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Lessons from the 2023 IEEE Autonomous Drone Chase Challenge

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The IEEE Drone Chase Challenge was held in 2022 and 2023 to foster development in Unmanned Aerial Systems and to provide a venue for collegiate students developing integrated UAS solutions in which to compete. The challenge is comprised of two stages: an online simulator-based stage and a physical in-person final. The development of each competitor's unique solutions and difficulties faced by each finalist team are described herein. Improvements for other future competitions are suggested based on the experiences of the competitors and hosts from the 2023 IEEE Drone Chase Challenge. First, software integration and documentation must be complete and easy to follow for competitors, allowing them to focus on solution development, rather than troubleshooting errors. Second, scoring metrics must be designed to test for robustness to mitigate the effect of luck and other external conditions on the evaluation of a solution. Despite the current limitations realized during the competition, competitors, hosts, and the research community benefit from developing soft and technical skills through competition participation.

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Introduction

Unmanned aerial systems (UAS) have seen widespread adoption across new and established markets in the past decade. The use of UAS in applications such as search and rescue, package delivery, farming, and mapping continues to increase as rapid advances in battery technology, computational capabilities, artificial intelligence, and communications improve. The projected market growth of UAS is expected to increase to $115 billion in 2035 due to the growth of unmanned aerial mobility and the potential delivery market (Federal Aviation Administration, n.d.). The continued advancement of UAS will continue to affect multiple industries across the globe. However, current limitations and challenges for UAS growth are focused on the limitations and restrictions on UAS artificial intelligence, automation, and operation. UAS systems require significant training investment for general operation to ensure safe and legal operation, as well as additional training on manufacturer-specific platforms. Despite training, UAS operators face limitations in commanding remote aircraft. In addition, operators may only operate one aircraft at a time, constrained by human perception and reaction limitations. Thus, increased automation, enabled by computational and energy capabilities advances, defines the frontier of UAS development (Yasin et al., 2020). Developing advanced algorithms and techniques for Unmanned Aerial Systems (UAS) to perform everyday tasks is vital in developing the technology.

Academic and research competitions have been shown to nurture these new algorithms and technologies. By hosting competitions, teams of students and researchers are given challenges and venues to competitively design, develop, and test real solutions to current and future applications. Thus, to foster the development of computer vision use in UAS applications, the 2023 Institute of Electrical and Electronics Engineers (IEEE) Drone Chase Challenge was hosted by Purdue University at its UAS Research and Test Facility. The competition was held successfully, with solutions from three finalists evaluated for the grand prize. Issues arose during the competition due to the design and software environments that distracted teams from optimizing their solutions. Instead, teams had to focus on achieving system stability after transitioning from the simulator environment. This paper offers details regarding the competition, highlighting lessons learned in hosting a UAS-focused competition based on the input and experiences of competitors. This article was written by some members of the hosting and participating teams to help other competition hosts learn from the successes and failures of the 2023 IEEE Drone Chase Challenge. The inclusion of the names participants and their picture were made at the request of the competing teams.

Computer Vision

Computer vision used in UAS has expanded to provide additional features to improve flight characteristics, obstacle avoidance, and supplement external navigational aids (McEnroe, 2022). Although prevalent on the major manufacturer's flagship models, challenges remain with the weight and power requirements of UAS and computing devices, limiting in-flight performance. Improving lightweight edge computing methods and techniques will expand the potential usage of UAS in existing industries (Wang, 2020). Focused improvements in computational capacity with proportional decreases in power consumption will be foundational for autonomous flight path planning, obstacle detection, and object tracking. Current solutions for computer vision focus on maintaining an internet or telemetry link with a ground station, with the UAS offboarding heavy computational requirements to a computer with little to no limitations.

Purdue UAS Research and Test Facility

The Purdue University UAS Research and Test (PURT) facility is a large indoor motion capture-equipped facility for developing and testing control algorithms and UAS platforms. The facility is equipped with sixty motion capture cameras that provide millimeter precision real-time position information with six degrees of freedom to UAS, or research objects operating in the facility. A Robot Operating System (ROS) node network is present to serve as communications between the cameras, flight vehicles, rovers, or additional devices that require information. The motion capture cameras provide ground truth information to the entire facility and can emulate positioning systems such as GPS. This facility served as the host venue for the UAS competition described below.

