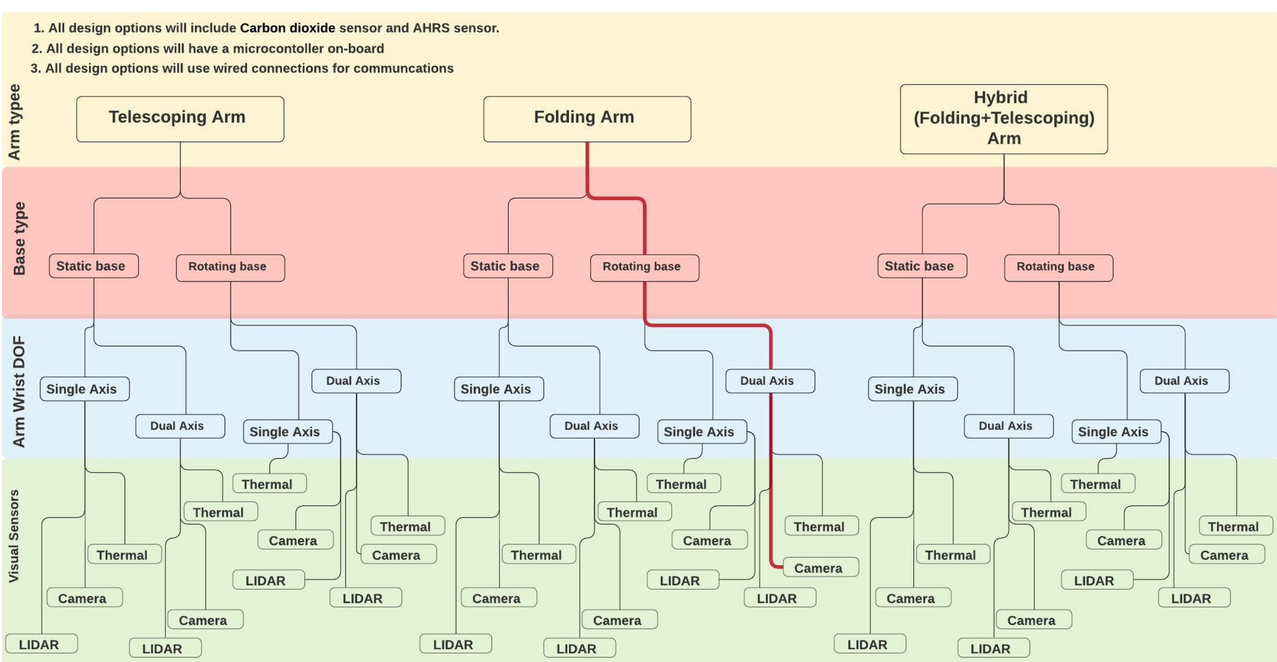


Figure 22: Baseline conceptual design tree

Once the team decided on going with a robotic arm, there were three variations of robotic arms that were considered: a telescoping arm, a folding arm, and a hybrid. The key criteria from the trade that resulted in the folding arm scoring the highest were the sensor bearing capacity and the availability of successful application research. For sensor bearing capacity, the team found through research that folding robotic arms generally have a higher load bearing capacity than telescoping arms or any sort of hybrid. Availability of successful research also separated the foldable arm from the other two design choices. As covered in section 2, foldable robotic arms have been successfully used in many applications can be researched extensively, where as telescoping arms are not nearly as commonly used in similar projects. A rough illustration of a folding arm with the components named is shown in figure 23. In the end, the folding arm had the highest score of 85%, while the telescoping arm and hybrid scored 67% and 53% respectively, so the folding arm is the winner out of the robotic arm options.

Based on exploring all the relevant design options and conducting trade studies to arrive to the most technical solution with respect to the FRs and TDR, a **Folding arm robotic arm with a rotating base and a dual axis wrist with a camera and carbon dioxide sensor** is the recommended technical solution. This solution will utilize a **a microcontroller, wired connections for communications, and AHRS sensors to determine attitude and position**. This solution is shown among all the possible technical alternatives in Figure 22. Figure 22 does not include Carbon dioxide sensors, AHRS sensor, and microcontrollers choice, because those are used for all possible designs. These specifications are discussed in previous section.

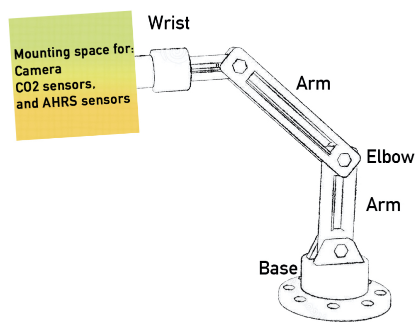


Figure 23: Baseline conceptual sketch for the robotic arm with key components named. Sketch is just an illustration to the conceptual idea and by no means a reflection of the actual design.

