Competition Rules
Tunnel Circuit
Revision 3
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1. Introduction

This document describes the Competition Rules (Tunnel Circuit) of the DARPA Subterranean (SubT) Challenge. This document supersedes the *SubT Challenge Competition Rules Tunnel Circuit Revision 2* document dated June 28, 2019. Significant revisions in this document are indicated by blue text. The intent of this document is to provide participants guidance on competition design and scoring objectives to inform their development efforts in preparation for the Tunnel Circuit. This document is subject to change and may be superseded by later versions. The latest official versions of all documents are posted on the SubT Challenge website (www.subtchallenge.com) and the SubT Community Forum (https://community.subtchallenge.com/).

With the exception of possible minor revisions, this document serves as the final *Competition Rules (Tunnel Circuit)* that will be enforced in the Tunnel Circuit Event. The final *Competition Rules (Urban Circuit)* and *Competition Rules (Cave Circuit)* will be released no later than three months prior to each respective event. DARPA intends to release a draft of the *Competition Rules (Final Event)* no later than nine months and finalized rules no later than three months before the Final Event.

The DARPA SubT Challenge Chief Official has the final authority to make any decisions related to the rules or scoring. All decisions made by the Chief Official are final.

The primary goal of the DARPA SubT Challenge is to discover innovative solutions that can rapidly and remotely map, navigate, and search complex environments, including human-made tunnel systems, urban and municipal underground infrastructure, and natural cave networks. The challenge elements and the competition structure itself are intended to address the secondary goal of increasing the diversity, versatility, cost-effectiveness, and robustness of relevant technologies and systems capable of addressing the myriad needs of a wide range of environments rather than single-purpose or specifically tailored solutions. The third goal of the competition is to establish a collaborative community by bringing together multi-disciplinary teams and cross-cutting approaches across disparate fields to address the autonomy, perception, networking, and mobility needs of the subterranean domain.

2. Overview

The DARPA SubT Challenge is organized into a Systems Competition and a Virtual Competition. Teams in the Systems Competition are developing physical systems to compete in live events on physical, representative subterranean courses. Teams in the Virtual Competition are developing software and algorithms using virtual models of systems, environments, and terrain to compete in simulation-based events. The Systems Competition focuses on discovering innovative breakthroughs in integrated physical systems that can successfully operate in real-world environments while the Virtual Competition focuses on developing software-driven innovations and a broader exploration of the capability trade space by leveraging the library of virtual models in the SubT Virtual Testbed. The two competitions are designed to cross-fertilize and accelerate

development across both Systems and Virtual Competition participants. The objectives, rules, and events for the two competitions are closely related, but provide different avenues for development of innovative approaches and technologies.

The Systems and Virtual competitions will each hold coordinated challenge events to include three Circuit Events and a Final Event, each motivated by an illustrative vignette that will provide context and constraints for the mission scenario. The three Circuit Events (a.k.a. the Tunnel Circuit, Urban Circuit, and Cave Circuit) will each focus on one of the three subdomains, and are intended to promote frequent "build-test-compete" iterations within and among all participating teams. The Final Event will combine elements of all three subdomains into a single integrated challenge course to demonstrate the versatility of solutions developed.

3. SubT Challenge Schedule Overview

The DARPA SubT Challenge is organized into three stages as illustrated in Figure 1. In the Development Stage, teams have approximately 12 months to complete their baseline design, development, integration, and testing of their proposed solutions. In the Circuits Stage, teams will participate in three Circuit Events (a.k.a. the Tunnel Circuit, Urban Circuit, and Cave Circuit) that will be approximately 6 months apart and are intended to promote frequent "build-test-compete" iterations within and among all participating teams. In the Finals Stage, teams will have approximately 12 months to finish their development, refinement, and testing, culminating with their respective Systems and Virtual Final Events.
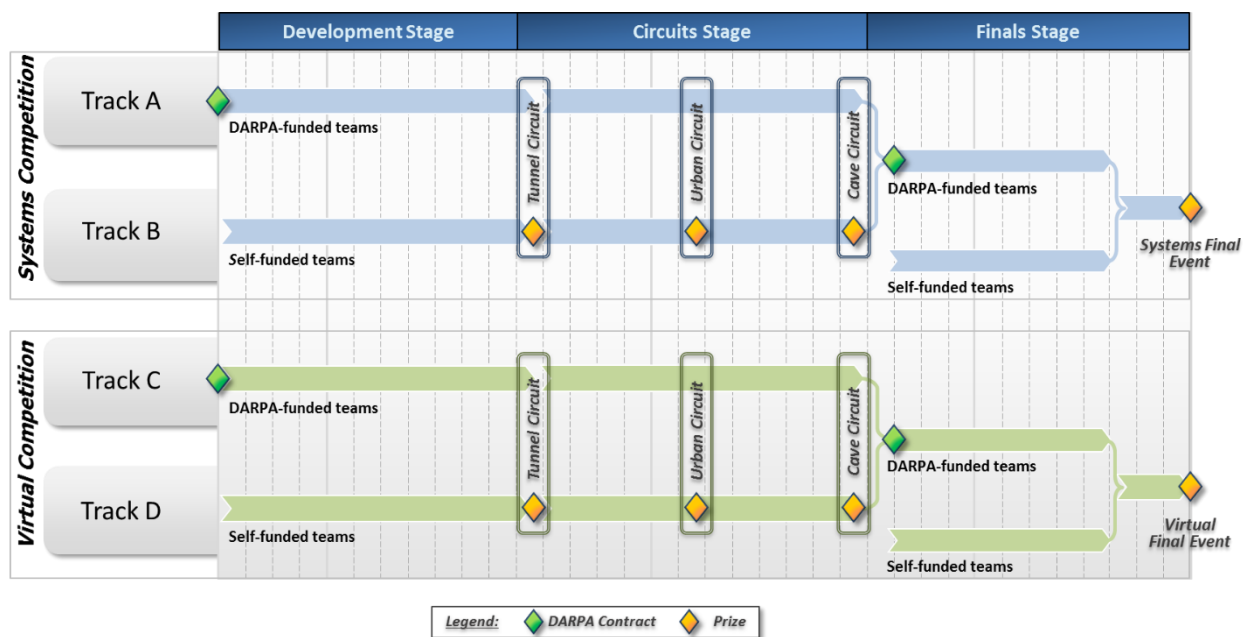
Figure 1: Program structure and schedule for the DARPA Subterranean Challenge

Event	Tentative Date
SubT Integration Exercise	April 5-11, 2019
Tunnel Circuit	August 15-22, 2019
Urban Circuit	February 2020
Cave Circuit	August 2020
Final Event	August 2021

Table 1: Schedule of DARPA-organized Systems and Virtual Competition events

The qualification deadline for any event, including the Circuits and Final Events is 100 calendar days before each event. The initial *SubT Challenge Qualification Guide* was released on October 31, 2018. The *SubT Challenge Qualification Guide* will continue to be updated for each event with the latest revision posted on the SubT Challenge Website and SubT Community Forum.

The SubT Virtual Testbed is a suite of simulation tools intended to support teams in both the Systems and Virtual Competitions and is expected to be continuously improved over the duration of the competition. The initial version of the SubT Virtual Testbed, released on Competitors Day, will be followed by stable releases of updates as shown in Table 2.

Event	Tentative Date
V1.0 – Starter Set Release	September 2018
V2.0 – Ignition Gazebo Release	February 2019
V3.0 – CloudSim Release	May 2019
V4.0 – Systems Track Release	October 2019
V5.0 – Final Event Release	November 2020

Table 2: Schedule of SubT Virtual Testbed releases

4. Prizes and Funding

Teams are charged with pursuing high-risk, high-reward approaches to meet and exceed the objectives of the Circuits and Final Events, and are motivated by the potential for winning monetary prizes and/or pursuit of funding. Monetary prizes will be awarded for both the Systems Competition and the Virtual Competition at each of the Circuit Events and Final Events as shown in Table 3. Self-funded teams in Track B and Track D are eligible for prizes in all of the Circuit and Final Events. DARPA-funded teams in Track A and Track C are only eligible for the prizes in the Final Events.

	Tunnel Circuit	Urban Circuit	Cave Circuit	Finals
Track A	*(not eligible)*	*(not eligible)*	*(not eligible)*	$2M
Track B	$200K	$200K	$200K	
Track C	*(not eligible)*	*(not eligible)*	*(not eligible)*	$750K (1st) $500K (2nd) $250K (3rd)
Track D	$250K (1st) $150K (2nd) $100K (3rd)	$250K (1st) $150K (2nd) $100K (3rd)	$250K (1st) $150K (2nd) $100K (3rd)	

Table 3: Prize Structure for the Circuit and Final Events per Competition Track

Track B Prizes and Funding: The Circuit Event prizes for Track B will be awarded to the best performing self-funded Systems Team in each event, provided that the team finishes in the top 5 overall (including DARPA-funded Track A) teams. High-performing Track B teams are also eligible to become a DARPA-funded Track A team during the Finals Stage. DARPA intends to fund up to six teams ($1.5M each) in the Finals Stage out of the teams competing in Track A and Track B.

Track D Prizes and Funding: The Circuit Event prizes for Track D will be awarded to the best performing self-funded Virtual Teams, provided that the team finishes in the top 5 overall (including DARPA-funded Track C) teams. High-performing Track D teams are also eligible to become a DARPA-funded Track C team during the Finals Stage. DARPA intends to fund up to six teams ($250K each) in the Finals Stage out of the teams competing in Track C and Track D.

The Government's obligation for prizes under the DARPA SubT Challenge is subject to the availability of appropriated funds from which payment for prize purposes can be made. No legal liability on the part of the Government for any payment of prizes may arise unless appropriated funds are available to DARPA for such purposes.

To be eligible for prizes, teams must first be registered. The award process requires recipients to furnish information that may trace or identify recipients either individually or as an organization (e.g., Social Security Number or Tax Identification Number). The primary contact of each registered team is responsible for providing the award information necessary for prize disbursement. DARPA will reach out by email to the primary contact of each registered team to either confirm their vendor status or request the required forms (e.g., SF-3881 or PIF). DARPA is not responsible for disbursement of prizes to any team members other than the primary contact/organization.

5. Team Registration

Teams may register their interest in participating and receiving informational updates by completing the *Team Registration* form at www.subtchallenge.com/register.aspx. Team registration is required prior to qualification and prior to event-specific enrollment. Registered teams will receive important competition-related updates and notices of information releases. Team registration is open on a rolling basis, but teams are encouraged to register early to avoid missing important updates.

