University of Colorado
Department of Aerospace Engineering Sciences
ASEN 4018

Project Definition Document (PDD)
Subterranean Reach

Approvals

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1.1. Project Customers

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2. Problem or Need

This project is intended to improve the performance of the University of Colorado's MARBLE (Multi-agent Autonomy with Radar-Based Localisation for Exploration) team's entry in the Defense Advanced Research Projects Agency (DARPA) Subterranean 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]. In the systems track of the competition, teams are challenged to design robots that can traverse urban underground, tunnel, and cave-like environments in order to score competition points by accurately locating "artifacts". These objects simulate targets for real underground search operations such as survivors, communications equipment, tools, entry and exit points, gas leaks, and backpacks. The challenge courses have myriad underground hazards: darkness, steep and rough terrain, narrow passages, water and dust exposure, ladders, interrupted communications, and smoke are all possible adversities for competing robots [2]. These hazards, paired with the diversity of possible artifacts, incentivize robot designs that can tolerate the challenge's difficult conditions while operating multiple sensor types successfully.

The primary problem this project aims to solve for the MARBLE team is improving their ground robot's ability to sense competition artifacts in hard to reach locations. The team operates a sensor equipped Clearpath Robotics Husky, which has an extended run time of approximately three hours and tires well suited for underground terrain [3]. At ground level, however, the vehicle's ability to sense all of the potential artifacts in the challenge, particularly those in elevated locations or narrow openings is extremely limited. Our project aims to improve the robot's performance with an attached or deployable set of sensors that can access these types of artifact locations.

Our project's success would primarily benefit the MARBLE team: improving their ground robot's sensing capabilities would likely lead to the team scoring more points in the subterranean challenge. Success would also provide a new proof of concept for autonomous sensing improvements in underground environments. Moving beyond the context of the DARPA challenge, underground sensor performance will likely be an important part of future aerospace efforts such as remotely exploring underground environments on Mars [4].

3. Previous Work

Being able to identify/detect an object, or *artifact* in the context of DARPA's SubT Challenge, whose line of sight to the robot's visual/detection sensor(s) is obstructed, is an integral part of the problem given to this team. In recent years, competing teams of DARPA's SubT Challenge, such as JPL's CoStar and Czech Technical University's CTU-CRAS, have come up with multiple sets of 'sensor arrays' to enable their robots to navigate through dark tunnel and cavern type environments as well as sense and detect objects of interest. Due to the variable levels of visibility and local terrain features, most teams have used a combination of lidar sensors and depth cameras, such as Velodyne and RealSense, respectively [5]. Some less common sensors include visual odometry sensors, millimeter wave sensors, forward-looking infrared (FLIR) sensors, and IMUs [5]. Team CoStar's NeBula (Networked Belief-aware Perceptual Autonomy) software is reported to work with a wide variety of sensors, including "vision, IMU, lidar, radar, contact sensors, and ranging systems (e.g., magneto-quasi static signals and UWBs)." [9] Some teams have mounted their selected sensors on UAVs to provide a complete 360-degree-view of the local environment at various heights and areas of interest, which allows improved sensor mobility and 3D mapping/localization.

The more variety of sensory information a robot has while traversing a somewhat nebulous environment with practically arbitrary topographical features, such as an underground tunnel or cave network, the more aware of its surroundings and able to sense objects of interest it is. In the context of DARPA's SubT Challenge, this enables higher accuracy of locating and identifying *artifacts*. The accuracy of localizing an object of interest has been shown to largely depend on the design choice of the sensor suite as well as the 3D mapping algorithm(s) involved. For the purpose of this project, this team acknowledges the need to improve 'object sensing' by enhancing the mobility and sensory capabilities of the sensor suite of an exploration/surveying type robot in order to better map obstructions and potential artifacts within a 5-meter radius of the robot's locality in a subterranean environment.

