Special Issue: DARPA Subterranean (SubT) Challenge

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The DARPA Subterranean Challenge: A Synopsis of the Circuits Stage

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Abstract: Complex underground environments present significant challenges for the autonomy, perception, networking, and mobility of robots operating in time-sensitive disaster response scenarios. In 2017, DARPA created the Subterranean Challenge to stimulate innovation and investment in solutions that can rapidly map, navigate, and search complex environments, including human-made tunnel systems, urban underground, and natural cave networks. The program is hosting a series of evaluations, namely, the three Circuit Events and the Final Event, which assess each competing team's approaches in representative subterranean environments. This paper provides an overview of the program and the results from the Circuits Stage of the competition.

Keywords: subterranean robotics, emergency response, cooperative robots, GPS-denied operation, mapping

1. Introduction

The Subterranean (SubT) Challenge is a Defense Advanced Research Projects Agency (DARPA) program to develop innovative technologies that can rapidly map, navigate, search, and exploit complex underground environments such as human-made tunnel systems, urban underground, and natural cave networks. Current technologies fail to address the multifaceted nature of these environments, which presents both a need and an opportunity for breakthrough innovations for public safety scenarios as well as a wide range of military, academic, and commercial applications, including infrastructure inspection, oil/gas/mining, construction, archaeology, and scientific exploration. The DARPA Subterranean Challenge aims to bring together multidisciplinary teams and cross-cutting approaches across disparate fields to address the autonomy, perception, networking, and mobility needs of the subterranean domain.

Vision of the DARPA Subterranean Challenge
To inspire and discover innovative technologies to provide actionable situational awareness in diverse underground environments

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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, postearthquake search and rescue in urban underground settings, and cave rescue operations for injured or lost spelunkers. These scenarios present significant dangers that would preclude employing a human team, such as collapsed and unstable structures or debris, the presence of hazardous materials, lack of ventilation, and potential for smoke and/or fire. To effectively respond in these scenarios, robots must be capable of providing time-sensitive situational awareness, exploring unknown and complex environments, providing accurate maps with georeferenced locations of important artifacts, and doing so without the need for substantive human interventions. The scenario of interest, competition design, and scoring function are all specifically derived from operational challenges faced in the real world. Insights from direct engagement with end-users across the spectrum of safety and security missions helped inject best practices, mission needs, and capability gaps into the SubT Challenge. Relevant parallels were extracted from, e.g., training manuals for mine rescue (National Mine Health and Safety Academy, 2013), urban subterranean operational doctrine (Headquarters, 2019; FEMA, 2006), and cave rescue (Mirza, Anmar, 2018), to highlight ongoing commitment to operational relevance.

DARPA has a legacy of using the "Grand Challenge" model to drive technological advancement in the context of addressing operational needs. Starting with autonomous off-road (DARPA, 2004, 2005) and urban driving (DARPA, 2007), and humanoid robotics (Krotkov et al., 2017) for disaster response scenarios, the DARPA Subterranean Challenge builds upon the lessons learned of these previous efforts and extends the Challenge model to inspire new ideas, incentivize novel approaches, and facilitate rich interactions among communities relevant to field robotics operating in complex and diverse underground environments. As DARPA's latest "Grand Challenge," the Subterranean Challenge is a robotics competition intended to set new benchmarks (Amigoni et al., 2015) for the current state of the art while creating and testing technologies with societal impact (Dias et al., 2016).

This paper details the scope and structure of the DARPA Subterranean Challenge, describing the efforts up through the Circuits Stage—a series of three events emphasizing tunnel, urban, and cave environments—with a focus on the field robotics-centric Systems Competition. Having described the vision and motivation for the SubT Challenge, in Section 2 we describe how it is broadly structured to maximize opportunities for iterative and innovative development. Section 3 highlights the technical details relevant to the design of the competition, followed by Section 4 to describe the events conducted through the Circuits Stage of the SubT Challenge. We conclude with a summary highlighting the contributions to date and final remarks looking towards the Finals Stage of the Subterranean Challenge.