Competition

Academic-focused competitions have fostered the development of advancing technologies and ideas across different fields, including computer vision. Building on successful competitions, such as the annual IEEE Low-power Computer Vision Challenge (LPCVC) (Alyamkin et al., 2019), the IEEE Drone Chase Challenge (DCC) has been hosted since 2022 to encourage the integrated development of computer vision applications in UAS. Rather than focusing on computer vision solutions' power consumption and accuracy, the IEEE DCC takes it further, requiring the integration of computer vision solutions with UAS path planning and command and control algorithms. The tasks needed to be completed by competitors' solutions can be seen in Fig. 1.

The Competition

Overview

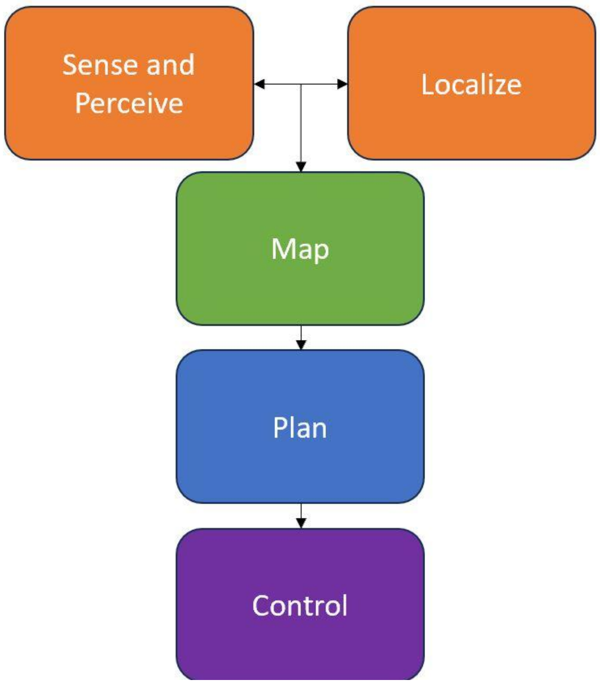
The 2023 IEEE DCC was an international competition where any team could submit their solutions for following a rover (ground vehicle) around a mock city landscape of buildings represented by solid blocks. Evaluation of the solutions was based on the distance between the UAV and the rover as it navigated around buildings. The competitors were not provided with the location of the rover and had to identify and track the rover using computer vision. The scoring algorithm used was shown in equation 1:

$$S_i = 1 - (|d - 1|/4) \qquad (1)$$

S_i was the instantaneous score measured every second and d was the distance between the drone and the rover. The final score for a given trial was the average of all instantaneous scores. Instantaneous scores were only calculated between a start and end flag and while d was under five meters. All values above five meters for d were recorded as a 0. Competitors were allowed to modify the core elements of object detection, path planning, and control solutions into one system to accomplish the objective.

Figure 1

Tasks required from each team's solution



The competition incorporated two stages. The first stage was an online digital twin (hardware, software, and layout) Gazebo simulator, where participants upload their solutions. A screenshot of the simulation environment is shown in Figure 2. The top-performing teams in the first stage were invited to the second stage, an in-person competition hosted at the PURT facility.