4. Specific Objectives

Objective	Level 1	Level 2	Level 3

R1: Sensing System Range	The sensing system is capable of sensing an environment that is within 5m from its stowing location in any given accessible **TBD** direction.	The sensing system can change its pointing orientation Horizontally to change the pointing orientation within a **TBD** angular range.	The sensing system can change its pointing orientation Vertically to change the pointing orientation within a **TBD** angular range.
R2: Artifact Signatures	Ability to sense artifacts with large, brightly colored visual signatures (Human, backpack, fire extinguisher) within FOV **TBD** and Pixels **TBD** as well as CO_2 gas leaks.	Ability to sense artifacts with small/darker visual signatures (rope, helmet, cell phone) within FOV **TBD** and Pixels **TBD**.	Ability to sense artifacts with partially-visible/non-visible signatures (WiFi/bluetooth signals, thermal radiations) within FOV **TBD**
R3: Apparatus Location	Sensor apparatus reports that it is within 5 meters of the ClearPath Husky, but not a specific position.	Sensor apparatus reports its position and orientation relative to the ClearPath Husky within 1m accuracy of its ground truth location.	Sensor apparatus reports the position and orientation of artifacts in its **TBD** FOV within 5m accuracy of its ground truth location.
R4: Mobility range	Sensor apparatus has the ability to physically reach a location that is along an unobstructed variable length of at least 5m radius from the system's stowed position.	Sensor apparatus has the ability to physically reach a location that is **not** within a clear line of sight from the ground robot. However, the sensor system **cannot** maneuver further past the obstruction.	Sensor apparatus has the ability to physically reach a location that is **not** within a clear line of sight from the ground robot. The sensor system **can** maneuver further (**TBD**) past the obstruction.
R5: Total Time and Usage	The total time from the activation command to returning back to standby configuration shall be **TBD** min. The sensor apparatus can withstand this process ≤ 5 times.	The total time from the activation command to returning back to standby configuration shall be **TBD** min. The sensor apparatus can withstand this process ≤ 10 times.	The total time from the activation command to returning back to standby configuration shall be **TBD** min. The sensor apparatus can withstand this process ≤ 15 times.
R6: Endurance	Sensor system is able to maintain an active state where it is sensing for 25% of MARBLE average competition operation **TBD** and a standby state for 100% average competition operation **TBD**.	Sensor system is able to maintain an active state where it is sensing for 50% of MARBLE average competition operation (**TBD**) and a standby state for 100% average competition operation **TBD**.	Sensor system is able to maintain an active state where it is sensing for 100% of MARBLE average competition operation **TBD** and a standby state for 100% average competition operation **TBD**.
R7: Dust/Mud/Water Resistance	Systemwide IEC IP51 rating or better [4].	Systemwide IEC IP52 rating or better [4].	Systemwide IEC IP54 rating or better [4].
R8: Data communication time and rate	Communicate sensing data with MARBLE before next deployment. (1-Way)	Communicate sensing data with MARBLE upon request. (2-Way)	Communicate sensing data with MARBLE continuously at a **TBD** rate as the sensor system operates. (2-Way continuous)

5. High Level Functional Requirements

5.1: High Level Functional Requirement Analysis

R1 Sensing System Range The sensor setup shall be able to "sense" artifacts up to 5m away from the stowing location in any given accessible direction (i.e. the sensor system shall NOT force its way through anything, but rather maneuver to reach the designated accessible destination). **Justification:** Customer/DARPA requirement. The customer requests the 5m distance based on how DARPA awards points for detected artifacts (see **R3**) [2]. Technical difficulty is added in higher objective levels as sensor maneuvering degrees of freedom are added.

R2: Sensing Artifact Signatures: The apparatus shall be able to sense artifacts with large, brightly colored visual signatures within its **TBD** operational field of view and shall be able to sense CO_2 gas leaks. **Justification:** DARPA specifies 9 possible artifacts in the final competition; all but the gas leak have visual signatures. These signatures are in all cases distinct color patterns and shapes; some also emit light [6]. Our customer did not specify which artifact signatures must be sensed. As such, the team is prioritizing sensing visual artifact signatures as well as CO_2 gas leaks, starting with the simplest DARPA states as possible, in order to maximize the number of possible artifacts that can be sensed with the same system [6].