2. Challenge Structure

The SubT Challenge is organized into two competitions (Systems and Virtual), each with two competitor tracks (DARPA-funded and self-funded), illustrated in Figure 1. Teams in the Systems tracks are developing and demonstrating physical systems to participate in live competitions on physical, representative subterranean courses. These teams focus on advancing and evaluating novel physical solutions in realistic field environments. Teams in the Virtual tracks are developing software and algorithms using virtual models of systems, environments, and terrain to compete in simulation-based events, with an emphasis on expanding the technical insights obtained by using the advantages of simulation. 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 two competitor tracks offer a hybrid approach involving DARPA-funded and self-funded teams as complementary avenues for advancing the state of relevant technologies. The

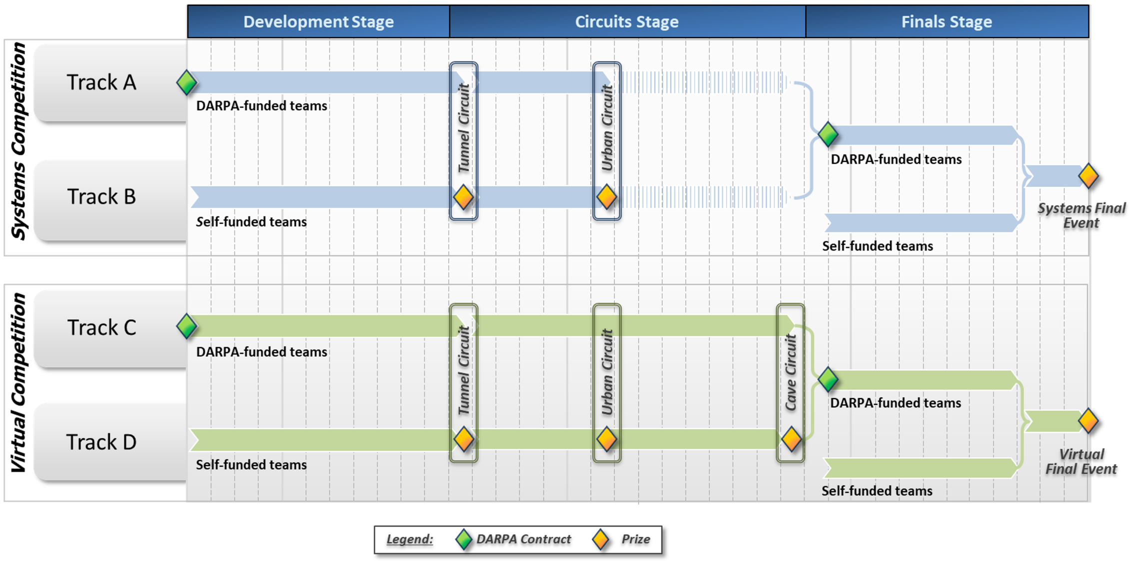

Figure 1. Program structure and schedule for the DARPA Subterranean Challenge, including the 15-month Circuits Stage. Competitors may compete in the Systems and/or Virtual Competitions, participate in one or more Challenge events, and may be eligible to win prizes at Circuit and/or Final Events.

DARPA-funded tracks (Track A and Track C) provide an opportunity for DARPA to directly invest in the development of promising technologies, calibrate the state of the art by supporting teams making significant research contributions, and mitigate technical risk by ensuring that well performing teams are able to continue participating for the duration of the competition. The self-funded tracks (Track B and Track D) encourage and welcome a broader range of participants through open competition, with prize incentives to draw out diverse innovators, regardless of geographic locations, organization types, or technical backgrounds.

The Systems and Virtual competitions comprise coordinated challenge events to include three Circuit Events and a Final Event, as shown in Figure 1. The 15-month Circuits Stage included three Circuit Events (a.k.a. the Tunnel Circuit, Urban Circuit, and Cave Circuit), each of which focused on one of the three subdomains. These Circuit Events were intended to promote frequent "build-test-compete" iterations within and among all participating teams. The Final Event combines elements of all three subdomains into a single integrated challenge scenario to demonstrate the versatility of solutions developed.