6. Qualification

Prospective teams are required to demonstrate baseline performance and utility capabilities (e.g., safety measures for Systems, simulator usage for Virtual), to be eligible to participate in events. All teams (DARPA-funded and self-funded) in both competitions (Systems and Virtual) must qualify for each event including the SubT Integration Exercises, Circuit Events, and Final Event.

The latest revision of the *SubT Challenge Qualification Guide* will always be posted on the SubT Challenge Website and SubT Community Forum. Qualification submissions for the Systems Competition will be accepted on a rolling basis but must be submitted approximately 100 calendar days before each event to be eligible to participate in the event. Qualification submissions for the Virtual Competition will be accepted on a rolling basis but must be submitted no later than 50 calendar days before each event to be eligible to participate in the event. The specific qualification deadlines for each event are provided in the *SubT Challenge Qualification Guide.*

Failing a previous qualification attempt does not preclude a team from resubmitting a revised qualification submission, subject to qualification deadlines for any given event. To achieve the primary goal of the DARPA SubT Challenge as stated in the Introduction above, DARPA may adjust the qualification rules for each event and may choose to award qualification waivers for teams that have successfully participated in a prior STIX or Circuit Event.

DARPA reserves the right to disqualify any team that is found to violate either the rules or applicable laws and regulations.

7. SubT Integration Exercise (STIX)

DARPA held the SubT Integration Exercise (STIX) in April 2019 in advance of the Circuits Stage. The STIX Event provided Systems Teams access to representative testing environments to test and evaluate their performance under competition-like conditions. Teams had opportunities to rehearse their runs, confirm integration with the DARPA instrumentation and scoring systems, and inform their development efforts in the months leading up to the Tunnel Circuit Event. These runs were not officially scored, but teams were encouraged to operate according to the Competition Rules. STIX Events are optional and not required for teams to participate in the Circuit or Final Events.

8. Competition Guidelines

8.1. Illustrative Scenario

The primary scenario of interest for the competition is providing rapid situational awareness to a small team of operators preparing to enter unknown and dynamic subterranean environments. Potential representative scenarios involve rescue efforts in collapsed mines, post-earthquake search and rescue in urban underground settings, and cave rescue operations for injured or lost spelunkers. Additional scenarios include a range of missions in which teams of systems could be sent in advance of service members to perform rapid search and mapping in support of follow-on operations. These scenarios present significant dangers that would preclude employing a human team, such as collapsed and unstable structures or debris, presence of hazardous materials, lack of ventilation, and potential for smoke and/or fire.

Each team is envisioned to deploy its systems to provide rapid situational awareness through mapping of the unknown environment and localization of artifacts (e.g., survivors, electrical boxes). As the systems explore the environment, these situational awareness updates are provided via reach-back to a Base Station in as close to real-time as possible. Given the large-scale nature and complexity of subterranean environments, the courses could include small passages, sharp turns, stairs, rails, large drops/climbs, mud, water, and other mobility-stressing terrain features and obstacles (see Section 8.2). Challenge participants should expect, for example, both constrained areas with human-crawlable cross sections as well as larger underground open spaces that could include large ledges or vertical shafts. No breaching, burrowing, or use of explosives is permitted.

8.2. Technical Challenge Elements

The Circuits and the Finals competition courses are intended to assess performance across various challenge elements, including: austere navigation, degraded sensing, severe communication constraints, terrain obstacles, dynamic terrain, and endurance limits (illustrated in Figure 2). These challenge elements are also encoded into the SubT Virtual Testbed (described in Section 8.4) to the fullest extent possible.

1. **Austere Navigation:** The challenge courses are expected to include features such as multiple levels, inclines, loops, dead-ends, slip-inducing terrain interfaces, and sharp turns. Such environments with limited visibility, difficult terrain, and/or sparse features can lead to significant localization error and drift over the duration of an extended run.

2. **Degraded Sensing:** The courses are expected to include elements that range from constrained passages to large openings, lighted areas to complete darkness, and wet to dusty conditions. Perception and proprioceptive sensors will need to reliably operate in these low-light, obscured, and/or scattering environments while having the dynamic range to accommodate such varying conditions. Dust, fog, mist, water, and smoke are within

scope of this challenge element. Extreme temperatures, fire, and hazardous materials are not expected to be within scope.

3. **Severe Communication:** Limited line-of-sight, radio frequency (RF) propagation challenges, and effects of varying geology in subterranean environments impose significant impediments to reliable networking and communications links. The physical competition courses as well as the SubT Virtual Testbed environments are designed to include these severe communications constraints to the extent possible. Teams are encouraged to consider innovative approaches to overcome these constraints, including novel combinations of hardware, software, waveforms, protocols, distributed or dispersed concepts, and/or deployment methods.

4. **Terrain Obstacles:** Systems are required to demonstrate robustness in navigating a range of mobility-stressing terrain features and obstacles. Terrain elements and obstacles may include constrained passages, sharp turns, large drops/climbs, inclines, steps, ladders, and mud, sand, and/or water. The environments may include organic or human-made materials; structured or unstructured clutter; and intact or collapsed structures and debris.

5. **Dynamic Terrain:** Terrain features and obstacles may include dynamic elements, such as mobile obstacles, moving walls and barriers, falling debris, and/or other physical changes to the environment that test the agility of the system autonomy to reason, react, and potentially recover from the possibility of a changing map.

6. **Endurance Limits:** It is expected that successful systems will need to be capable of a team-aggregated endurance of 120 minutes to be mission-relevant. It is expected that each Circuit run will be between 60-90 minutes and each Finals run will be between 60-120 minutes. This aggregate endurance may require novel deployment concepts, energy-aware planning, heterogeneous agents of varying endurance, energy harvesting or transfer technologies, and/or a combination of various approaches to overcome the various challenge elements.
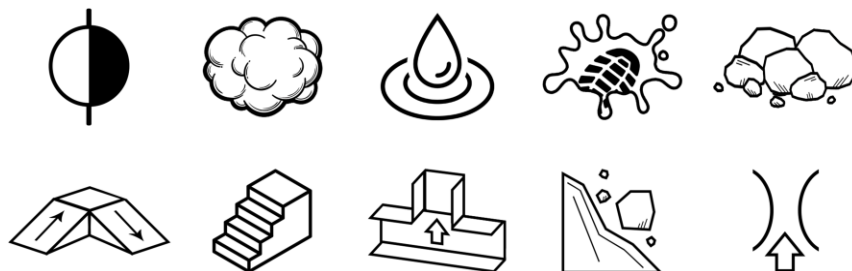

Figure 2: SubT Course Challenge Elements may include: (top row) light/darkness, particulates, water, mud, uneven terrain; (bottom row) inclines, steps/ledges, vertical shafts, dynamic obstacles, constrained passages

8.3. Artifacts

The main scoring objective is the need to search for, detect, and provide spatially referenced locations of artifacts relevant to each of the three subdomains. These artifacts could vary in their size, quantity, and detection signatures (e.g., visual, thermal, chemical). DARPA will announce the final artifacts in advance of each Circuit Event as part of the finalized event rules (approximately 90 days before each event) so teams will know what to look for, but the locations and distribution of the artifacts within the course will not be known. It is expected that the number of artifacts will be in the range of 10-30 and multiple copies of each artifact type are possible. The total number of artifacts, but not the number of each type, will be disclosed to the competitors.

The perception problems of interest in the SubT Challenge are focused on the difficulties of sensing in low-/no-light, obscured, and/or scattering environments. The detection and/or recognition tasks may benefit from multimodal sensing approaches. Various sensor modalities and combinations are allowed, including but not limited to: visual, light detection and ranging (LIDAR), thermal, acoustic, radio frequency (RF), and multi-gas sensors. For example, the detection of a survivor could potentially be made using a combination of visual, thermal, and/or auditory cues.
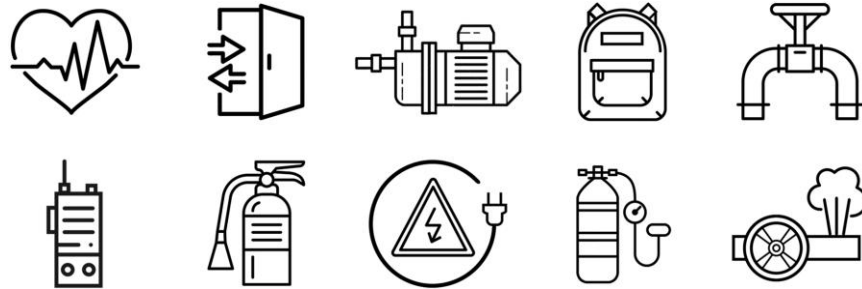
Figure 3: Candidate artifacts include: (top row) survivors, ingress/egress points, electric pumps, backpacks, valves; (bottom row) radios/cell phones, tools/fire extinguishers, power sources, oxygen level, and gas leaks

8.4. SubT Virtual Testbed

DARPA is investing in the development of a SubT Virtual Testbed, illustrated pictorially in Figure 4, comprising the (1) SubT Tech Repo, described below; (2) SubT Simulator, an extensible Gazebo-based simulation environment; (3) automated testing and assessment tools; and (4) associated software support infrastructure. This suite of simulation tools is intended to support teams in both the Systems and Virtual Competitions as they develop and evaluate their approaches.

The SubT Tech Repo is an online catalog of virtual subterranean technologies including models of Government-developed, team-developed, and/or commercial off-the-shelf (COTS) systems. The SubT Tech Repo initially includes a limited "Starter Set" of platforms and sensor configurations but will be continuously updated as new models are made available and validated.

As part of their interim deliverables, DARPA-funded Systems Teams will provide virtual models of their developmental systems. DARPA will work with each of the Systems Teams to perform physical validation of the virtual models and ensure that these models reflect sufficient fidelity (e.g., geometry, kinematics, performance) for integration and use in the SubT Tech Repo.

The SubT Tech Repo also includes a catalog of scenarios made up of virtual environments and their associated configurable parameters. Some of the scenarios are distributed to teams in advance of the Circuits to provide representative environments in which to develop and evaluate their solutions. Other scenarios will serve as the Circuit Event competition scenarios and will not be released until after the respective Circuit Event has been completed. Teams are also given access to a scenario generator with which they can compose their own custom scenarios for further testing and contributions to the SubT Tech Repo for sharing with other teams.