R3: Sensor Apparatus Localization: The sensor apparatus shall report that it is within 5 meters of the ClearPath Husky, but not a specific position. **Justification:** DARPA cave circuit rules section 11.1: Competition points are only awarded if artifacts are located within 5m euclidean distance of their ground truth location, and the customer states that the MARBLE team robot is able to accurately locate itself within DARPA's coordinate system [2]. As such, the objective levels set for this requirement are based on working towards ultimately providing MARBLE with the location of the sensor and the locations of sensed artifacts relative to it.

R4 Mobility Range: The sensor apparatus shall have the ability to at minimum physically reach a location that is along an unobstructed variable length of at least 5m radius from the system's stowed position. **Justification:** The customer requests being able to physically reposition the sensor system based on DARPA's competition obstacles including elevated surfaces, ledges, holes, and gaps that the ClearPath Husky cannot physically access [2, 8]. The objective levels for this requirement were determined based on research into typical DARPA competition terrain [8].

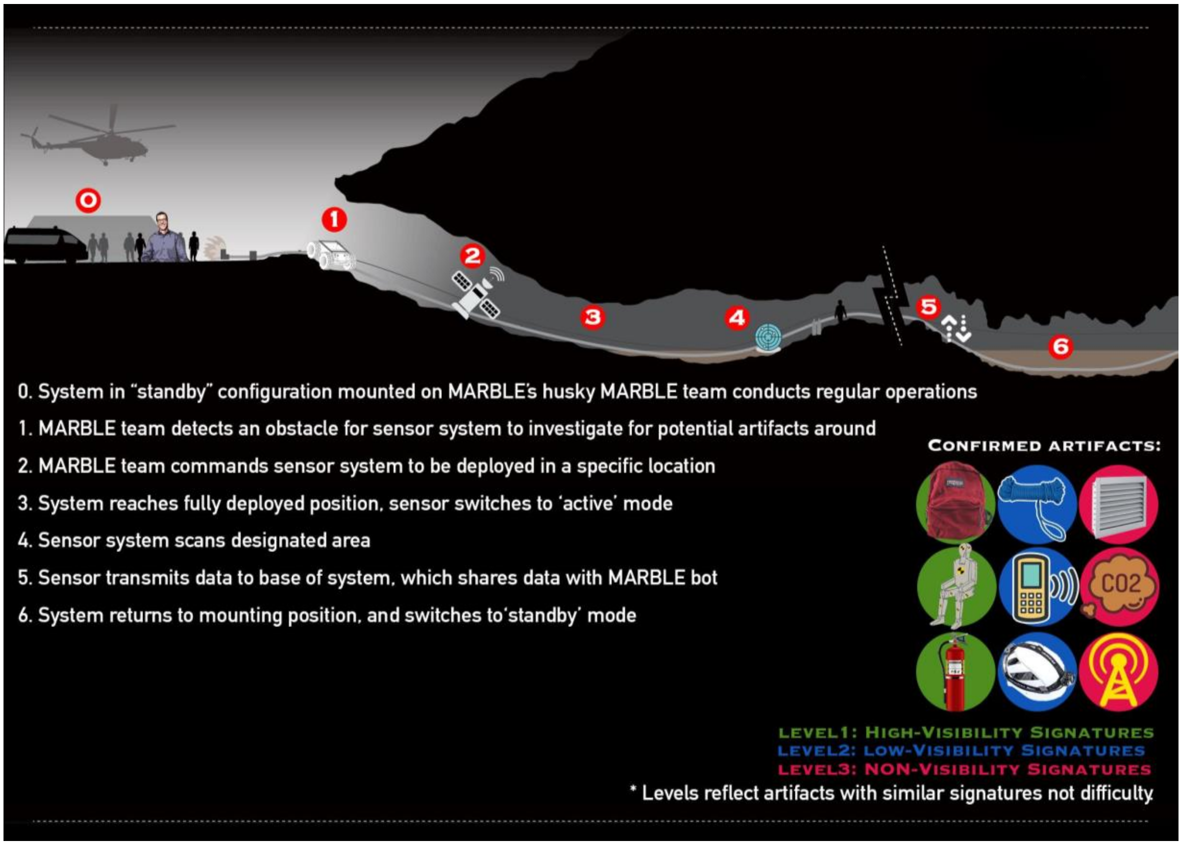
R5 Total Time and Usage: The total time from the activation command to returning back to standby configuration shall be **TBD** min. The sensor apparatus shall withstand this process at least 5 times. **Justification:** This requirement is based on our customer's suggestion that reusability would be useful and on the DARPA rule limiting each team's final competition run to be between 60 and 120 minutes [2]. Given that team MARBLE must navigate the entirety of the course within this time constraint while localizing objects and avoiding obstacles, our team's solution must deploy quickly and repeatedly to maximize benefit to MARBLE's score.