For the visual sensors: Based on the results of the trade study conducted in Section 5.2.1, the perception team decided to use a camera as their primary visual sensor. This was driven by the fact that the cameras being considered were, on average, much less expensive than any other sensor type. Most importantly, the cameras are able to sense all necessary artifacts to satisfy FDR 2.1.1. From the trade study seen in Table 45, the **Intel RealSense d435i** scored the highest. This is primarily due to its low weight and ability to detect all visually identifiable artifacts. Furthermore, with the on board IMU the Intel RealSense d435i will allow for measurement calibrations with the decided upon attitude sensor.

For Carbon Dioxide sensor: The perception team decided to use the Sensirion SCD30 due to it being the only available CO_2 sensor that has a proven accuracy without any boot up time. For more details see section 4.2.

For attitude and position sensors: It was decided to use the **3-Space^{TM} Watertight USB/RS232** AHRS sensor developed by YOSTLABS. This sensor comes with complicated filtering algorithms, and at a weight of 150 grams and orientation accuracy of 1.5 for dynamic conditions all orientations, satisfies the requirement of the project. This sensor has accleroamters sensitivity that ranges from 0.00024g/digit to 0.195g/digit, based on the mode it is working on, and hence it will provide accurate measurements to the position estimations.

For Microcontroller selection: The results of the trade in section 5.4 showed that the best microcontroller for the purposes of this project is the Raspberry Pi 4 Model B. This Raspberry Pi only costs $55.00 and has a processing speed of about 1.5 GHz. Although its power consumption is 15 watts or greater, it is the easiest to integrate and most compatible for both the software and hardware. The

MARBLE team already uses Raspberry Pi 4's on their Husky ground robot so it will integrate well with their system and is known to be compatible with ROS.

For software language: From the trade study in Section 5.5, the primary programming language that will be used is C++. However, since both MATLAB and Python scored highly on the trade studies as well, they will also be considered for specific tasks in which runtime may not be as crucial. This is achievable because it is not necessary to interface with all ROS nodes in the same programming language.

For communications methods: From the communications method trade study in Section 5.3, the continuous-flex-and-twist(CFAT) cable will be used as the primary vehicle for data transfer. The drivers for this decision were that the CFAT cable provides an astounding data transmission rate that is greater than 330 gigabytes per second. In addition, the CFAT is extremely reliable in that the signal is almost never obstructed or lost. This is largely due to the CFAT's ability to resist continuous motion and twisting up to 450 degrees. For all of these reasons, the continuous-flex-and-twist transmission cable will be used.

6.1 Subsystems integration

With all of these different technical solutions in mind, it is important to consider how these solutions might be integrated. Figure 23 will serve as a guide to some of the terminology used.

The arm will serve as the carrier of all the artifact sensors, which will be mounted to the arm writs. The arm is goal is to enable the sensors to sense whatever they need to sense by providing a transportation method and a mounting platform. The artifact sensors will move with the wrist, and hence whatever is sensed is going to change based on the arm orientation. The base of the arm will provide extra mobility and structural integrity. Since attitude and position sensors care about the location of the sensors, the AHRS will be placed along with the artifact sensors at the wrist of the robotic arm.

Tentatively the microcontroller will be located at the base of the robotic arm. This is intended to simplify the communication interfaces. All the wired connections could run around the arms or inside them, and such a specificaiton is past the level of CDD.

A Appendix: Artifacts

All artifact descriptions were pulled from the DARPA competition rules [25].

A.1 Survivor

The survivor artifact will be represented by an anatomical, thermal manikin to represent both human shape and body temperature. The manikin will be fitted in a high-visibility jacket, grey work pants, and standard yellow steel-toed work boots. It is anticipated that survivor manikins will be placed in a sitting position in the competition course.

A.2 Cell Phone

The cell phone artifact will be represented by a standard smartphone (Samsung Galaxy J J19M/DS). It will be placed in the competition course with the screen on and playing a full-screen video with audio. The phone will also have 2.4GHz WiFi operating as an access point with a visible SSID, as well as a Bluetooth radio operating in discovery mode. The latter two features will reflect the artifacts unique name, which will have the form 'PhoneArtifactXX,' where XX will be a random, but static, combination of any 2 letters or numbers.

A.3 Backpack

The backpack artifact will be a JanSport backpack whose front and back portions are all-red and all-black, respectively. All of the zippers will be closed. The artifact may be found on the ground, hanging on a wall, or resting on a work surface in the competition course. The backpack will be placed with its red front portion facing outward or upward.

