Editorial

Editorial: Special Issue on Advancements and Lessons Learned during Phases I and II of the DARPA Subterranean Challenge

Complex underground environments such as tunnels, underground urban settings, and natural caves present significant challenges for first responders in the event of an emergency. Each of these subdomains has unique hazards while sharing some common elements. Apart from challenging terrain features and aspects such as smoke and dust, communications in these environments are often severely degraded as well. Motivated by these difficulties, the Defense Advanced Research Projects Agency (DARPA) Subterranean Challenge (SubT) was set up to drive the global robotics community to develop novel approaches to rapidly map, navigate, and search underground environments under time pressure.

The DARPA SubT,[1] conducted from April 2019 to September 2021, was organized as two competition tracks. In the systems track, teams developed and demonstrated physical systems and competed live in real subterranean environments representative of the three subdomains. In the virtual track, teams developed software and algorithms using virtual models of systems and environments to compete in simulation-based events representative of the three subdomains. Phase I and Phase II of the systems track of this challenge consisted of the following events:

1. SubT Integration Exercise (STIX) at the Edgar Experimental Mine in Idaho Springs, Colorado, USA, in April 2019.
2. Tunnel Circuit event at the National Institute for Occupational Safety and Health (NIOSH) mine in Pittsburgh, Pennsylvania, USA, in August 2019.
3. Urban Circuit event at the Satsop Nuclear power plant in Elma, Washington, USA, in February 2020.

The Cave Circuit event scheduled for August 2020 was canceled by DARPA due to the COVID-19 pandemic. As a result, a number of the competing teams held their local Cave events to evaluate their system performance in natural cave environments.

In each of these events, the task was to deploy a fleet of robots into the subterranean course to locate and identify a set of predefined artifacts within the 60-minute run time. These artifacts included cell phones, backpacks, power drills, fire extinguishers, survivors (thermal mannequins), air vents, rooms with high carbon dioxide concentration, climbing rope, and helmets. A point was scored for each correctly identified artifact located within a 5-meter accuracy. Only one human supervisor

[1] www.subtchallenge.com

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DOI: https://doi.org/10.55417/fr.2022062

was allowed to control and communicate with the robots once the run started. A pit crew of 10 personnel was allowed to set up the robots in the staging area outside the course entrance in the 30-minute period immediately prior to the run.

For Phase I, DARPA initially selected seven teams to be funded to compete in the systems track with provision for self-funded teams to qualify and compete as well. The first event in this track was STIX, the SubT Integration Exercise where teams got an opportunity to evaluate their systems in a competition-like setting at the Edgar Experimental Mine. While there were no score tallies or leaderboards, teams gained invaluable experience in identifying limitations of their systems.

The first scored event was the Tunnel Circuit, where a total of 11 systems track teams competed, including 4 self-funded teams. There were two courses at the site and each team got two runs in each course. Each team's final score was the sum of their best score in each course.

For Phase II, DARPA funded 5 teams and the second scored event, the Urban Circuit, had a total of 10 systems track teams, including 5 self-funded teams. Once again, there were two courses at the site and each team got two runs in each course. As with the previous circuit event, each team's final score was the sum of their best score in each course.

This special issue presents nine articles consisting of one from the Challenge organizers and eight from teams that competed in the systems track. The content covers the advancements and lessons learned by the teams during Phase I and Phase II of the SubT Challenge. All articles were subject to the standard *Field Robotics Journal* peer-review process. A summary of each of the articles is as follows.

"The DARPA Subterranean Challenge: A Synopsis of the Circuits Stage" by Orekov and Chung provides an overview of the challenge, its structure, and competition design with background on the challenging technical elements designed for the courses. The Tunnel and Urban Circuits of the DARPA SubT system track are detailed with a summary of the results achieved by the participating teams.

"System for multi-robotic exploration of underground environments CTU-CRAS-NORLAB in the DARPA Subterranean Challenge" by Rouček *et al.* provides a field report on the performance of using a heterogeneous team of different types of tracked robots, hexapods, as well as quadcopters. The report discusses the unique communications architecture and approach to achieve systems resilience via resilience in each of the software modules. The report discusses results from deployments of the system at the circuits as well as at the team's own test locations.

"A Heterogeneous Unmanned Ground Vehicle and Blimp Robot Team for Search and Rescue using Data-driven Autonomy and Communication-aware Navigation" by Lu *et al.* discusses the architecture and implementation of a heterogeneous robot team consisting of a blimp and ground vehicles navigating unknown subterranean terrains for search-and-rescue missions. The report details unique aspects of this robot team, ranging from (1) the blimp's long flight time and collision tolerance characteristics to (2) the teams of millimeter-wave radars for navigation through smoke, to (3) their communication system based on mesh WiFi, XBee, and UWB comprised of nodes that can be shot or dropped in the environment. The report discusses the results and lessons learned from the Urban and Tunnel phases of the DARPA SubT Challenge.