Teams in the Systems Competition will compete for up to \$3.5 million in the Systems Final event, with up to \$850,000 in additional prizes available for self-funded teams in each of the Systems Circuit events. Teams in the Virtual Competition will compete for up to \$1.5 million in the Virtual Final event, with additional prizes of up to \$500,000 available for self-funded teams in each of the Virtual Circuit events. Only self-funded teams were eligible for prizes in the Circuit events. All qualified teams are eligible for prizes in the Final events.

3. Competition Design

3.1. How to Win

The main scoring objective for the SubT Challenge is to search for, detect, and provide spatially referenced locations of artifacts placed in the environment. The teams have no *a priori* knowledge of the expanse, length, topology, or terrain of the competition courses. 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. Teams attain the highest score by finding the most artifacts in the shortest amount of time. In this way, artifacts not only serve as a surrogate for mapping, but also extend and accentuate the utility of the developed systems beyond mapping to providing actionable situational awareness.

As deployed systems identify artifacts, they must report the type of artifact and its spatially referenced location to the DARPA Command Post via the team's Base Station. 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. Each team is given a fixed number of artifact report attempts to discourage spurious guessing.

Teams earn one point for each valid artifact report. For the competition courses in the Circuits Stage, 20 artifacts were emplaced throughout, allowing for a maximum of 20 points possible per run. A team's overall Circuit score is computed by adding the best runs on each course (denoted as bold in the tables below). In the case of a tie, the team rank is determined by the earliest time that the last artifact was successfully reported averaged across the team's best runs on each course.

3.2. Artifacts

Artifacts include human (manikin) survivors, cell phones, backpacks, fire extinguishers, drills, heated vents, gas-filled rooms, helmets with headlamps, and bundles of rope. Three artifacts are common to all three subdomains and are included in all three Circuit Events, as illustrated in Figure 2. Two additional artifacts are specified for each Circuit Event that are event specific and do not appear in the other Circuit Events. Each course in the Circuit Events includes 20 artifacts total, including multiple copies of each artifact type. The total number of artifacts, but not the number of each type, is disclosed to the competitors.

The artifacts are selected to vary in their size, quantity, and detection signatures (e.g., visual, thermal, chemical) to highlight the difficulties of sensing in low-/no-light, obscured, and/or scattering environments. Teams are incentivized to take multimodal sensing approaches that could include visual, light detection and ranging (LIDAR), thermal, acoustic, radio frequency (RF), and multigas sensors. For example, the detection of a survivor could potentially be made using a combination of visual, thermal, and/or auditory cues.

3.3. Challenge Elements

The Circuits and the Finals competition courses are designed to drive innovation that addresses the gaps in autonomy, perception, networking, and mobility by presenting teams with the following technical challenge elements.

- **Austere Navigation**: The challenge courses 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 often lead to significant localization error and drift over the duration of an extended run.
- **Degraded Sensing**: The courses include elements that range from constrained passages to large openings, lighted areas to complete darkness, and wet to dusty conditions. Perception and proprioceptive sensors 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 fall under this challenge element.
- **Severe Communication**: Limited line of sight, 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.
- **Terrain Obstacles**: Systems are required to demonstrate robustness in navigating a range of mobility-stressing terrain features and obstacles. Terrain elements and obstacles include

Figure 2. Common and event-specific artifacts for each of the SubT Challenge Circuit Events, including common (`survivor`, `cell phone`, `backpack`), tunnel (`drill`, `fire extinguisher`), urban (`gas`, `vent`), and cave (`rope`, `helmet`) artifacts.

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.

- **Dynamic Terrain**: Terrain features and obstacles 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.
- **Endurance Limits**: The courses are designed such that successful teams of systems need to be capable of an aggregated endurance of 60 minutes to be mission relevant. This aggregate endurance requires 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.

3.4. Competitor Concept of Operations

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 teams have no *a priori* knowledge of the expanse, length, topology, or terrain of the competition courses.