Figure 2

Drone Following Rover in the Simulator

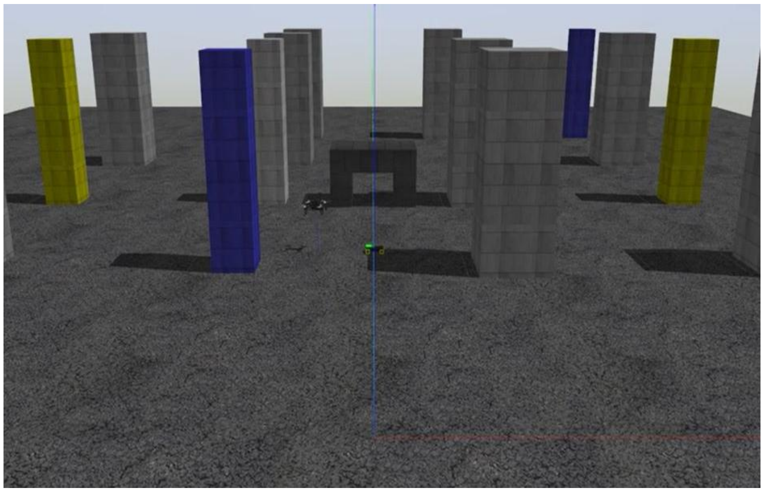


Figure 3

Drone Following Rover at PURT

A sample solution for the simulator was available to all competitors as a baseline and reference solution for implementing path-finding navigation and identifying and tracking the rover. Each solution component was packaged as ROS nodes to improve system performance and communication. The solution used the obstacle detection and avoidance vision algorithms created by PX4. Rover identification and tracking were trained using Openvino. Finally, the implementation of quadcopter planning used Rapidly Exploring Random Trees Star (RRT*). The entire sample solution was provided inside a Docker container to reduce installation overhead.

Due to restrictions during the COVID-19 pandemic, the 2022 competition was held remotely by participants, who provided solutions and were supervised in person by facility staff. Due to the remote nature, all solutions were flown on a Holybro PX4 Vision V1 with an Intel

Neural Compute Stick 2 and an Intel RealSense D435i camera. The 2023 competition's second stage was held in person, with competitors invited to bring and use any system with a wheelbase less than 500 mm. A PX4 Vision, with the same configuration as the 2022 competition, was available for competitors who did not travel with a drone.

Challenges/Trials

The simulator and in-person stages each contained four identical trials. The scores from the most challenging and complicated trial, the fourth, were used to judge winners during the simulator phase. However, for the in-person stage, weighted scores across all trials were used to calculate the final score. Scores from trials 1 and 2 were worth 15% of the final score, while trials 3 and 4 were each worth 35%. The sum of the weighted scores was the final score used to determine the winners. Additionally, the score from Trial 3 could replace a lower or missing score from Trial 1, while a score from Trial 4 could replace the score for all other trials.

In the second stage of the 2023 competition, time slots were allotted for teams to fly their solutions in PURT. Two one-hour periods per day across two days were scheduled for each team. Within their respective time slots, teams had unlimited attempts at trials. The highest score achieved in any attempt for a given trial was recorded as the respective score. For all the trials the rover's path and location after the starting position was unknown to the competitors.

Trial 1

For the first trial, the competitors were required to follow the rover with a red ball attached. The color of the ball was unique in the environment and provided simple identification of the UAV's target. The rover completed one lap of a figure-eight pattern around the competition course. During the duration of the trial, the motion capture system of PURT was used to calculate the distance between the UAV and the rover.

Trial 2

For the second trial, the solution required tracking the rover as it completed the same path as in the first trial. However, a tunnel structure in the rover's path was added to disrupt the vision of the UAV and the rover. The tunnel structure tested the solution's capability of finding and reidentifying the rover.

Trial 3

The third trial was identical to the first trial in regard to the rover's path, speed, and location, except that the red ball was removed from the vehicle. This trial required more complex and sophisticated object detection models to identify and follow the rover.

Trial 4

The fourth trial again utilized a rover with no distinguishing red ball attached. The same course and tunnel as Trial 2 were used. Figure 4 shows the drone following the rover and the tunnel used for Trial 4 in the simulated environment, while Figure 5 shows the same scenario during the real-world-trial from the same perspective. Figure 6 shows how the drone appeared while following the rover in the real-world trials from a third person perspective.