Teams are able to compose a virtual Team Configuration comprising models selected from the SubT Tech Repo; load their own respective software-based innovations (e.g., algorithms for mapping, navigation, and search); and complete simulated runs in the virtual scenarios from the SubT Tech Repo. The simulations can be run either locally or in a cloud-based Ignition Gazebo environment. The simulations enable teams to evaluate how their systems and solutions perform in the selected scenario and generate a Run Score and Logfile which can be used to compare performance against other teams on the SubT Challenge Leaderboard.

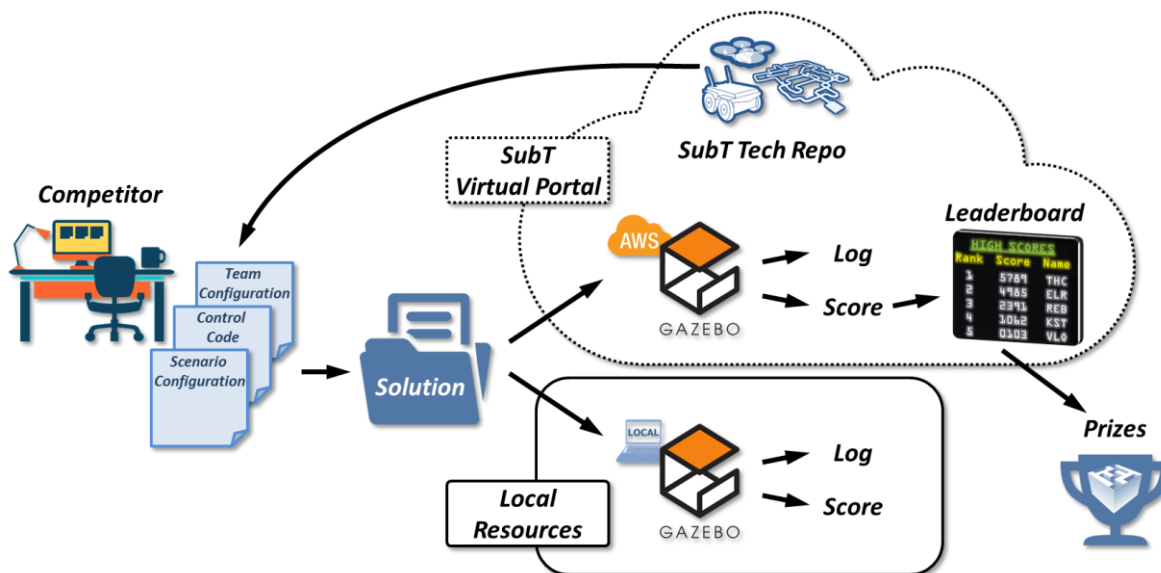*Figure 4: SubT Virtual Testbed Workflow*

The initial version of the SubT Virtual Testbed and corresponding infrastructure, released on September 27, 2018, will be followed by stable releases of updates and enhancements. DARPA intends to continue adding significant improvements and new capabilities to the SubT Virtual Testbed over the life of the competition, with the goal of realistically emulating the same

subterranean environments and challenge elements that are presented in the Systems Competition courses.

8.5. Systems Competition Courses

Teams in the Systems Tracks are developing physical systems to compete in live competitions on physical, representative subterranean courses. Figure 5 shows a notional workflow and data sharing for the competition events. The competing team will set up and begin their run in the Staging Area, which will be outside of a known entrance. At the beginning of a run, teams will deploy their systems into the course where they will explore, map, and search for artifacts. Relevant observation data will be transmitted to the team's Base Station which will, in turn, provide regular map updates and artifact reports to the DARPA Command Post where the reports will be automatically evaluated and scored. The DARPA Command Post will provide score updates back to the team's Base Station.

An *Interface Control Document (ICD)* and reference implementation detail the mechanism for providing artifact reports and map updates to DARPA. The initial *Interface Control Document (ICD)* was released on February 11, 2019 and is expected to be regularly updated.
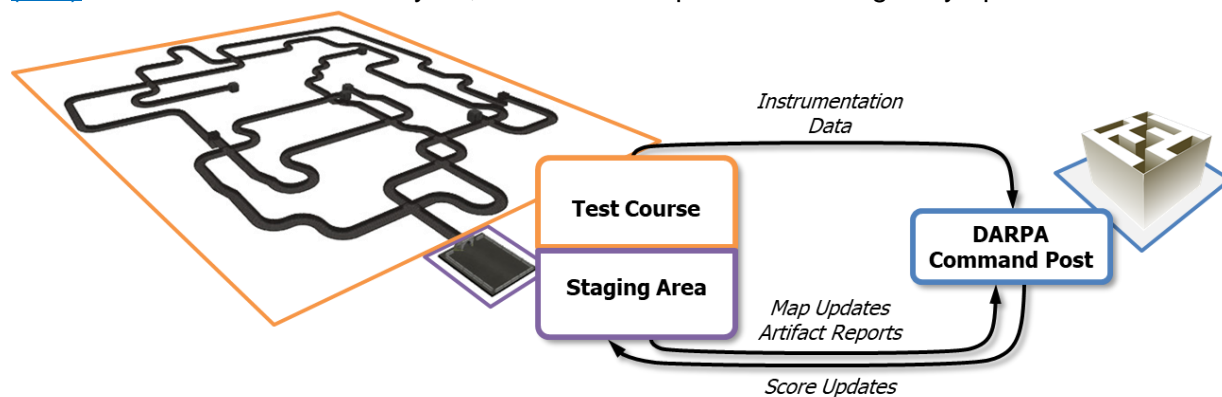
Figure 5: SubT Challenge Systems Competition Workflow

8.6. Mapping

Systems Teams must provide real-time 3D volumetric map updates to the DARPA Command Post at a minimum frequency of one update per 10 seconds. Virtual Teams are asked to provide updates via a virtual Base Station, which is expected to provide both artifact reports and map updates to the DARPA scoring interface. These map data updates are expected to be in the same DARPA-defined reference frame that is used for artifact reports. The *Interface Control Document (ICD)* provides details on the supported map representations and data types, which were selected with the goal of keeping the computational and implementation burden on teams low.

Each team's provided map will be used to visualize and validate the team's progress and evaluate the team's perception and mapping capability. Both stakeholders and spectators will likely form opinions about the quality of a team's solution based on its map representation. As rapid and

remote mapping is an important capability to DARPA, the quality of a team's mapping capability may be used, in part, to inform continued funding decisions.

9. Systems Competition Rules

9.1. Event Operations

9.1.1. Competition Courses

The NIOSH mine will be separated into two different competition courses: "Safety Research" and "Experimental." It is anticipated that teams will have up to four (4) scored runs through the Tunnel Circuit event, two (2) on each course.

For the Systems Teams, the final ranking in the Tunnel Circuit will be determined based on the sum of a team's top score on each competition course. The highest scoring run on the Safety Research course will be added to the highest scoring run on the Experimental course.

9.1.2. Staging Area

All systems will be required to start in the Staging Area behind the Starting Gate at or near the course entrance. The Starting Gate will be within line-of-sight of the entrance. The design and placement of the Starting Gate may vary between events and in some cases could use an existing entrance to serve as the Starting Gate. In the Tunnel Circuit, existing entrances to the mine will serve as the Starting Gate for each course. No systems will be permitted to operate above ground or outside of the competition course boundaries except within the Staging Area.

9.1.3. Course Access

Systems are allowed to enter, exit, or reenter the competition course at any time within the duration of the run. All human operators and personnel must stay within the Staging Area. No manual physical intervention or entry by any (human) team member on the course will be permitted. A system may only be handled or retrieved if it has completely crossed back into the Staging Area past the front face of the Starting Gate. Only authorized DARPA personnel are allowed to enter the course preceding, during, and following the run.

9.1.4. Run Termination

A scored run terminates upon any of the following conditions:
- Time Expiration: The scored run time expires before another termination criterion is met
- Run Completion: The deployed systems successfully report all artifacts, and successfully exit the course
- Run Cancellation: Competition Staff cancels the run due to an external factor such as weather, including lightning, rain, snow, or wind
- Emergency Stop: Competition Staff initiates an emergency stop because of an unsafe condition
- By Request: The Team Lead requests an end to the run

9.1.5.   Terminated Runs

A team may be eligible for an additional attempt if a run is canceled or stopped due to an emergency or external factor outside of the team's control. The Chief Official will review eligible cases and determine the course of action. The Chief Official has the final authority to make any scoring-related decisions.

9.1.6.   Prior Knowledge

The spirit and intent of the SubT Challenge is to develop technologies to rapidly and remotely explore unknown subterranean environments. Teams that align their solutions to these goals will be significantly more likely to succeed in the competition.

No prior knowledge about the competition course may be used by the deployed systems or team personnel to plan or execute their runs. Prohibited prior knowledge includes publicly available information, information collected from a prior run, and any information from challenge-related public feeds provided to spectators during the event.

The degree to which the environment is partially known may depend, in part, on site availability and could vary across events. In some cases, the event site may have publicly available information (e.g., general layout, map data). Teams may also conduct multiple scored runs, leading to the possibility of prohibited knowledge being used from a prior run.

DARPA intends to take multiple approaches to limiting the viability of using prior knowledge:
- Course Access: Once the event site is announced, teams will not be allowed to access the competition site for any reason other than completing their scored runs.
- Course Layout: DARPA intends to alter the competition courses to add sections, block passages, add obstacles, and/or move artifact locations. The layout and accessibility of the course segments is expected to vary from run to run.
- Sequestration: Team personnel may be sequestered from observer areas until they have completed their scored run to prevent gaining knowledge from another team's run.
- Staging Area Monitors: Competition Staff will be present in the Staging Area during each run to observe the Base Station, Human Supervisor, and other Pit Crew personnel.

DARPA reserves the right to disqualify any team that is found to violate either the rules or the intent of the rules. The Chief Official has the final authority to make any rules-related decisions. All decisions made by the Chief Official are final.