Figure 3 illustrates an annotated concept of operations and how information may be shared between the systems, team Base Station, team personnel, and DARPA Command Post. The competing team begins its run in the Staging Area, which is immediately outside of a known entrance to the otherwise-unknown underground course. At the beginning of a run, the team deploys its robotic systems into the course where they explore, map, and search for artifacts. Relevant observation data is transmitted to the team's Base Station, which 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

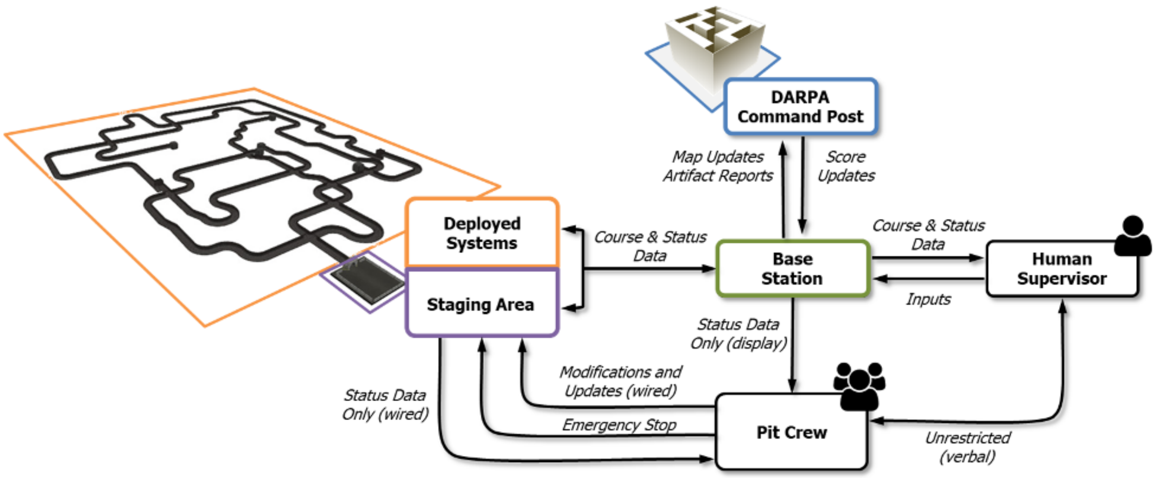

Figure 3. SubT Challenge Systems Competitor Concept of Operation illustrates how information may be shared among competitor systems and competition infrastructure.

monitoring, for communicating with the deployed systems and relaying artifact reports and map updates to the DARPA Command Post. The DARPA Command Post automatically evaluates the artifact reports and provides score updates back to the team's Base Station.

Two categories of data are delineated: *status data* and *course data*. Status data are 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 are primarily derived from exteroceptive sensors that acquire information directly or indirectly from the competition course. Course data specifically include any information related to mapping and/or artifacts.

The team is permitted to have a single Human Supervisor at a Base Station external to the course but within the Staging Area. The Human Supervisor is permitted to monitor and manage the communications with their deployed systems as they choose. Only the Human Supervisor is permitted to use wireless communications with the systems during the competition run. The Human Supervisor is permitted to view, access, and/or analyze both course data and status data.

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. Pit Crew personnel are permitted to view and access status data but are not permitted to view or access course data.

4. Challenge Events

The DARPA Subterranean Challenge officially commenced with Competitors Day on September 27, 2018, at Louisville Mega Cavern in Louisville, Kentucky. At the Competitors Day event, DARPA provided the vision of the competition, released the SubT Challenge Guidelines, and announced the competition time line and prize pool. The event was also an opportunity to engage potential competitors and provide a space for technical and operational exchange to support teaming between organizations. This event marked the beginning of the 12-month Development Stage that preceded the Circuits Stage.