Figure 4

Computer Vision Example from Simulator Trial

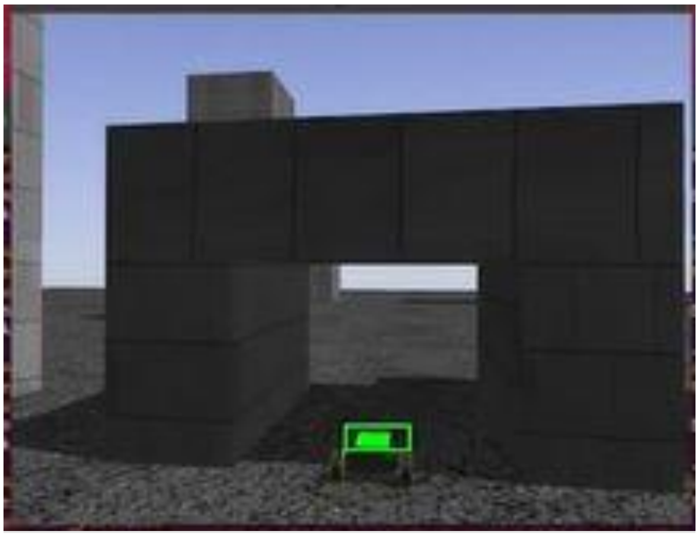


Figure 5

Computer Vision Example from Real-world Trial

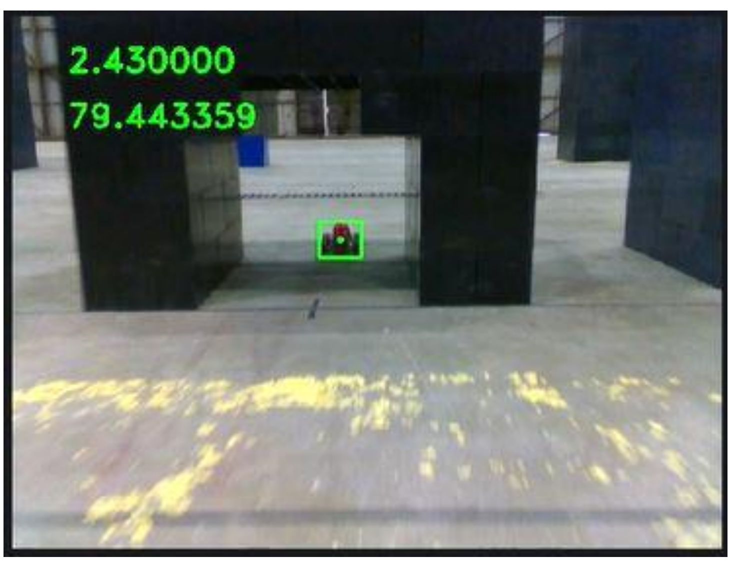
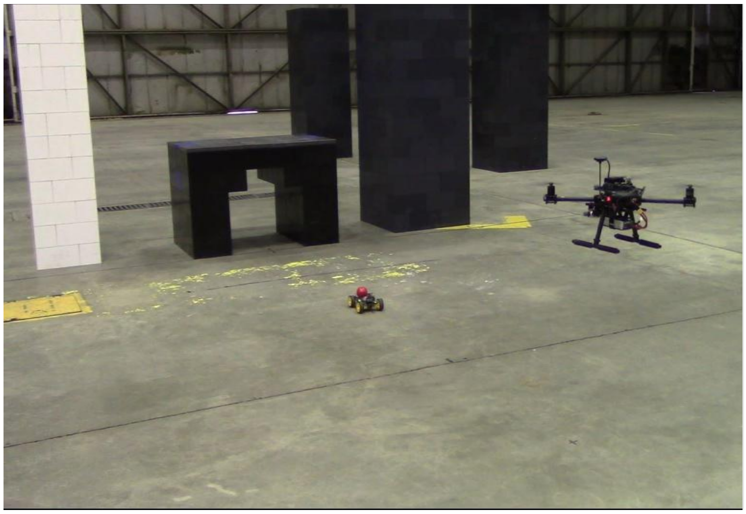


Figure 6

Drone Following Rover as it Approaches Tunnel (Real-world)



Competitors' Performance and Solutions

While 13 teams registered for the 2023 IEEE DCC, only four teams submitted solutions for the initial simulation stage before the deadline. However, one of the four solutions did not successfully track the rover or navigate the obstacle course. Hence, the top three finalists were selected from the remaining working solutions. Scores from the top three teams in the first stage are presented in Table 1. Due to software issues, some submissions could not be verified (indicated by N/A). Trial 4 for all submissions was valid and was used for the simulator stage results.

The top three finalists then participated in the competition's second and final stage. Due to travel restrictions, team Edrone could not participate in person and thus participated remotely with assistance from staff at the facility. During the finals, BioRobotics finished first, followed by Edrone, then HighFlyers, the same ranking as in the first stage. The best trial scores and final weighted scores of each team are presented in Table 2. All teams competed on the same courses. However, methods to accomplish these tasks differed. Descriptions regarding each team's composition, difficulties, and approach are described in the following section.

