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Design, Build, and Fly Autonomous Lighter-Than-Air Vehicles as a Project-Based Class

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The ENGR-E 399/599 Autonomous Sports course at Indiana University was recently redeveloped to focus holistically on integrated vehicle design and development in a capstone-like, project-based course format. As part of the class, advanced undergraduate (3rd and 4th year) and graduate students (MS and PhD) developed autonomous lighter-than-air vehicle (LTA) vehicles (i.e., autonomous blimps) to compete in the ”Defend the Republic” (DTR) competition. In the competition, students aim to use their blimps to autonomously capture helium balloons and score them into the opponent's goals—effectively Robotic Quidditch. The challenge involves designing and controlling robot swarms that operate in challenging environments with limited sensing, actuation, and computation capabilities. Students work in teams, performing vehicle design, fabrication, prototyping, embedded development, systems engineering, feedback control, motion planning, and computer vision. The course provides students the opportunity to learn by applying their knowledge to real-world challenges, i.e., experiential learning, to "learn-by-doing", which is becoming universally recognized as crucial by educational institutions. This paper provides details on the course offering including a description of the student competition, course structure, student performance at DTR, and lessons learned.

I. Introduction

The Department of Intelligent Systems Engineering at Indiana University (IU) offers Bachelors, Masters, and Ph.D. degrees focusing on using technology, specifically computing, machine learning, and artificial intelligence, to create solutions at any scale. Recently, during the Fall 2023 semester, the ENGR-E 399/599 Autonomous Sports course offering was redeveloped to focus holistically on integrated aerial vehicle design and development in a capstone-like, project-based course format. Specifically, students were tasked with developing of autonomous lighter-than-air vehicle (LTA) vehicles (i.e. autonomous blimps) to compete in the inter-university "Defend the Republic" (DTR) competition.[1]

In the DTR competition, students aim to use their blimps to autonomously capture helium balloons and score them into the opponent's goals—effectively Robotic Quidditch. The challenge involves designing and controlling robot swarms that operate in challenging environments with limited sensing, actuation, and computation capabilities. Students work in teams, performing vehicle design, fabrication, prototyping, embedded development, systems engineering, feedback control, motion planning, and computer vision. A photo from the competition is shown in Fig. 1 with the 3 IU LTA vehicles.

The Autonomous Sports course is being offered to advanced undergraduate (3rd and 4th year) and graduate students (MS and PhD) and allows them to apply their engineering, physics, and mathematics knowledge from other courses to hardware in the lab. The courses also highly aligns with the Luddy School's (college's) strategic vision of providing students the opportunity to learn by applying their knowledge to real-world challenges,[2] i.e., experiential learning, to "learn-by-doing", which is becoming universally recognized as crucial by educational institutions. This paper will provide details on the revised offering of the Autonomous Sports course, which will hopefully help the broader aerospace educational community.

This paper is structured as follows: Section II presents the information on the Defend the Republic competition, including a breakdown of tournament structure, game rules, and vehicle design rules. Then, in Section III, the course

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structure is discussed, including details regarding how the project was broken down by task and functional team. Next, Section IV presents the IU team's performance at the November 2023 Defend the Republic competition. Finally, the paper conclude in Section V with lessons learned and student feedback that can be applied to similar project-based courses.

Figure 1: Indiana University DTR team's LTA vehicles (blue) navigating the game space during an match against Baylor University (red) with goal posts (yellow) and game balls (green and purple) in the background.

II. Defend the Republic Competition

The Defend The Republic (DTR) Competition consists of collegiate teams fielding their autonomous LTA vehicles to autonomously capture green and purple helium balloons and score them into the opponent's fluorescent yellow or orange goals. The scope of the challenge includes the physical architecture, sensor payload and design, software implementation, and cyber-physical development of the entire system. Designs are constrained by total buoyancy, limiting complexity, sensing capabilities, and overall computational power. Typical implementations include camera-based computer vision navigation with brushless motor propulsion. Basic nets are used for ball capturing and mylar balloons provide the lift for the vehicles.

Teams typically compete at a hosting university twice per year to compete in a round robin or bracket tournament and demonstrate their LTA vehicles and technologies. The Fall 2023 DTR competition was hosted by Lehigh University at their Mountaintop Campus from November 13 to 17. Teams participating in DTR included Baylor University, Drexel University, George Mason University, Indiana University, Lehigh University, University of Florida, Virginia Tech University, and West Virginia University. Teams are typically structured as either faculty-led research laboratories with graduate and undergraduate student teams and/or with senior (4th year) undergraduate capstone students.

A. Tournament Structure

The competition is structured with a predefined schedule for each team with several games. Each team is then paired with their closest competitor for a final match to determine the final rankings. In the case of a tie, the team with the most total points across all the games wins.

B. Game Rules

Each game has two 30 minute halves and 30 minute halftime. During each 30 minute half, there are six 5 minute intervals, with 30 seconds of manual blimp control, and 4.5 minutes for autonomous flight. In order to score points, teams must capture and score balls through goals placed on opposite ends of the field. Teams advance by scoring the most points during a game, with different point values based on the level of autonomy used to complete a task. Capturing and scoring the ball with uninterrupted autonomy is worth 10 points. Autonomous capture of a game ball, without scoring is worth 1 point. Scoring a goal manually is worth 1 points. And intentionally passing a ball between vehicles is worth 10 points.