9.2. Personnel Guidelines

Teams are permitted up to 10 personnel in the Staging Area. Figure 6 provides a detailed workflow for how data may be shared between the systems, team Base Station, team personnel, and DARPA Command Post. For the sake of this discussion, two categories of data are delineated: *status data* and *course data*. Status data is primarily derived from proprioceptive sensors for the purposes of calibration and internal health monitoring. Status data may also include exteroceptive

sensor measurements that are collected within the Staging Area for the purposes of calibration. Course data is primarily derived from exteroceptive sensors that acquire information directly or indirectly from the competition course. Course data specifically includes any information related to mapping and/or artifacts.
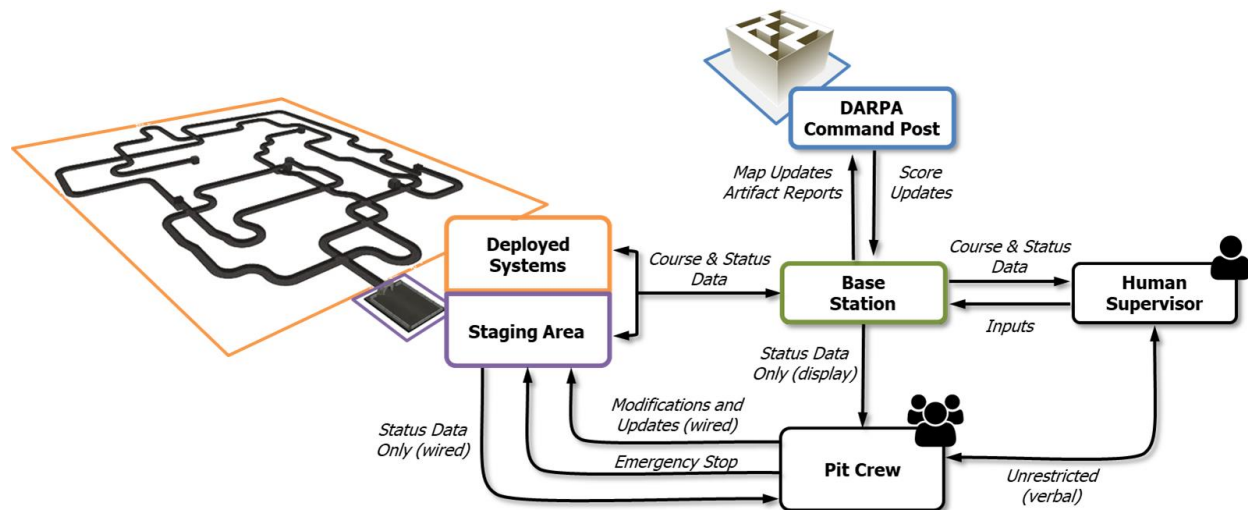

Figure 6: SubT Challenge Systems Competition Detailed Workflow

9.2.1. Human Supervisor

As the operational scenario suggests, DARPA is interested in approaches that are highly autonomous without the need for substantive human interventions; capable of remotely mapping and/or navigating complex and dynamic terrain; and able to operate with degraded and unreliable communication links.

The team is permitted to have a single Human Supervisor at a Base Station external to the course but within the Staging Area. The Base Station is defined as one or more computers or controllers that serve as the interface between the systems, the DARPA Command Post, and the Human Supervisor. The Base Station is responsible, either automatically or with supervisor monitoring, for communicating with the deployed systems and relaying artifact reports and map updates to the DARPA Command Post.

The Human Supervisor is permitted to monitor and manage the communications with their deployed systems as they choose. With the exception of the Safety Officers described in Section 9.2.3, only the Human Supervisor is permitted to use wireless communications with the systems. The Human Supervisor is permitted to view, access, and/or analyze both course data and status data. The Human Supervisor is permitted to provide inputs to the deployed systems and/or to serve as a buffer between the deployed systems and the DARPA Command Post. Once a team's run has begun, the Human Supervisor may not be substituted with other personnel.

9.2.2. Pit Crew Personnel

Up to nine additional team personnel are permitted in the Staging Area to serve as a "Pit Crew" to assist with operations tasks such as physically deploying the systems, performing repairs, modifying software or firmware, and changing batteries. Once a team's run has begun, the Pit Crew personnel may not be substituted with other personnel outside of the Staging Area.

The Pit Crew personnel and Human Supervisor are permitted to verbally communicate without restrictions. The Base Station can also provide status data to the Pit Crew via a wired display to support operations tasks such as calibration or completing startup checklists. Pit Crew personnel are permitted to view and access status data but are not permitted to view or access course data collected from the competition course. Pit Crew personnel are only permitted to view or access exteroceptive data that are collected within the Staging Area (e.g., for the purposes of calibration). Pit Crew personnel are specifically prohibited from viewing or accessing information related to mapping and/or artifacts.

With the exception of the Safety Officer roles described in Section 9.2.3, Pit Crew personnel are only permitted to use wired connections to interface with the systems within the Staging Area, for example, to make software or firmware updates. The Pit Crew is also permitted to plug in cables or extract physical storage devices to facilitate the transfer of data from the systems to the Human Supervisor at the Base Station. Once the system has crossed the front face of the Starting Gate, Pit Crew personnel may not send or receive data from the deployed systems, whether wired or wireless.

9.2.3. Safety Officer

Teams may identify specific members of the Pit Crew to serve as Safety Officers. The role of the Safety Officer is to preserve the safety of personnel and property. Safety Officers are permitted to activate Tier 1 wireless emergency stop transmitters and/or operate remote controls for safety purposes only.

For aerial systems, the Safety Officer may aid in initial takeoff and hover as long as the system is within the Staging Area and does not intrude past the front face of the Starting Gate. However, any further maneuvering of the aerial system must be initiated or controlled by the Base Station (via autonomous or Human Supervisor commands). If the safety of Staging Area personnel is at risk, the Safety Officer is permitted to take control of the aerial system for the sole purpose of safely landing the system. The Safety Officer is not permitted to take control of a system that has crossed into the competition course beyond the front face of the Starting Gate except to trigger a Tier 1 emergency stop for the sole purpose of preserving the safety of personnel in the Staging Area.

9.2.4. Teleoperation

While not expressly prohibited, it is not expected that manual teleoperation of individual systems will be a viable strategy, and teams should expect to provide at most only high-level interactions due to the likelihood of a naturally degraded communications network. Any teleoperation, whether

in the Staging Area or inside the competition course, must be under the exclusive control of the Human Supervisor. No manual physical intervention or entry by any (human) team members on the course is permitted. Only authorized DARPA personnel are allowed to enter the course preceding, during, and following the run.

9.3. Tunnel Circuit Course

9.3.1. Course Layout

The spirit and intent of the SubT Challenge is to develop technologies to rapidly and remotely explore complex and unknown environments. The exact course layout will not be known in advance and may be changed between runs. DARPA intends to alter the competition courses to add sections, block passages, add obstacles, and/or move artifact locations. The layout and accessibility of the course segments is expected to vary from run to run.

9.3.2. DARPA-Defined Reference Frame

Artifact reports and map updates shall be transmitted with respect to a DARPA-defined reference frame. The origin of the DARPA-defined reference frame is centered horizontally and aligned with the ground plane of the Starting Gate. The x-axis orientation vector is approximately aligned with the perpendicular centerline of the Starting Gate as shown in Figure 9.

Two survey markers are used to fully define the reference frame. The origin location of the reference frame (0, 0, 0) is defined by a physical origin survey marker (origin marker) permanently installed flush with the ground and horizontally centered between the inside edges of the Starting Gate. The z-axis is defined as facing upward from the origin marker and is aligned with gravity. The x-axis, y-axis, and z-axis are mutually perpendicular based on a right-handed coordinate frame definition as shown in Figure 9.

With the z-axis orientation aligned with gravity, the orientation of the reference frame can be fully constrained by defining the orientation of the x-axis in the xy-plane. The orientation of the x-axis can be defined by a line extending through the origin marker and any other point on the xy-plane. We choose to define the x-axis orientation using a second survey marker (orientation marker) permanently installed within the Staging Area. By definition, the y-coordinate of the orientation marker is exactly 0. The x-coordinate and z-coordinate of the orientation marker are arbitrary and depend on the installation accuracy and terrain of the Staging Area which may not be level.

The origin markers at the Tunnel Circuit Event are installed approximately 0.5 meters away from the front face of each entrance portal along the x-axis. The x-coordinates of the origin markers are, by definition, still exactly 0. The orientation marker at the Tunnel Circuit Event is installed at approximately 5 meters along the x-axis from the origin marker.

The origin marker and orientation marker serve as the two control points from which all of the other fiducial locations are derived. The coordinates of the origin marker are, by definition, (0, 0, 0) in the DARPA-defined reference frame. The y-coordinate of the orientation marker is, by

definition, exactly 0 meters. The x-coordinate of the orientation marker is approximately -5 meters but is dependent on installation accuracy. The z-coordinate of the orientation marker is approximately 0 meters but is dependent on the terrain of the Staging Area.

9.3.3. Starting Gates

The design and placement of the Starting Gate may vary between events and, in some cases, could use an existing entrance to serve as the Starting Gate. In the Tunnel Circuit, existing entrances to the mine will serve as the Starting Gate for each course. Figure 7 and Figure 8 show the Starting Gates for the Safety Research course and for the Experimental course, respectively.
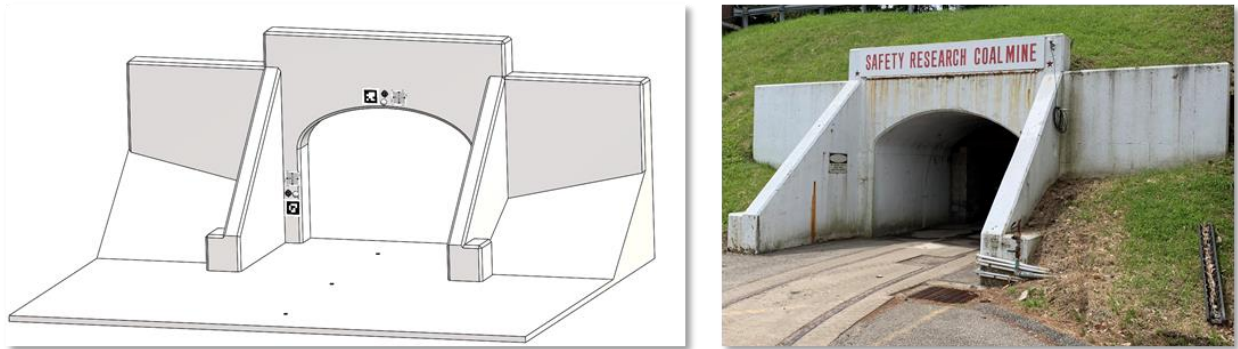
Figure 7: Model and picture of the Safety Research competition course Starting Gate
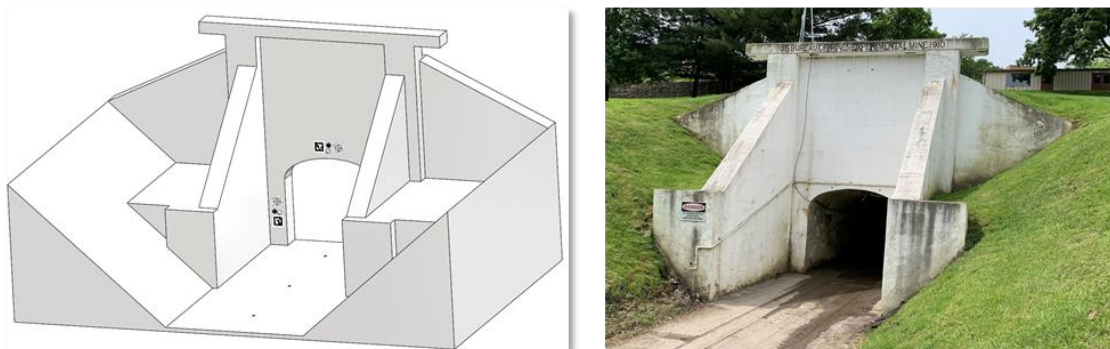
Figure 8: Model and picture of the Experimental competition course Starting Gate