Table 1

Results from First Stage

Team	Trial Scores			
	Trial 1	***Trial 2***	***Trial 3***	***Trial 4***
BioRobotics	N/A	0.9311	0.9186	0.9388
Edrone	N/A	0.9319	N/A	0.9288
HighFlyers	0.9567	0.9137	0.9363	0.9202

Table 2

Results from Second/Final Stage

Team	Best Trial Scores (Weight)				Final Weighted Score
	Trial 1 (0.15)	*Trial 2 (0.15)*	*Trial 3 (0.35)*	*Trial 4 (0.35)*	
BioRobotics	0.870[b]	0.552[a]	0.870	0.552	0.711
Edrone	0.790[b]	0.600[a]	0.790	0.600	0.695
HighFlyers	0.392[b]	0.244	0.392	0	0.233

[a]Scores were carried over from Trial 4; [b]Scores were carried over from Trial 3

BioRobotics

Team BioRobotics from the Scuola Superiore Sant'Anna was a team of two researchers and eight undergraduate students from Italy. The team finished first overall in the 2023 IEEE DCC, scoring the highest in Trial 1 and 3 and the second highest in Trial 4. After preparing two workstations by installing all the software necessary for the simulation phase, BioRobotics adopted a "divide-and-conquer" strategy for the tasks described earlier in section B, allowing for parallel development of the solution.

These sub-tasks were identified:

· Drone navigation, common to all trials,

· Drone vision, differentiating it between trials 1 & 2 and 3 & 4

· Obstacle avoidance, trials 1 & 3 and 2 & 4.

The most challenging task was undoubtedly obstacle avoidance. During the simulation phase, a SLAM algorithm based on the Rtabmap library was developed, but it was found after simulation testing to be computationally expensive. The solution's computational cost was evaluated by deploying the entire software stack on an UPcore board with an Intel atom x5-z8350 CPU. The drone's behavior in the simulation was inadequate for tracking the rover, so given that development times were limited by the submission deadline, the team's approach to the problem changed. Instead of calculating the trajectory and then controlling the drone by position, a reactive system was implemented by controlling the drone "with speed". This consisted of calculating speed along x, y, z, and angular speed of yaw based on visual stimuli. Then to avoid unwanted side-effects such as overshooting and dampening, they implemented a proportional-integral-derivative (PID) system to mediate and filter the instantaneous speeds, also considering the past and the future states to make the drone's flight smoother.

Assuming the rover's path would be required to be free of obstacles, and the only "suspended" obstacles would have been the tunnels, the task was divided into two sub-problems: one for obstacle avoidance during the rover's pursuit and one for avoiding tunnels. This new strategy reduced the drone's reaction times to obstacles to a few hundredths of a second, eliminating the bottleneck in the trajectory calculation and limiting the reaction time to the camera's acquisition rate of 30fps (1 frame every 0.0333s).

The team's positive experience with the simulation phase was enhanced by the opportunity to travel to Purdue University and test the algorithms in a real scenario. Unfortunately, the transition from simulator to reality was difficult, and the only test day was primarily used to readjust indoor flight codes. Simultaneously, the vision group calibrated the color threshold and retrained the neural network to recognize the rover, while the navigation and obstacle avoidance groups tried their best to calibrate the various PID parameters to control the speeds in the various flight phases. Unfortunately, this approach required an accurate calibration phase, and the simulation parameters were unsuitable for the real drone. During the few hours made available for testing, the team made the flight stable enough to follow the rover correctly but were far from the performance obtained in the simulation phase.

Edrone

Team Edrone was composed of ten individuals from Beihang University and SenseTime. The team was composed of graduate students, researchers, and working professionals. The team finished second overall and had the highest score for Trial 4.

The team took a conventional approach focused on optimizing and robust solutions. Initially using only the red, green, and blue (RGB) input from the RealSense camera, the team decided to use depth information to estimate the distance of the rover from the drone, as utilizing RGB information alone was difficult for the later challenges. However, utilizing RGB and depth information led to a computational bottleneck that the team addressed. The reconciliation process between RGB and depth images was sped up by matching only the corners of the images rather than the entire image.

Despite these steps, the team found that the drone was too slow to process visual information and consistently track and follow the drone at a close distance. Additionally, the loss of rover identification led to problems in reidentifying and continued tracking. Thus, the team implemented a PID algorithm to provide control feedback. The PID implementation further improved drone tracking and control while being a relatively robust solution. However, the continuation of tracking after the loss of the rover in many circumstances still occurred. Hence, another improvement to their solution was made by adding a prediction algorithm that anticipated the general direction of the rover's movement rather than anticipating the next point of the rover's travel.