"Multi-Agent Autonomy: Advancements and Challenges in Subterranean Exploration" by Ohradzansky *et al.* provides a summary of the approach by the MARBLE team. The overview of the hardware used in Tunnel and Urban Circuits is accompanied by a detailed description of the developed continuous frontier view planning employed in MARBLE 3D exploration using ground and aerial vehicles with explicit coordination based on UDP-based mesh communications. The report is concluded with an extensive review of the lessons learned from the field deployments in the first two DARPA SubT circuits.

"Teleoperation for Urban Search and Rescue Applications" by Isaacs et al. provides an overview of Team Coordinated Robotics' approach in the SubT Challenge with an emphasis on the Urban Circuit. The strategy to use teleoperation and focus mainly on mobility and networking challenges makes their approach unique. They discuss the pros and cons of this approach where the human operator was responsible for tasks that are typically delegated to autonomy and perception systems.

The primary contribution of the paper is their teleoperation strategy for rapid exploration and mapping that serves as a baseline for comparison with other autonomous approaches.

"CERBERUS: Autonomous Legged and Aerial Robotic Exploration in the Tunnel and Urban Circuits of the DARPA Subterranean Challenge" by Tranzatto et al. provides Team CERBERUS's system-of-systems approach to the Tunnel and Urban Circuit events in the SubT Challenge. While multiple ANYmal quadruped robots were used as their primary platform, unmanned aerial vehicles (UAVs) with conventional airframes were used as rapid explorers. Furthermore, collision-tolerant UAVs were also used to explore narrow and constrained sections of the course. Their wheeled rover with a fiber-optic tether back to the base station was used as a high gain communications node that can be deployed deep into the course. The paper goes on to give details about Team CERBERUS's path planning and multi-modal multi-robot perception, their object detection and reporting solution, as well as the robot-deployable communication solution along with their human supervisor interface.

"Heterogeneous Ground and Air Platforms, Homogeneous Sensing: Team CSIRO Data61's Approach to the DARPA Subterranean Challenge" by Hudson et al. discusses a heterogeneous team of multiple ground and aerial robots collaborating in underground spaces to explore the course with a homogeneous sensing pack. The article discusses the team's platforms that include tracked, quadruped, hexapod, and aerial platforms and outlines the autonomy system, simultaneous localization and mapping (SLAM) approach, peer-to-peer map sharing, communications, multi-agent task allocation, and human interaction and conveys the performance of the system in a wide range of courses in four courses and discusses lessons learned.

"Resilient and Modular Subterranean Exploration with a Team of Roving and Flying Robots" by Scherer et al. provides Team Explorer's approach where they emphasize the two themes driving their system design: modularity and resilience. While pointing out that no single robot or sensing system would be optimal for the different environments in the challenge, they also acknowledge the increase in overall system complexity when there is too much variation in the deployed robots. The concept of modular autonomy is presented to address this challenge. In terms of resilience, Team Explorer extends this paradigm all the way from mechanical robustness of platforms to software engineering and algorithm design with redundancy. The paper gives details of how these two themes were successfully applied to the overall systems fielded by the team.

"NeBula: TEAM CoSTAR's Robotic Autonomy Solution that Won Phase II of DARPA Subterranean Challenge" by Agha et al. conveys their approach to the challenge that focuses on the idea of an uncertainty-aware framework that aims at enabling decision making in belief space. The paper discusses the key ideas of the team's approach to SLAM, mapping, exploration, traversability analysis, decentralized decision making, and risk-aware mission planning. The team presents results of using the system on wheeled, legged, and flying robots in several environments, and conveys results of testing the approach in simulation, various field testing sites, as well as during the STIX, and competition experiments.

We strongly believe these papers presented in this special issue would be of high value to the field robotics community as well as for domain experts and practitioners in subterranean applications. The nature of the SubT Challenge, in line with previous challenges organized by DARPA, demanded innovation and pushing the boundaries of the state of the art in almost all aspects of field robotics. While the the trajectory of innovation has continued to advance as the teams went into the third phase of the challenge culminating in the final event held in September 2021, the collection of papers given here provides deep insights into the advancements and lessons learned in Phases I and II of the DARPA Subterranean Challenge.

The editorial team would like to extend our sincere gratitude to the numerous reviewers who collectively contributed to maintaining a high quality standard for each submission appearing in this collection.

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