R6 Endurance: The sensor apparatus shall be able to maintain an active state, where it is sensing, for 25% of MARBLE's average competition operation **TBD** and shall be able to maintain a standby state for 100% of average competition operation **TBD**. **Justification:** DARPA cave circuit competition rules section 8.2.6 state that a competition finals run can last between 60 and 120 minutes [2]. However, the average runtime of team MARBLE through any given course is currently **TBD**. Our customer states that the baseline expectation for active state endurance is 25% of MARBLE average competition operation. The standby state requirement ensures that the device can be activated at any time during competition.

R7 Water/Mud/Dust Tolerance: The project shall achieve a IEC IP51 rating or better. **Justification:** DARPA's cave circuit competition rules section 8.2.4 specify that the system may be exposed to water, mud, and sand [2]. The customer requests the system be specifically protected against mud and water. Electronic and mechanical component resistance to these factors can be qualified using the International Electrotechnical Commission's Ingress Protection (IP) Coding system, which also includes industry defined testing requirements [4]. The desired IP codes in section 4 indicate that the system must be able to function after at least dripping water exposure, and must tolerate moderate dust exposure [4]. The customer explicitly stated that managing fog and smoke hazards falls out of project requirements.

R8 Data communication time and rate: At minimum the sensor system shall communicate its sensing data with MARBLE before next deployment. (1-Way). **Justification:** The DARPA cave competition rules reward accurately reporting as many artifacts as possible, which incentivizes rapid efficient communication of sensor findings. As such, the customer suggests that at minimum the sensor system should report its sensing data prior to each deployment in order to separate each use of the sensing apparatus. This is also discussed further in **T1**.

5.2: CONOPS



6. Critical Project Elements

Technical

T1 Communications: The sensor apparatus shall communicate the sensed data to the Robot Operating System (ROS) nodes in the existing MARBLE software architecture. The purpose of the sensor platform is to augment team MARBLE's sensing capabilities, but this data must be communicated in a usable form. MARBLE already implements ROS to manage its communication, which means the data obtained from the sensing apparatus must also communicate in a manner conducive to this operating systems processes. Once activated, all sensor and location data recorded must be transmitted back to the base\receiver attached to MARBLE. The communication methods used by the sensing apparatus must not limit the current communication systems deployed on MARBLE. In other words, it must not interfere with the other communication channels or impede any of MARBLE's communication capabilities.

T2 Sensors: The data gathered will depend on the sensors the team acquires. The sensors chosen will define how many different signals and therefore artifacts the team can locate. The terrain the team is designing for is not ideal and therefore the sensors chosen must be able to function despite any difficulties. The number and quality of sensors will be determined both by the budget and by what the team determines are the most feasible ways to scan for artifacts. Certain sensors can be very expensive so the team will need to balance quality with price to find the best fit for the project.

T3 Mechanics/Autonomy: The only command the device will be given is to deploy from MARBLE. From there it must deploy, scan the environment, transmit the data back to its base\receiver and return to MARBLE on its own. This must be a quick process. The faster this process is, the higher potential more artifacts can be found.

T4 Lighting: How much light the team provides the final sensing setup and how this light is directed will depend on the hardware selected/developed and will need to be optimized accordingly. Failure to provide adequate lighting for the system would likely render it useless.