HighFlyers

Team HighFlyers came in third in the competition's first and second/final stages. The team comprised five undergraduate and graduate students from the Silesian University of Technology.

The team had implemented the A* algorithm for path planning (Hart et al., 1968). As for the mapping, the team used the Octomap server available from ROS, similar to team BioRobotics.

During the in-person finals, the team could not field a consistent solution that tracked the rover through the course. Furthermore, without an error-correcting system, the team's solution could never correct its path after a false object detection. Following the competition, the team mentioned that their most significant difficulty was integrating their solutions from the simulator to the real-world system, calling it "integration hell". Cited differences between the simulator stage and the in-person stage include a different camera (RealSense instead of Depth Core Depth Camera), imprecision and errors in the camera, and object detection algorithms not encountered in the simulator. It led to a similar lack of robust real-world camera error-catching. In addition, the team also had problems integrating the open-source software needed, encountering dependency problems, even in the Docker environment provided. Finally, the team mentioned that finding the appropriate documentation and sufficient examples for some of the libraries needed in ROS and for the autopilot was difficult. The limited documentation made the team unable to test some functions before arriving on-site for the finals.

Discussion

Improving Integration and Software

The competition aimed to challenge teams to develop and optimize computer vision, localization and mapping, and control solutions for UAS. Much of the work performed to accomplish the tasks demanded by the competition focused on successfully implementing algorithms and software. While competitors were provided two days to conduct competition flights, they occurred only on the second day. The limited flights indicated that the transfer of solutions from the simulated environment to the real-world environment was not as simple as expected. All teams encountered software implementation and integration issues throughout the competition, including a mismatch in coordinate frames between simulated and actual environments. BioRobotics and HighFlyers cited the solution transfer from the simulator to the in-person system and the software documentation as their most significant problems. While not explicitly mentioned by team Edrone, integrating the software into the real-world drone was also an apparent problem, evidenced by the time the team spent working with the facility's staff to upload their team's solution to the drone.

The challenges faced by the competitors demonstrated to the organizers that improvements to the documentation, sample solution, and facility software are required for future competitions. While the organizers cannot know or provide information for all packages that competitors may use, information regarding the sample solution packages should be refined and provided. Clear instructions to transfer the simulator to a drone should be available in the future to reduce integration difficulties and shift more focus to the solutions. Some participants have suggested that presentation videos explaining underlying concepts, rather than just example code, may be helpful and allow a broader range of competitors to participate. Additionally, a review of the simulator needs to be performed so that it represents real-world conditions more accurately. Issues such as a different camera used in the simulation compared to the in-person final could be easily fixed by ensuring settings before deploying the software. The simulator should also incorporate processing limitations due to the drone's limited capabilities. Furthermore, ensuring the smooth transition between simulator and in-person stages will reduce the time per team for preparing and running their solutions, increasing efficiency and reducing the cost of hosting the competition. In addition to these individual lessons, the authors recommend that competition hosts test the distributed software, their instructions, and workflow on various computer setups to verify that they are understandable, complete, and functional. Having beta testers sample competition material can mitigate some of the difficulties faced by competitors even before the first iteration of such a competition.

Improving Scoring and Challenges

Improvements to the scoring system and challenges are required to ensure that the competition evaluates competitors fairly and in line with objectives. A simple scoring system based on the approximate distance of the drone from the rover was used. The system led to penalties searching for the rover at different parts of the competition area led to different penalties, with advantages for drones that stop in the middle of the competition area rather than a corner. This results from the maximum distance a rover can get from a drone being higher in non-central locations. A solution to this problem would be to apply penalties on the score based on the distance traveled by the rover since the last time the drone tracked the rover.

Additionally, during the competition, less robust solutions outperformed better solutions in the static environment. BioRobotics' control algorithms worked well because of the information gathered during the test phase. Increased complexity and unique yet equivalent trials can force competitors to develop more robust solutions by adding additional unknowns to the competition task. Examples include varying the height and shape of the tunnel, changing the location of the buildings, and changing the rover's paths from practice runs to score runs, which can be used to test for robustness in solutions.