During this period, DARPA also held the SubT Integration Exercise (STIX) at the Edgar Experimental Mine in Idaho Springs, Colorado, during the week of April 5–11, 2019, in advance of the Circuits Stage. The STIX Event provided the Systems teams access to representative testing environments to test and evaluate their performance under competitionlike conditions. Nine teams

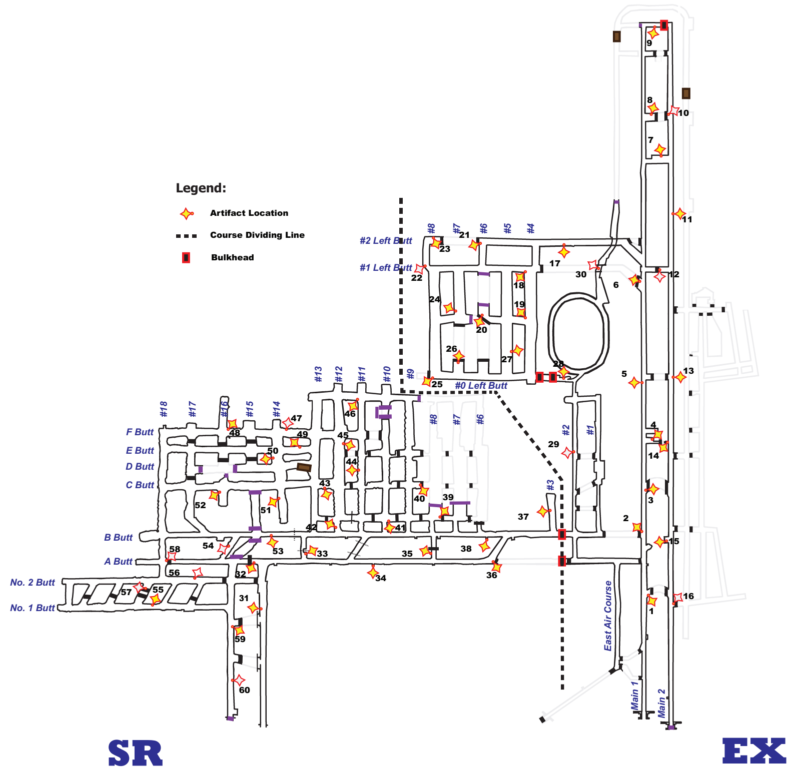

Figure 4. Tunnel Circuit competition course maps, including the Safety Research (SR) and Experimental (EX) courses, and artifact locations.

qualified and were given the opportunity 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. In addition to the value of a practice setting, the STIX Event also offered competitors their first opportunity to experience the ambitious scope and scale envisioned by DARPA and the SubT Challenge.

4.1. Tunnel Circuit Systems Competition

The Subterranean Challenge Tunnel Circuit was the first of three Circuit Events held on August 15–22, 2019, at the National Institute for Occupational Safety and Health (NIOSH) Mining Program's Safety Research Coal Mine and Experimental Mine in Pittsburgh, Pennsylvania. To compete, 11 teams used 21 uncrewed air vehicles (UAVs) and 64 uncrewed ground vehicles (UGVs, e.g., wheeled, tracked, and legged robots). The Tunnel Circuit comprised two competition courses, namely, the Experimental (EX) and Safety Research (SR) courses, which varied in difficulty and presented different challenge elements for teams to overcome. The overall map and configuration of these competition courses is illustrated in Figure 4. Each team conducted four total runs—two 60-minute runs on each of two courses (denoted EX1, EX2, SR1, and SR2). The courses were each populated with 20 artifacts that included five types: survivors, cell phones, backpacks, fire extinguishers, and drills.

Figure 5 provides representative pictures from the Tunnel Circuit competition courses. The courses included rails (1,2), water (2,3), mud (3,6), obstacles and clutter (4,5,7), rough terrain

Figure 5. Representative cross section of the technical challenge elements presented to teams in the Tunnel Circuit competition courses.

(4,6,9), complete darkness (4,5,6), and fog (8). The Tunnel Circuit Environment Preview[1] video provides additional insight into the terrain and environmental challenges present on the competition courses.