9.3.4. Reference Frame Fiducials

Several types of reference points are being provided to help teams align their systems to the DARPA-defined reference frame including survey markers, visual fiducials, and reflective fiducials. Three sets of visual and reflective fiducials are affixed along the perimeter of the Starting Gate and another set is installed approximately 25 m inside the competition course. The configuration of the Starting Gate and reference frame fiducials in future events is subject to change.
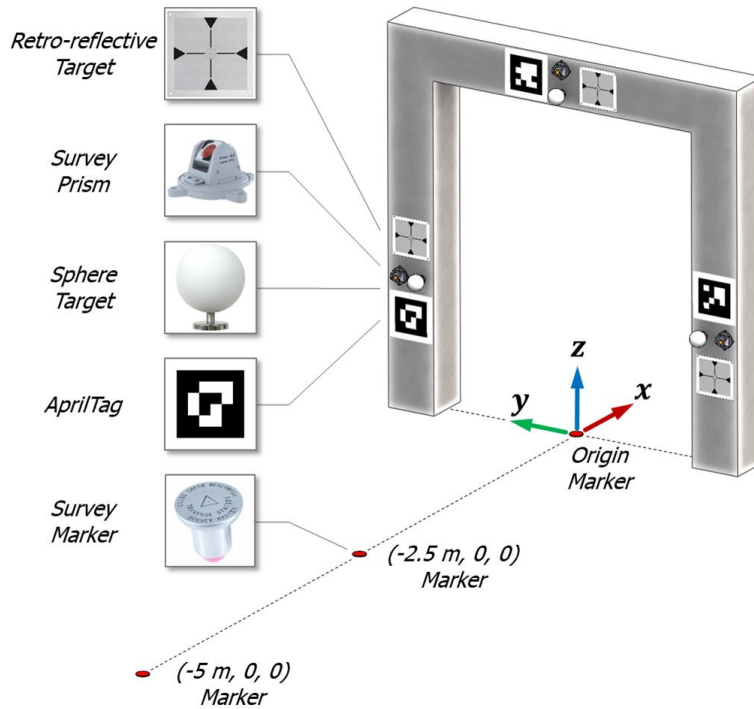
Figure 9: Reference frame fiducials on a representative Starting Gate

Survey Markers: The origin marker and orientation marker serve as the two control points from which all of the other fiducial locations are derived. An additional survey marker (alternate marker) is also installed at approximately 2.5 meters into the Staging Area, approximately aligned with the x-axis. The exact x, y, and z coordinates of the alternate marker depend on installation accuracy and terrain. The alternate marker is intended to provide teams an additional reference point closer to the Starting Gate. The precise locations of all three survey markers relative to the DARPA-defined reference frame are provided to teams at check-in.

Visual Fiducials: A series of three visual fiducials are arranged around the perimeter of the front face of the Starting Gate as shown in Figure 9. Each visual fiducial is a planar, black and white AprilTag[1] with a unique identification id. The AprilTag targets are in the 16h5 family and are mounted onto a rigid backing material. The outer white border dimensions are 12" x 12" and the black boarder dimensions are 9" x 9". The precise position, i.e., (x, y, z) coordinates relative to the DARPA-defined reference frame, of the center of each AprilTag are supplied to teams before any runs commence. The AprilTag targets are affixed to the Starting Gate, which is approximately aligned with the y-z plane. However, it is not expected that the AprilTag targets will be perfectly coplanar or parallel with the y-z plane.

Additional Fiducials: Three 0.22 m x 0.22 m retro-reflective targets, three survey prisms, and three 100 mm spherical targets are also being provided as shown in Figure 9. The precise

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[1] https://april.eecs.umich.edu/software/apriltag

position, i.e., (x, y, z) coordinates, of the center of each fiducial in the DARPA-defined reference frame will be supplied to teams.

Distal Reference Points: Two additional fiducials, one AprilTag and one reflective target, are placed at approximately 25 m within the competition course. The precise position relative to the DARPA-defined reference frame, i.e., (x, y, z) coordinates, of the center of both fiducials will be supplied to teams. The AprilTag and reflective target are being mounted approximately 0.5-1.0 m from the floor of the tunnel and at an approximately 45-degree angle to the main axis of travel in the tunnel. The distal reference points may not be visible within line-of-sight of the Starting Gate. No additional lighting is expected to be provided for the distal reference points, which in some cases may be in complete darkness. These distal reference points are intended to provide teams with a longer baseline to help align their systems to the DARPA-defined reference frame. No orientation information for the distal fiducials is provided.
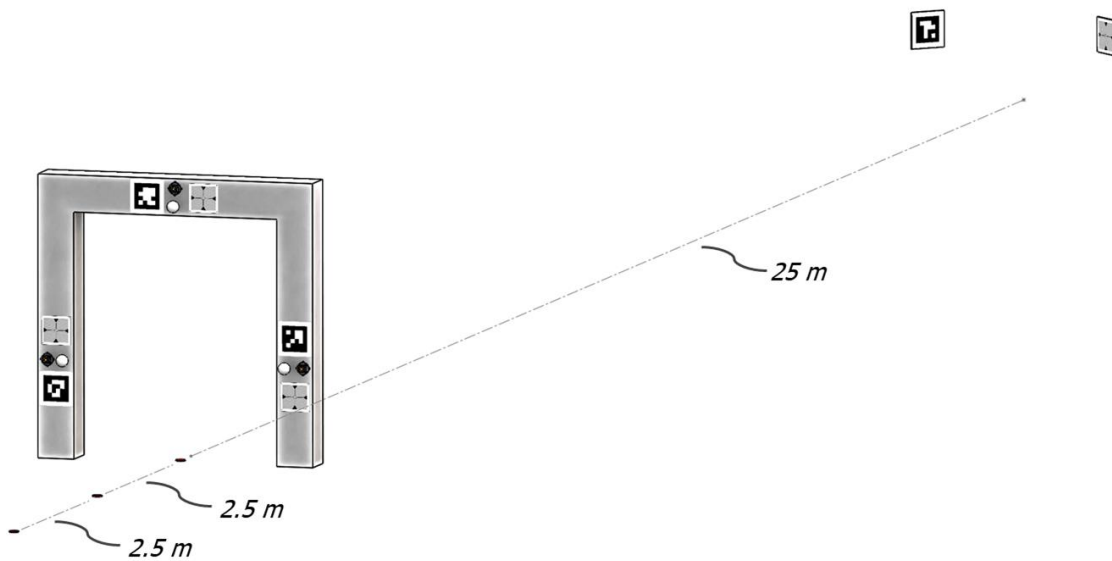
Figure 10: Distal reference points relative to a representative Starting Gate

Table 4 provides a notional table of coordinates for each of the reference points (cf. Figure 11). The x, y, and z coordinates of all reference points will be provided to teams, including the distal fiducials. By definition, the coordinates of the origin are (0, 0, 0) and the y-coordinate of the orientation marker is 0 since this survey marker is being used to define the x-axis orientation. **All other values in the table are approximate and given in meters.**

The "~" values in Table 4 are meant to convey that the y-axis and z-axis coordinates of the distal fiducials are dependent on the topology and terrain of the site. Note that the x-coordinates of the fiducials are approximately 0.5 meters due to the origin marker being installed approximately 0.5 meters away from the front face of each entrance portal.

ID #	Reference Point	x	y	z
"Safety Research" Portal			
1	Origin Marker	0	0	0
2	Alternate Marker	-2.5	0	0
3	Orientation Marker	-5	0	0
4	AprilTag (ID = 4)	0.5	1.671	0.6
5	AprilTag (ID = 5)	0.5	0.25	2.56
6	AprilTag (ID = 6)	0.5	-1.671	1.1
7	Distal AprilTag (ID = 7)	25	~	~
8	Reflective 1	0.5	1.671	1.1
9	Reflective 2	0.5	0.25	2.56
10	Reflective 3	0.5	1.671	0.6
11	Distal Reflective	25	~	~
12	Sphere 1	0.5	1.596	0.85
13	Sphere 2	0.5	0	2.485
14	Sphere 3	0.5	-1.596	0.85
15	Prism 1	0.5	1.746	0.85
16	Prism 2	0.5	0	2.635
17	Prism 3	0.5	-1.746	0.85

ID #	Reference Point	x	y	z
"Experimental" Portal			
21	Origin Marker	0	0	0
22	Alternate Marker	-2.5	0	0
23	Orientation Marker	-5	0	0
24	AprilTag (ID = 24)	0.5	1.44	0.6
25	AprilTag (ID = 25)	0.5	0.25	2.56
26	AprilTag (ID = 26)	0.5	-1.44	1.1
27	Distal AprilTag (ID = 27)	25	~	~
28	Reflective 1	0.5	1.44	1.1
29	Reflective 2	0.5	0.25	2.56
30	Reflective 3	0.5	1.44	0.6
31	Distal Reflective	25	~	~
32	Sphere 1	0.5	1.365	0.85
33	Sphere 2	0.5	0	2.485
34	Sphere 3	0.5	-1.365	0.85
35	Prism 1	0.5	1.515	0.85
36	Prism 2	0.5	0	2.635
37	Prism 3	0.5	-1.515	0.85