A.4 Drill

The hand drill artifact will be represented by a Black Decker GC960 Cordless Drill with an orange body, black battery, and black chuck collar. It will not be in operation during the competition run, and may be found on the ground or on work surfaces. The drill's resting orientation is unspecified.

A.5 Fire Extinguisher

The fire extinguisher artifact will be a typical red hand-held, metal cylinder fire extinguisher commonly found in everyday environments. This artifact will not be in operation during the competition run, and its hose will be attached in the stored configuration. It may be found on the ground, hanging from a wall, or resting on a work surface in the competition course.

A.6 Gas

The gas artifact will be represented by CO_2 emitted in a confined area to maintain a concentration of approximately 2000 parts per million. This confined area will be a room with a clearly defined ingress/egress point (doorway). This artifact will have no visual identifier.

A.7 Vent

The vent artifact will be a Grainger 4MJV3 three-cone square ceiling diffuser that is fabricated from sheet metal and painted white. This artifact will be actively heated to produce a distinct thermal signature that is at least 30°C above ambient temperature. The air vent may be found on a wall or ceiling at any height, protruding no more than 300 mm.

A.8 Helmet

The helmet artifact will be a typical white caving helmet and headlamp, with the latter operating in the 'low spot' setting. This artifact may be found on the ground, on a wall, or on a ledge. The localization point at the crown of the helmet will be visible, but the front of the helmet may be pointing in any direction in the competition course.

A.9 Rope

The rope artifact will be represented by a coiled 35m length of blue climbing rope, held together by a black strap located approximately in the middle. This artifact may be found on the ground, suspended from a wall, or on a ledge. The coiled rope may be accompanied by additional uncoiled sections of the rope and/or other climbing equipment nearby.

B Appendix: References

References

[1] DARPA. *DARPA Subterranean Challenge Competition Rules: Cave Circuit*. 2020.

[2] IEEE. *P1490/D1, May 2011 - IEEE Draft Guide: Adoption of the Project Management Institute (PMI) Standard: A Guide to the Project Management Body of Knowledge (PMBOK Guide)-2008 (4th edition)*. URL: https://ieeexplore.ieee.org/document/5937011.

[3] Wikipedia. *IEC IP Code*. 2020.

[4] N. H. Darton. *Geothermal Data of the United States*. 1920.

[5] L3Harris. *T4 Robotic System*. 2019.

[6] Nancy Owano. *TRobot arm can work out how to stack stones*. 2017.

[7] Les Hall. *Rotating Base Designed, 3D Printing has begun!* 2015.

[8] Wiki. *Stepper Motor*. 2020.

[9] NASA. "NASA systems engineering handbook". In: NASA, Rev1 2007.

[10] Arora et. al. *An Approach to Autonomous Science by Modeling Geological Knowledge in a Bayesian Framework*. 2017.

[11] Jason C. Geist et. al. *Robotic System Including Foldable Robotic Arm*. n.d.

[12] aselsan. *KAPLAN Explosive Ordinance Disposal Robot*. 2020.

[13] Suzumori Endo Robotics Laboratory. *20m Super Long Robot Arm - Giacometti Arm with Balloon Body -*. 2016.

[14] Caroline Rees. *iRobot Enhance Inflatable Robotic Arm Used on Unmanned Ground Vehicles*. 2012.

[15] SunFounder. *SunFounder 20KG Servo Motor Waterproof High Torque Servo, SF3218MG Metal Gear Digital Servo, Aluminium Case, Control Angle 270 for RC Robot Cars*. 2020.

[16] Hai Prassath K. *Choosing Motors for Robots*. 2020.

[17] Dilwe. *RC Drone Camera Gimbal, Metal Brushless Gimbal Board BGC 2.2 for 3/3+ / 4 Camera RC Drone Quadcopter Component Part Accessory*. 2020.

[18] Flyability. *Drone flies in crevasse*. URL: https://www.youtube.com/watch?v=Vklo_ng1hv8&t=37s.

[19] Allan Huynh. *Study of Wired and Wireless Data Transmissions*. Tech. rep. 2010.

[20] Janice Friedman. *Understanding the Differences Between C#, C++, and C*. May 2018.

[21] Open Robotics. *Documentation - ROS Wiki*. n.d.

[22] EduCBA. *Python vs. C++*. n.d.

[23] NASA. *Trade Studies Module Space Systems Engineering, version 1.0*. Tech. rep. n.d.

[24] Crowd-sourced. *The Computer Language Benchmarks Game*. n.d.

[25] DARPA. *Artifacts Specification Urban Circuit*. 2019.