Table 1 summarizes the scores of all teams' runs, with Team Explorer as the highest scoring team.

4.2. Urban Circuit Systems Competition

The Subterranean Challenge Urban Circuit was the second of three Circuit Events, held on February 18–27, 2020, at Satsop Business Park in Elma, Washington. To compete, ten teams used 38 UGVs and 12 UAVs. The two courses used in the Urban Circuit—named Alpha and Beta—varied in difficulty and comprised multiple floors of the building, as shown in Figure 6. To limit the use of prior knowledge, the Urban Circuit presented two configurations of each course with different layouts and accessibility. Each team conducted four 60-minute runs, i.e., two configurations of two

[1] DARPA Subterranean Challenge Tunnel Circuit Environment Preview: https://youtu.be/LAziR-R-07c

Table 1. Tunnel Circuit scored results across all runs.

Team	Score	SR 1	SR 2	EX 1	EX 2
Explorer	25	**13**	12	10	**12**
CoSTAR	11	4	**7**	2	**4**
CTU-CRAS	10	1	**5**	5	**5**
MARBLE	9	2	**2**	**7**	6
CSIRO Data61	7	2	**3**	2	**4**
CERBERUS	5	1	**4**	**1**	0
NCTU	2	0	**0**	0	**2**
Robotika	2	**1**	0	1	**1**
CRETISE	1	**1**	1	0	**0**
PLUTO	1	**1**	1	0	**0**
Coordinated Robotics	0	0	**0**	0	**0**

Table 2. Urban Circuit scored results across all runs.

Team	Score	Alpha 1	Alpha 2	Beta 1	Beta 2
CoSTAR	16	5	**7**	4	**9**
Explorer	11	**6**	4	**5**	5
CTU-CRAS-NORLAB	10	4	**6**	3	**4**
CSIRO Data61	9	3	**4**	3	**5**
CERBERUS	7	**4**	1	**3**	3
Coordinated Robotics	4	1	**3**	**1**	1
MARBLE	4	**1**	1	**3**	3
NCTU	2	**1**	0	**1**	0
Robotika	2	**1**	1	**1**	1
NUS SEDS	1	**0**	0	**1**	1

courses, denoted Alpha 1, Alpha 2, Beta 1, and Beta 2. The courses were each populated with 20 artifacts that included five types: survivors, cell phones, backpacks, vents, and gas.

Figure 7 provides representative pictures from the Urban Circuit competition courses. The courses included corridors with side rooms (1), vertical shafts (2,5), mezzanine levels (3,6), stairs (4), large cavernous rooms (1,6), rails (7), fog (8), and narrow passages (9). The Urban Circuit Environment Preview[2] video provides additional insight into the terrain and environmental challenges present on the competition courses.

Table 2 summarizes the scores of all teams' runs, with Team CoSTAR as the highest scoring team.

4.3. Cave Circuit

Due to safety considerations surrounding COVID-19, DARPA made the difficult decision to proceed only with the Virtual Competition for the Cave Circuit, held on November 17, 2020. Nevertheless, Systems competitor teams completed their own extensive field testing in real-world cave environments, often emulating competition conditions, in preparation for the Final Event. DARPA released a Cave Environment Preview[3] video to give teams an insight into the cave environments that are being used to inspire the cave segments of the Final Event competition course. Systems Competition technologies also played a significant role in the Virtual Competition Cave Circuit. Of the 16 teams that participated in the Virtual Cave Circuit, five were teams that also competed

[2] DARPA Subterranean Challenge Urban Circuit Environment Preview: https://youtu.be/cmyJJG4E8NA
[3] DARPA Subterranean Challenge Cave Circuit Environment Preview: https://youtu.be/BElle2mSuRY