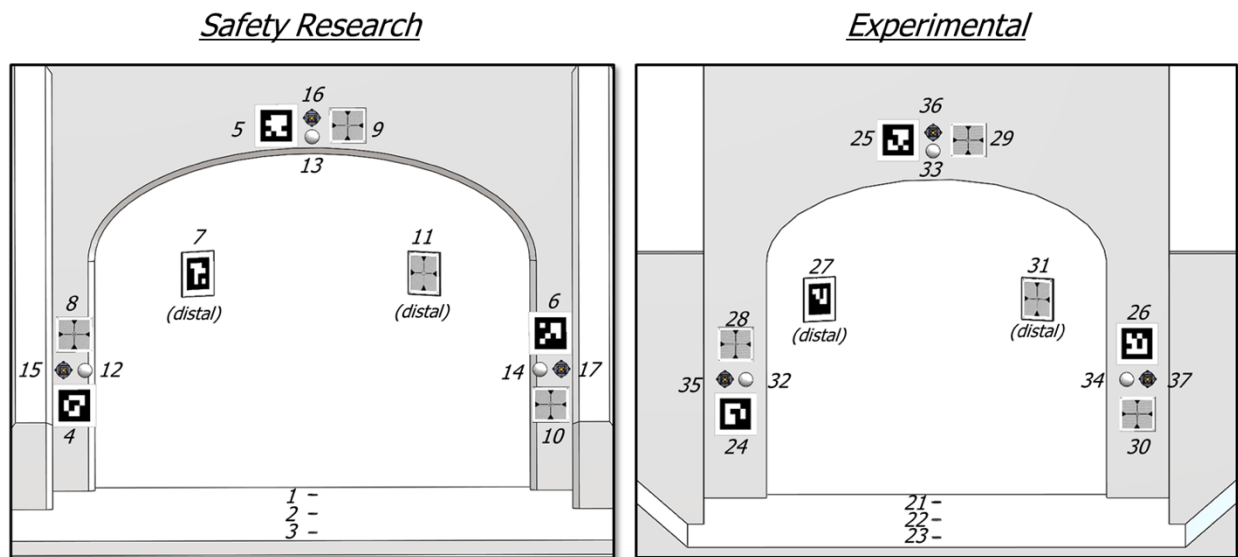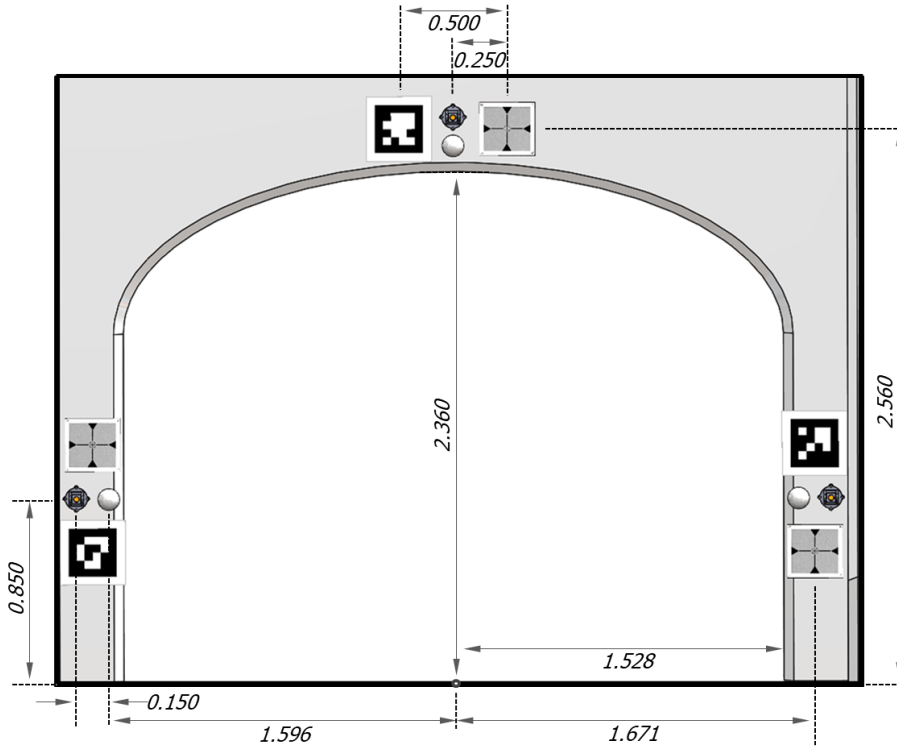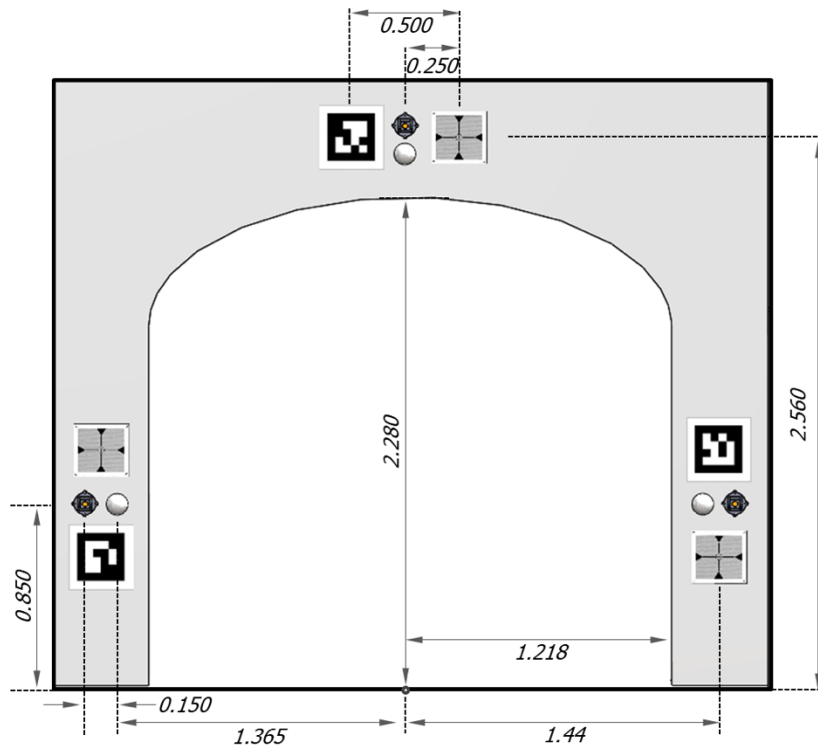Table 4: Reference point identification numbers and notional coordinates

Safety Research

Experimental

Figure 11: Mapping of reference point ID numbers for Starting Gate fiducials

Figure 12: Starting Gate and reference frame fiducials dimensions in meters; dimensions are approximate pending final installation

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9.3.5.   Tunnel Circuit Artifacts

DARPA will announce the expected artifacts in advance of each Circuit Event, approximately 90 days before each event. Teams will know what artifacts to look for, but the locations and distribution of the artifacts within the course will not be known. It is expected that the total number of artifacts will be in the range of 10-30 and multiple copies of each artifact type are possible. The total number of artifacts will be known to the competitors but not the number of each type.

It is expected that each run at the Tunnel Circuit will have 20 artifacts. The Tunnel Circuit artifact types and specifications are provided in the *Artifacts Specification (Tunnel Circuit)* document available on the SubT Challenge Website and SubT Community Forum.

9.3.6.   Tunnel Circuit Course Length

The scale and complexity of competition courses is expected to vary across events. The competition course for the Tunnel Circuit is expected to have a cumulative linear distance in the range of 4-8 kilometers. The cumulative linear distance of the competition course may vary from run to run due to changes in the layout (e.g., blocked passages).

9.3.7.   Tunnel Circuit Constrained Passages

The majority of passages in the Tunnel Circuit competition course are expected to be 2-2.5 meters in height and 3-4.5 meters in width. It is expected that some portions of the course will only be accessible via passages that are approximately one meter in height and/or one meter in width. The most constrained portions of the competition courses are not expected to be immediately at the Starting Gate, but may be located in sections that would preclude access to significant portions of the course for systems that cannot traverse constrained passages. For the Tunnel Circuit Event, it is expected that up to 50% of the competition course could be inaccessible for systems that cannot traverse the constrained passages.

The Tunnel Circuit competition courses also feature circular and rectangular bulkheads that are more constrained than one meter by one meter. The circular bulkhead design is approximately 0.98 meter in diameter with protrusions that reduce the passable width to approximately 0.8 meter. The rectangular bulkhead design is approximately 0.75 meter in width and 0.9 meter in height. Some artifacts may be reachable by taking an alternate route; however, some number of artifacts (up to 10%) may be inaccessible without traversing the bulkheads.

9.3.8.   Tunnel Circuit Run Duration

For the Tunnel Circuit, DARPA intends for scored runs to be 60 minutes in duration. It is expected that future Circuit Event runs will be between 60-90 minutes and Final Event runs will be between 60-120 minutes.

9.4. System Guidelines

9.4.1. Human/Animal Use

Teams may choose to deploy a wide variety of systems to complete the course objectives including but not limited to robotic platforms, sensors, and communication components. No humans or animals will be permitted as any part of the deployed systems that enter the competition course. The representative scenarios of interest present significant dangers, such as collapsed and unstable structures or debris, presence of hazardous materials, lack of ventilation, and potential for smoke and/or fire that would preclude employing a human or animal team.

9.4.2. Size Limits

DARPA does not expect to place explicit limits on the size of deployed systems, but teams should consider how their systems will operate in the often space-constrained subterranean environments.

9.4.3. System Cost and Quantity Constraints

DARPA does not expect to place limits on the minimum or maximum number of deployed systems; however, teams should expect and plan for some level of failures and/or attrition. Such incapacitation could occur due to, e.g., inability to overcome obstacles, failed interactions with dynamic terrain (e.g., moving walls), loss in communications, or reaching of endurance limits. Due to these likely factors, DARPA is interested in solutions that are cost-effective and attrition-tolerant. While there are currently no limits on the total quantity or aggregate cost of deployed systems, DARPA may introduce additional constraints as the competition progresses to appropriately incentivize such solutions.

9.4.4. System Retrieval

All systems must begin the run in the Staging Area. It is encouraged but not required for the deployed systems to return to the Staging Area at the end of the run. Any systems that have not autonomously exited the course at the termination of a run will be retrieved by authorized DARPA Competition Staff. The Competition Staff will make their best effort to collect a team's systems after each run. However, if systems are not able to be recovered in a safe or timely manner by the Competition Staff, teams will have to operate without them on subsequent runs.

Due to the need for exclusive handling by Competition Staff, several safety measures will be required for robotic platforms. These include but are not limited to a DARPA-specified transponder, a DARPA-approved emergency stop, and a competitor-provided *Handling Manual*.