T5 Terrain Clearance: If the device is accidentally damaged by contacting terrain, it could potentially create a problem for the entire MARBLE mission. Ensuring that the deployment process does not damage the system even in hazardous terrain is critical and will likely require additional costs and specific technical focus. In addition, the apparatus must be resistant to collisions from small (~2.5 cm) falling debris that could be encountered in a cave or tunnel environment [2]. In the stowed configuration, the apparatus must be physically contained within the top-down footprint of the robot itself.

Logistical

L1 Testing: The team must design and build the device to meet the approved requirements, ideally while operating in an environment with conditions similar to those that will be encountered in the DARPA competition. This will likely require creative test design and/or travel to locations better simulating the challenge environment.

L2 Safety: The device must not have the potential to harm any operators, artifacts, or the MARBLE robot. Importantly, although this device will be operated remotely, it has to be deployed by people and could be used to locate people; therefore it must be considered safe near humans.

L3 Financial: Certain sensor performance types and system improvements may pose greater financial challenges. For example, preliminary hardware review suggests that avoiding terrain collisions with a LIDAR system may be prohibitively expensive.

L4 Integration with MARBLE: The system is intended to be used on the MARBLE team's existing modified Clearpath Husky. As such, the entire system must operate within the power, size, mass, and mounting area constraints **TBD** MARBLE allocates on the vehicle. Additionally, our team's system must not interfere with any existing MARBLE sensing architecture. This necessarily includes the constraints covered in T.1.

7. Team Skills and Interests

Teammate Name	Skills/interests	Critical Project Elements
Seth Krein	SolidWorks, MATLAB, C++, Python, ANSYS, STK, Structures, PM experience	T3, T4, T5, L3
Johnathan Tucker	C++, Python, MATLAB, Algorithmic motion planning, SLAM, State Estimation, Dynamics	T1, T.2, T3, T4, T5, L4

Michael Martinson	SolidWorks, 3D Printing, Soldering, Mechanism design, Circuit Prototyping, MATLAB, Python, CircuitPython, Javascript, Component Purchasing	T2, T3, T5, L4, L3
Abdulla AlAmeri	MATLAB, SolidWorks, ANSYS, CAD (SolidWorks, Fusion 360), structures, Data analysis, Dynamics, Mechanics.	T2, T3, T5, L1, L2
Riley Swift	MATLAB, C++, SolidWorks, ANSYS, Electronics, Data analysis, Soldering	T1, T4, L1, L2
Ryan Hughes	Python, MATLAB, C/C++/C#, JavaScript, Data Analysis, CAD, Manufacturing, UX design, ROS interface software	T1, T3, L3, L4
Alexander Kryuchkov	CAD, FEA, Mechanical Systems, Mechanisms, MATLAB, Fusion 360, ANSYS, Abaqus	T3, T4, L1, L2, L4
Evan Welch	SolidWorks, MATLAB, ANSYS, laser cutting, soldering, structures, thermodynamics, dynamics	T3, T5, L1
Jack Zeidlik	CAD(SolidWorks, Fusion 360), Manufacturing, ANSYS FEA, Mechanical Systems, Structures	T3, T5, L1, L2
Frederick Vurst	C/C++, Java, MATLAB, Python, Linux Shell Scripting; Developing ROS Interface-Software; Control and Electronic Systems; SLAM Systems; Data and Performance Analysis using MATLAB/Python; Component Design and Modeling using Solidworks; Testing and Validating Hardware and Software	T1, T2, T3, L3

8 . Resources

Critical Project Elements	Resource/Source
T.1	Professor Jade Morton, Professor Zachary Sunberg
T.2	Professor Jade Morton, Professor Trudy Schwartz, Professor Zachary Sunberg
T.3	Professor Eric Frew, Professor Bobby Hodgkinson
T.4	Professor Eric Frew, Professor Trudy Schwartz
T.5	Professor Matt Rhodes, Professor Morteza Lahijanian
L.1	Professor Eric Frew, Simulated Cave/Underground, Simulated Artifacts, Professor Bobby Hodgkinson
L.2	Professor Eric Frew, Professor Bobby Hodgkinson
L.3	Professor Eric Frew
L.4	Professor Eric Frew

9. References

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