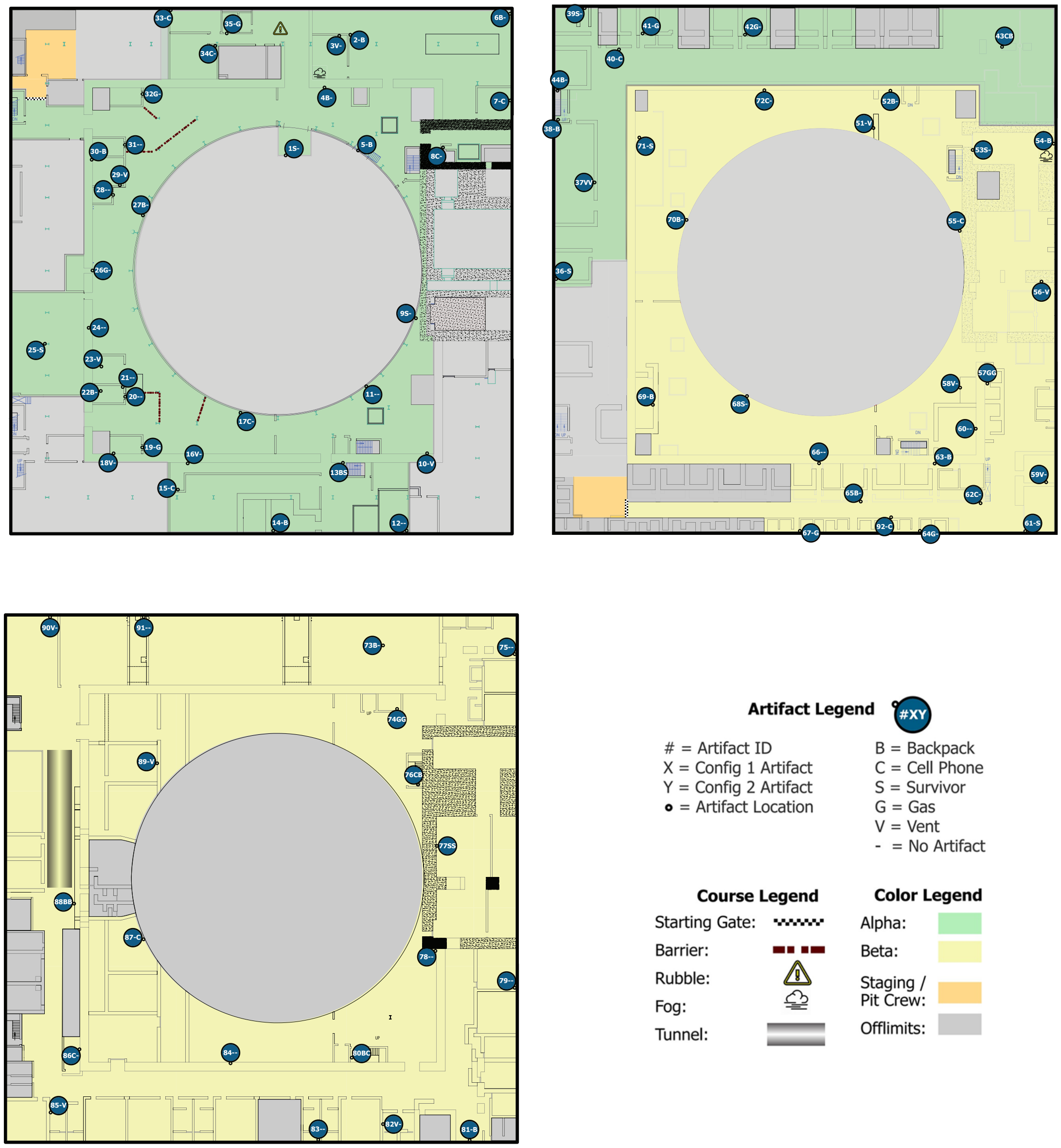

Figure 6. Urban Circuit course maps and artifact locations for Floors 1, 2, and 3 (clockwise from top left).

in Systems Competition events. Eight out of 16 teams in the Virtual Competition used platform models and sensor configurations that were based on Systems Competition robots.