9.4.5. Handling Manual

The *Handling Manual* must provide information on proper termination of platform power and safe handling instructions for each platform type. The systems are not required to be hand-carried. For larger systems, it is possible that safe handling may include recommendations for use of a powered remote-operated procedure, transportation by cart, or towing.

9.4.6.   Transponder

In addition to aiding extraction, the transponder is used to track and monitor progress of systems throughout the competition course. Teams are required to accommodate a third-party sensor package as described in the *[Transponder and Emergency Stop Integration Guide](#)*. To reduce the integration burden on teams, DARPA has integrated the transponder functionality with the Tier 2 E-Stop hardware described in Section 9.4.7.

9.4.7.   Emergency Stop

The emergency stop (E-Stop) requirements are designed to ensure the safety of personnel, equipment, and the Circuit course environment. All systems participating in the SubT Challenge Systems Competition will utilize a complementary three-tiered emergency stop system.

Tier 1: Team Wireless E-Stop
Teams are required to implement a wireless emergency stop capability as a component of their system's communication architecture. The emergency stop must be able to be triggered from the team's Base Station and/or portable wireless transmitter. The Tier 1 E-Stop transmitter must instruct mobile platforms within effective communication range to come to a halt. The emergency stop procedures implemented on the mobile platforms must, upon receiving a Tier 1 E-Stop trigger, render a platform completely motionless within 30 seconds. The emergency stop must include clear visual feedback of the mobile platform's safe, halted state (e.g., red LED). The emergency stop capability may be targeted to a specific platform, but should also provide the functionality to rapidly render all platforms safe. A team must be able to render all platforms within communication range completely motionless within 60 seconds.

Tier 2: Recovery Wireless E-Stop
Teams must integrate a DARPA-defined emergency stop receiver on all mobile platforms weighing more than 0.5 kg. The module specifications and configuration guidelines for the Tier 2 E-Stop are detailed in the *Transponder and Emergency Stop Integration Guide*. The Tier 2 E-Stop receiver is designed with size, weight, power, and RF considerations in view to minimize the impact on teams.

The Tier 2 emergency stop capability is required to qualify and participate in all Circuit Events and the Final Event.

Teams must integrate and/or mount the receiver to their mobile platforms and monitor a single digital output pin that will indicate the trigger of a Tier 2 E-Stop. The remote trigger will come from DARPA personnel carrying a DARPA transmitter while operating within an active course. The emergency stop procedures implemented on the mobile platforms must, upon receiving a Tier 2 E-Stop trigger, render the receiving platform(s) completely motionless within 30 seconds.

Tier 3: On-Platform E-Stop
Teams must integrate at least one emergency stop button on each platform that weighs more than 10 kg. The button must be a red mushroom-capped button at least 25 mm in diameter, with

clear markings indicating that it is an emergency stop button. The buttons must latch when triggered and must require a twisting motion to release the latch. The buttons must be completely unobstructed and must be easily accessible by recovery personnel. The emergency stop procedures implemented on the mobile platforms must, upon receiving a Tier 3 E-Stop trigger, render all platforms completely motionless within 5 seconds.

E-Stop Qualification
In accordance with the *SubT Qualification Guide* document, all teams are required to demonstrate emergency stop compliance to be eligible for participation in the STIX Event, Circuit Events, and Final Event. Qualification requires teams to demonstrate fully functional emergency stopping in compliance with all three tiers outlined in this document. Demonstration requirements are outlined in the "Emergency Stop" section of the *SubT Qualification Guide*.

Emergency stop functionality and compliance will be verified by DARPA at each official SubT Challenge event. DARPA reserves the right to deny a team's participation in one or more runs if any of their mobile platforms are non-compliant with the emergency stop rules.

9.4.8. Dropped Components
Teams are permitted to make use of dropped components and leave-behind peripherals. However, all such components will need to be extracted by Competition Staff at the end of each run, so teams are required to provide the Competition Staff with reasonable methods to locate any deployed components to aid course reset. Such methods may include, for example, an inventory of deployed systems, log of estimated locations, and/or beacons (e.g., LED, sound).

9.4.9. Course Alteration
The course may not be willfully altered by any of the deployed systems, including but not limited to digging, burrowing, or intentional degradation or destruction of the environment's walls, floors, ceiling, immobile barriers or obstacles, or other course infrastructure or instrumentation.

9.4.10. Fuel and Power Sources
All fuel and power sources must be safe for subterranean operations and will need to be approved by DARPA for use in the competition. Teams may be required to submit safety protocols and DARPA may require additional site-specific approvals which could require significant lead time. Most electric battery and diesel fuel sources are expected to be approved. Some fuel cells may be approved but will require additional information and approvals. Teams are encouraged to address any potential concerns early in preparations.

9.4.11. Communications Frequency Spectrum and Power Limits
DARPA is interested in novel networking solutions and will work with teams to get their approaches approved if possible. However, each competition event location may have frequency spectrum limitations, including applicable FCC guidelines. Teams are encouraged to raise any potential concerns about their planned approaches early. Additional details and restrictions are expected to be released in the *Operations Guide* for each official event.

9.4.12. Internet and Cloud Resources

DARPA does not plan to provide or allow the use of internet or cloud connectivity during the runs in the Systems Competition. Access to such resources are often limited in the field and in real-world scenarios following natural disasters.

10. Virtual Competition Rules

10.1. Scored Event Submissions

10.1.1. Versions and Releases

The SubT Virtual Testbed is based on Linux Ubuntu 18.04, Robot Operating System (ROS) Melodic Morenia, and Ignition Gazebo. The Circuit and Final Events will all take place in an Ignition Gazebo cloud environment using Amazon Web Services, so compatibility with these software tools is required of any Virtual Competition team.

10.1.2. Scored Competition Scenarios

Teams must submit their solutions to the SubT Virtual Portal where cloud-based simulations will be run against unreleased Circuit Event competition scenarios. The competition scenarios, run scores, and logs will not be released until the Circuit Event results are announced.

Each qualified team must submit a single solution to be scored. The submitted solutions will be evaluated against ***m*** number of competition scenarios to test the versatility of the solutions. Each competition scenario will, in turn, be evaluated over ***n*** replications to account for random variability. See Figure 13 for a graphical depiction. The Event Score of the ***m***x***n*** runs is given by:

$$Event\ Score = \frac{1}{m}\sum_{i=1}^{m}\left(\frac{\sum_{j=1}^{n} run\ score_{ij}}{n}\right)$$

Figure 13: Virtual Competition approach to scoring competition scenarios

10.1.3.   Solution Submissions

For scored event submissions, teams must submit their solution in the form of Docker Images to the SubT Virtual Portal, where it will be evaluated against the hidden competition scenarios. Submissions must be self-contained and evaluated through an automated process. Entries that require additional user input or external commands will not be scored.

The solution submission window for the Tunnel Circuit opens on July 1, 2019 and closes on August 1, 2019. Each qualified team must submit a single solution to be scored. The submissions will be evaluated and the final results will be announced alongside the Systems Competition results on August 22, 2019.

10.1.4.   Human Supervisor

The submitted solutions will be evaluated with no external operator interfaces such as command line inputs or user interventions. Virtual Teams are required to develop self-contained solutions that map, navigate, and search entirely autonomously without Human Supervisor interactions.

10.1.5.   Staging Area

Each scored scenario begins with a Staging Area similar to the Systems Competition, inside which all platforms in the team may spawn. Platforms will not be spawned outside of the Staging Area. At spawn time, platforms are provided their ground truth location and orientation. Platforms may operate freely within the Staging Area, but are not allowed to leave its borders or ascend to a height greater than 15 meters above the Staging Area ground level.

10.1.6.   SubT Simulator Mechanics

The SubT Simulator utilizes a number of simulator mechanics to address the environmental accuracy of the competition and reduce the operational disparity between the Systems and Virtual Competitions. To that end, team submissions must fully utilize and not seek to circumvent use of simulator mechanics including the RF propagation networking model, the built-in battery mechanic, and the vehicle damage plugin.

10.1.7.   Disabled Platforms

During the course of a run, individual platforms may be disabled due to battery expiration, exceeding a vehicle damage threshold, or leaving the permitted operating regions. If a platform is disabled, it can continue to operate as a processing or communications node, but will no longer be able to move in the environment.

10.1.8.   Run Termination

A scored run terminates upon any of the following conditions:
- Time Expiration: The given time expires before another termination criterion is met
- Disabled Platforms: All platforms are in a disabled state
- Maximum Score: All artifacts have been successfully reported and the maximum score has been achieved
- Artifact Reports Limit: The team reaches the maximum limit of allowed artifact reports

10.2.   Tunnel Circuit Scenarios

10.2.1.   Tunnel Circuit Competition Environments

The scale and complexity of the environments is expected to vary across competition scenarios and across events. The competition environments for the Tunnel Circuit are expected to be similar in scale to the Systems Competition course, which is expected to have a cumulative linear distance in the range of 4-8 kilometers.

It is expected that some portions of the environments will only be accessible via passages that are approximately one meter in height and/or one meter in width. The most constrained portions of the competition environments are not expected to be immediately at the Starting Gate, but may be located in sections that would preclude access to significant portions of the environment for systems that cannot traverse constrained passages. For the Tunnel Circuit Event, it is expected that up to 50% of the competition environment could be inaccessible for systems that cannot traverse the constrained passages.

10.2.2.   Tunnel Circuit Artifacts

DARPA will announce the expected artifacts in advance of each Circuit Event, approximately 90 days before each event. Teams will know what artifacts to look for, but the locations and distribution of the artifacts within the course will not be known. It is expected that the total number of artifacts will be in the range of 10-30 and multiple copies of each artifact type are possible. The total number of artifacts will be disclosed to the competitors but not the number of each type.

The artifacts used in the Virtual Competition will be similar to those used in the Systems Competition and will be made available in the SubT Tech Repo in advance of each event. Artifact distribution throughout the competition scenarios will be consistent across all runs for any given scenario but will vary across scenarios.

It is expected that each run in the Tunnel Circuit will have 20 artifacts. The Tunnel Circuit artifact types and specifications are provided in the *Artifacts Specification (Tunnel Circuit)* document available on the SubT Challenge Website and SubT Community Forum.

10.2.3.   Tunnel Circuit Run Duration

For the Tunnel Circuit, DARPA intends for scored runs to be 60 minutes in duration. It is expected that future Circuit Event runs will be between 60-90 minutes and Final Event runs will be between 60-120 minutes.