Submission Rate

Another issue encountered during the competition was the low submission rate from registered teams. While 13 teams registered, only four teams provided solutions, with only three of those solutions being viable. This was an issue that the authors suppose could have been caused primarily by two issues.

First, the tasks demanded by the competition were difficult. Not only were teams expected to use computer vision to identify and track a moving rover, they were also expected to control a flying drone based on the vision input alone. While some students may be expected to accomplish these tasks, many may not be able to without significant study. Second, while teams were able to compete with their own drones, the qualifying simulator stage was built in Gazeboand configured to run with specific software. Hence, not only were teams expected to be able to perform the already difficult competition task, but they were also expected to perform these tasks in a very specific software environment which they may not have been familiar with.

Constant delays in the production of the simulator environment exacerbated this issue as teams were left with only two months to learn, use, and qualify for the competition using the simulator. Several software bugs and compatibility issues compounded this problem.

While related to the high attrition among registered teams, the authors felt that the organizers could have promoted the competition better by posting information about the competition on additional channels and distributing this information through the institutions of potential competitors, and at relevant conferences. Increased promotion may have improved the turnout and output of the competition.

From these experiences, the authors suggest that competitions, especially those targeted towards undergraduate students, be limited in scope such that barriers to entry be reasonable for students who may not be able to dedicate significant amounts of time to the competition or who may not have the combination of skills required to participate. For example, this competition could have focused solely on the control of the drone based on input from a predeveloped computer vision system. Additionally, having a more flexible and open competition where participants did not need to use the simulator and software provided by the hosts could have allowed participants who were capable but not familiar with the competition's preferred software to compete. However, doing so introduces other variables that can imbalance the competition. In summary, the competition's submission rate likely could have benefited from narrowing the scope of the competition or increasing the flexibility of entries.

Value of the Competition

While the 2023 IEEE DCC may not have generated novel developments in path planning, object detection, or command and control algorithms, the competition resulted in learning experiences for the participating competitors and the opportunity to use some of the unique equipment available at PURT. Competitors mentioned that they had learned new technical skills due to participating in learning different software and algorithms commonly used in robotics and UASs. In addition, soft skills were also developed as team members from each team worked in sub-teams specializing in specific tasks required of the entire solution and collaborating to integrate all their work into the final solution. In the case of all three finalist teams, individuals from different backgrounds, majors, and stages in their studies or careers were involved, promoting collaboration and cooperative learning. Participants mentioned how the competition provided them with a venue and means to learn more about the challenges related to UAS and provided motivation to learn more about the subject.

From the host's perspective, the competition, which was primarily organized and run by students, provided practical experience in developing, organizing, and executing an international event. The educational value of hosting such events should not be overlooked by educators and institutions. Students at the host institution learned to coordinate with international participants, develop schedules, answer questions, and coordinate between stakeholders such as the university's risk management team, airport management, safety officials, and legal offices.

Based on these experiences, the authors believe that additional competitions should be hosted to foster not only the engagement of students and researchers in UAS issues, but in other aviation topics, as well. Competitions allow teams from various schools and organizations to participate in environments and contexts they may not otherwise be exposed to at their home institutions. Bringing together people from various backgrounds fosters additional learning and the potential for collaboration, while allowing institutions and students to compare their knowledge and output with others. This competition provided a unique experience for all its participants and the hosts to learn from, providing a tangible learning experience for all the students involved.

Figure 7

Competitors and Organizers of the 2023 IEEE Drone Chase Challenge at PURT

Conclusion

As autonomous UAS are introduced for various applications, additional development and research in computer vision, localization and mapping, and command and control will be necessary. Through competitions, progress in these fields will be fostered Using the capabilities available at PURT, the IEEE DCC, held since 2022, aims to provide an opportunity for researchers, students, and industry professionals to compete against others worldwide in developing integrated UAS solutions. In trying to achieve this, the competition organizers have found through the 2023 competition that software integration from simulator to real-world needs to be improved together with software documentation to improve the competition environment and focus on what matters most: developing better UAS algorithms and solutions. Furthermore, changes to the competition rules and scoring metrics are required to ensure that better, more robust solutions are rewarded over luck-based factors. Despite the issues faced, the 2023 IEEE DCC offered a learning experience for the competitors and hosts alike that will hopefully translate to further developments for the field in the future.

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