5. Contributions and Impact

The SubT Challenge offers a unique opportunity to generate and curate data products and resources for the field robotics community to develop open datasets that include common benchmarks, support reproducible robotics research, and collectively enhance the integration and evaluation of relevant technologies. Several resources have been publicly released and are available on the SubT public repositories, as described in detail below.

Figure 7. Representative cross section of the technical challenge elements presented to teams in the Urban Circuit competition courses.

5.1. Ground Truth

In an effort to provide broader opportunities to maximize the unique access to the SubT Challenge-enhanced test environments, DARPA has made substantial efforts to capture high-quality data relevant to the sites themselves, e.g., for 3D reconstruction or sensor processing, as well as the SubT Challenge competition scenarios, i.e., artifact locations and configurations, for further testing or validation. These extensive ground-truth data products benefit from survey-grade measurements and high-precision scans, offering a rich and validated foundation for future research endeavors.

The Tunnel Ground Truth Repository[4] and Urban Ground Truth Repository[5] provide several resources:

- Spreadsheet listing each artifact, its type, and (x, y, z) location in the relevant DARPA coordinate frame for each course and configuration
- Spreadsheet listing reference frame fiducial coordinates for each course
- Map of artifact locations and associated artifact types for each course configuration

[4] Tunnel Ground Truth Repository: https://github.com/subtchallenge/systems_tunnel_ground_truth
[5] Urban Ground Truth Repository: https://github.com/subtchallenge/systems_urban_ground_truth

- Survey-grade high-resolution 3D point-cloud scans of the courses
- Virtual fly-throughs of the point-cloud data for each course
- Course walk-through videos showing the courses and relevant challenge elements
- Virtual tours of each course based on data collected with a Matterport™ scanner.

5.2. SubT Reference Datasets

Subterranean environments present a starkly different set of environment characteristics than those found in typical SLAM datasets: poor to no lighting, varied levels of roughness and irregularity in structure, sometimes significant changes in topography, and they are wet, dirty, and have no access to GPS. The SubT Reference Datasets Repository[6] includes datasets collected from the competition courses and analysis tools intended for benchmarking simultaneous localization and mapping (SLAM) algorithms in subterranean environments.

The following datasets are available on the SubT Repository:

- STIX Dataset, Edgar Experimental Mine, Idaho Springs, CO
- Tunnel Circuit Dataset, NIOSH Experimental Mine, Bruceton, PA
- Urban Circuit Dataset, Satsop Business Park, Elma, WA

In addition to the datasets, Rogers et al. (2020) provides a description of the data collection procedures, proposes an absolute-accuracy analysis metric for map evaluation, provides a set of open-source support tools to evaluate mapping approaches against this metric, and presents a baseline comparison of common SLAM algorithms.

6. Summary and Future Efforts

The DARPA Subterranean Challenge represents an ambitious approach to accelerate and advance field robotics research, carefully designed to highlight both technical and operational hurdles to employing robots in complex underground environments. The Circuits Stage, which presented competitors with diverse terrain, topology, and technical challenges across the three SubT subdomains individually, offers myriad applied insights for enriching the robotics research community.

These collective insights, whether common across all competitors or unique to individual approaches, represent the preliminary impact and technical contributions of the SubT Challenge and will continue to inform the development of increasingly robust and resilient robotic technologies. The experiences shared and expertise honed throughout the Circuits Stage will undoubtedly be critical as competitors prepare for the Final Event, expected to be held in Fall 2021. The Final Event combines elements of all three subdomains into an integrated challenge course designed to accentuate and assess teams' advances in agility and the versatility of their respective solutions.

In preparation for this culminating event, DARPA continues to identify and integrate key features into the SubT Challenge competitions, seeking to not only help reveal the limits of the developed SubT technologies, but also to illuminate avenues for potential breakthrough capabilities for operating effectively in complex and challenging real-world environments. Indeed, DARPA envisions that the SubT Challenge and the growing SubT robotics community will continue to positively and dramatically impact the future of field robotics in the months and years to come.

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[6] SubT Reference Datasets Repository: https://github.com/subtchallenge/tunnel_urban_reference_datasets

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