For each scored run, the chosen team configuration will spawn inside the Staging Area. The run will be given 60 minutes of in-simulation time as shown below in Figure 14.
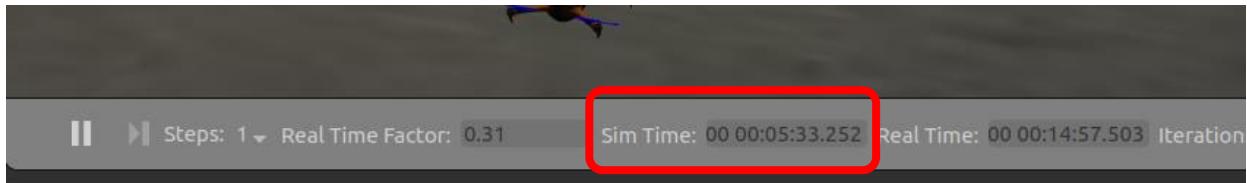
Figure 14: Simulation time elapsed is visible in the lower toolbar of Ignition Gazebo

10.3. Team Configuration

10.3.1. SubT "Credits"

To ensure relevant mission constraints, the Team Configuration is limited by a maximum allowable budget of 1,000 "SubT Credits." Each of the configurations in the SubT Tech Repo has an assigned SubT Credit value, which is based on several factors of interest to DARPA (e.g., cost, packed volume, sensor payload). SubT Credit values are viewable on the SubT Virtual Testbed wiki. DARPA reserves the right to adjust the assigned values throughout the competition to encourage teams to better explore the design space. The Virtual competitors can compose their Team Configuration by "mixing and matching" one or more models selected from the SubT Tech Repo with an aggregate value up to the maximum allowable 1,000 SubT Credit budget. Submissions composed of team configurations exceeding the allowable SubT Credit budget will not be scored.

10.3.2. Model Configurations

Virtual competitors must use existing model configurations from the SubT Tech Repo. The use of custom mobility or sensor hardware models by Virtual Teams is not permitted, including but not limited to additional configurations of or modifications to the model files supplied by the SubT Tech Repo. For the Tunnel Circuit, competitors will be able to use any combination of the 20 configurations available through the SubT Tech Repo, described on the SubT Virtual Testbed wiki.

10.3.3. Model Requests

Teams may request or contribute models for potential inclusion in the SubT Tech Repo, but no guarantee is provided that such requests will be approved. In addition to platform models, teams may also submit sensors and scenarios as contributions for consideration. Any proposed models will undergo review and validation before being included in the SubT Tech Repo. Note that a model contributed by a team, if found viable and deemed appropriate for the spirit of the competition, will be made publicly available to all teams through the SubT Tech Repo.

10.4. Communications and Score Reporting

10.4.1. SubT Simulator RF Propagation Plugin

The SubT Virtual Testbed will leverage a number of tools to create realistic radio-frequency behaviors in underground environments. As communications and networking is one of the cornerstones of the SubT Challenge, teams participating in this competition are required to utilize

the SubT Simulator's RF communications interfaces for all inter-platform communication, including communications to report found artifacts to the Base Station computer. No other wired or wireless communications is permitted. Additional details are available in the SubT Simulator API documentation.

10.4.2. Reporting Artifacts

Similar to the Systems Track, teams should account for simulated environmental communications degradation and the need to present relevant information to a virtual Base Station to provide near-real-time situational awareness updates and reports that are scored in the same manner as the Systems Competition. To report an artifact for scoring, the artifact report must originate from a platform and be sent to the virtual Base Station using the RF Propagation Plugin.

10.4.3. Log File Scoring

At the termination of a run, a log file is generated. The log file includes all artifact reports, their corresponding timestamps, score updates, and other details. Additionally, this log file allows replaying and viewing of the run by Competition Staff to ensure fair and consistent team performance in the virtual scenario in keeping with the rules and spirit of the SubT Challenge.

11. Scoring Criteria

The goal of the DARPA SubT Challenge is to develop innovative solutions that provide rapid and actionable situational awareness in complex subterranean environments. As such, teams are evaluated based on the number of artifacts they accurately report within a single run. Upon receiving an artifact report, the DARPA Command Post evaluates the validity of the report and provides score updates back to the team's Base Station. Artifacts are distributed throughout the competition course in a manner which rewards teams that are able to rapidly explore and maneuver through more of the course elements. The placement of the artifacts is not known in advance of a run by competitors and may be varied from run to run.

> **Scoring Objective** | **Find the most Artifacts before time runs out**

11.1. Accuracy

Upon identifying an artifact, the deployed system must report the type of artifact and its spatially referenced location to the DARPA Command Post via the team's Base Station. The location must be reported in the form of Cartesian coordinates (x,y,z) relative to a global origin $(0,0,0)$ established by the Reference Frame Fiducials (Section 9.3.2). The reported locations are compared against the DARPA ground truth dataset. To be designated a valid artifact report, the artifact type must be correct **AND** its reported location must be less than or equal to five (5) meters (Euclidean distance) from the ground truth location.

A valid artifact report earns the team one (1) point. Any artifact reports outside of the allowed error range do not earn any points. Upon submitting an artifact report, teams receive a response that includes the report status and the score change. Score updates during a run are expected to happen immediately after a report receipt (within 1 second). Additional details are provided in the Interface Control Document (ICD) available on the [SubT Challenge Website](#) and [SubT Community Forum](#).

If an initial report was deemed invalid due to insufficient accuracy or incorrect type, a team may submit another report, which would be scored using the same scoring metric. Such a scenario may arise, for example, when an initial report is not accurate but further exploration (e.g., loop closure, averaged readings) results in a more accurate estimate of type or location. Duplicate reports, whether valid or invalid, are subject to the limitations described in Section 11.3.
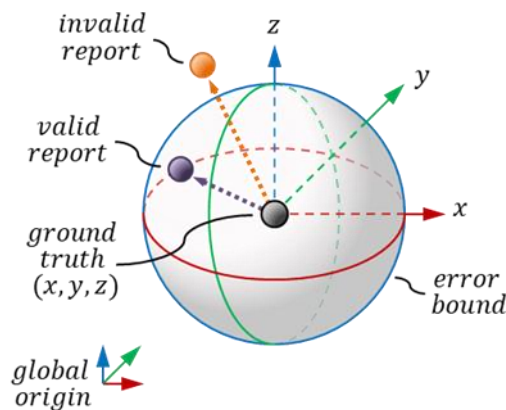

Figure 15: Accuracy-based scoring of artifact reports

11.2. Time

The time of artifact reports does not explicitly contribute to a team's score. Though time is not an explicit scoring factor, the course layout is designed such that finding a majority of the artifacts requires significant speed in covering the course. Furthermore, time serves as the tiebreaker as described in Section 11.4. Time is measured from the start of the run and is based on the time that a valid report is received at the DARPA Command Post, regardless of when the original detection took place.

11.3. Artifact Reports

Artifact reports are expected to be transmitted to the DARPA Command Post over an Ethernet link from the Base Station. The detailed format, protocol, and example implementation are specified in the Interface Control Document (ICD) available on the [SubT Challenge Website](#) and [SubT Community Forum](#).

To discourage false reports, the DARPA Command Post limits the total number of scored reports to twice the number of total artifacts. Any further reports are rejected. For the Tunnel Circuit, the

total number of artifacts is 20 and the total number of allowed scored reports is 40. Once an artifact has been successfully reported, any duplicate reports will be considered invalid and will count against the total number of reports.

DARPA intends to perform additional validation tests to discourage false reports and invalid guesses. For example, artifact reports in areas of the competition course that have not been explored by a team's systems may be deemed invalid.

11.4.   Final Ranking

For the Systems Teams, the final ranking in each Circuit Event and the Final Event will be determined based on the sum of a team's best runs on each competition course. The highest scoring run on the Safety Research course will be added to the highest scoring run on the Experimental course. In the event that multiple teams have an identical score, tiebreakers will be applied in the following order until the tie is broken:

- earliest time that the last artifact was successfully reported, averaged across the team's best runs on each course
- earliest time that the first artifact was successfully reported, averaged across the team's best runs on each course
- lowest average time across all valid artifact reports, averaged across the team's best runs on each course

For the Virtual Teams, the final ranking in each Circuit Event and the Final Event will be determined based on each team's event score as described in Section 10.1.2. In the event that multiple teams have an identical event score, tiebreakers will be applied in the following order until the tie is broken:

- earliest time that the last artifact was successfully reported, averaged across all of the team's runs
- earliest time that the first artifact was successfully reported, averaged across all of the team's runs
- lowest average time across all valid artifact reports, averaged across all of the team's runs

Appendix 1 SubT Challenge Glossary

Base Station – One or more computers or controllers that serve as the interface between the systems, the DARPA Command Post, and the Human Supervisor

Chief Official – DARPA-designated individual with the sole and final authority to make any decisions related to the rules or scoring

Competition Course – Physical or virtual environment in which deployed systems are expected to explore, map, and search for artifacts

DARPA Command Post – Computer interface which receives artifact reports and map updates from teams and returns score updates

Human Supervisor – Team-designated individual permitted to interface with the Base Station, provide high-level interactions with the deployed systems, use wireless communications, and access both course data and status data

Pit Crew – Team personnel permitted in the Staging Area to assist with operations tasks such as physically deploying the systems, performing repairs, modifying software or firmware, and changing batteries

Safety Officer – Team-designated members of the Pit Crew responsible for preserving the safety of personnel and property, activating emergency stop transmitters, and/or operate remote controls for safety purposes

Staging Area – Specified area immediately outside of the Competition Course entrance from which teams deploy their systems

Starting Gate – Installed structure or existing entrance which serves as the threshold between the Staging Area and the Competition Course

SubT Simulator – Simulation environment being used for the SubT Challenge that is implemented in Ignition Gazebo and can be either cloud- or desktop-based

SubT Tech Repo – Online catalog of virtual subterranean technologies including models of systems, sensors, environments, and artifacts models (subtchallenge.world/models)

SubT Virtual Portal – Web-based point-of-entry (subtchallenge.world) for accessing simulation resources, submitting solutions, and leaderboards

SubT Virtual Testbed – Suite of simulation tools comprising the SubT Virtual Portal, SubT Tech Repo, SubT Simulator, automated testing and assessment tools, and associated software support infrastructure

Team Lead – Team-designated individual responsible for making official team decisions (e.g., termination of a run) and communicating with the DARPA Competition Staff