The playing field consists of two sets of three uniquely shaped goals hung from the roof of the competition space at either end. Each set of goals have one triangle, square, and circle in either yellow or orange. The circle has an interior diameter of 36.5 inches, and an outer diameter of 44.5 inches. The square has an inside leg length of 38 inches, with there outside length being 46 inches. The triangular goal is an equilateral triangle hung upside down, with the total height from base to tip being 55 inches. The goals are made from plywood and retro-reflective tape in order to enhance visibility. Fig. 2 presents a two-dimensional birds-eye diagram of a DTR match.

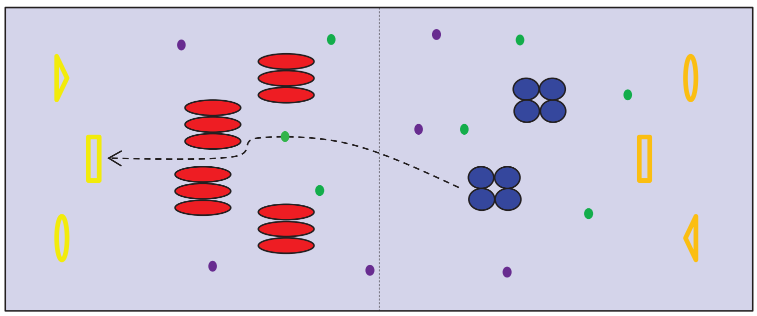


Figure 2: Birds-eye view representation of a DTR match layout.

C. Vehicle Design Rules

Vehicle design rules constrain the helium usage, overall weight, and capture mechanisms that each LTA may have. Teams are allotted 200 cubic feet of helium to inflate their entire fleet for the week of competition. Each vehicle must have a buoyant weight of no more than 100 grams, i.e. the apparent mass on a scale with the balloons inflated. Additionally, each vehicle may not use more than 50 cubic feet of helium. Finally, all vehicles cannot use outwardly sticky adhesives for capturing objects in the game environment. All signals affecting the LTA must originate from within the control tent of the respective team, and the vehicle cannot sit at rest on the ground during autonomy.

III. Course Structure

Indiana University has for several years entered into the DTR competition a team that is composed of students from the ENGR-E 399/599 Autonomous Sports course. Historically, the course was run like a computer engineering lab course with with a relatively open-ended course structure, yeilding modest student engagement and team placement at the “Defend the Republic” competition.

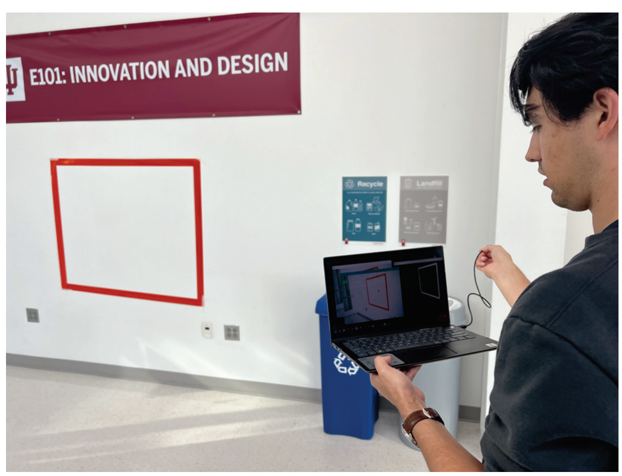
This past year the course was redeveloped as an integrated vehicle design or systems engineering project-based, capstone-like course. However, the challenge in this course redevelopment is that the majority of students are from the ISE degree program (akin to an application and systems-focused, computer engineering degree program) and from the computer science (CS) degree program. Therefore, the students lack a lot of prerequisite vehicle design and hardware knowledge that students in a vehicle capstone course would typically have (e.g. offered by a mechanical or aerospace engineering program).

However, from an educational perspective, quickly teaching students overview material that would alternatively be learned over semesters of traditional course may provide minimal information transfer and learning experience. Thus, the instruction style adopted for the course focused more on the students learning “how to learn”, to gain the information they needed. Specifically, they learned how to attain knowledge through traditional technical literature searches as well as online searches. Similarly, the students were gently nudged outside their comfort zone to learn new fabrication techniques and how to use new materials. In adopting this teaching philosophy, it was apparent that having students learn new information, techniques, etc. seemed to instill a sense of design flexibility, whereby for example, the first design they had in their head may not be the optimal choice (as they had previously thought).

Therefore, the class was split into 3 functional teams that all worked together to create an integrated vehicle and software design, i.e. a well developed Cyber-Physical System (CPS). The teams were (1) vehicle design; (2) sensing, control, and communications; and (3) computer vision. The vehicle team went through multiple rounds of iteration of design, construction, and testing to develop the LTA vehicle that would provide the necessary strength, be sufficiently buoyant, be able to capture multiple balloon targets, have propulsion controls allowing good control and movement agility, and of course, to support the energy, power, and mounting requirements for the hardware being supplied by the computer vision and sensing, control, and communications teams. The sensing, control, and communications and the computer vision teams likewise went through similar development iterations in their choice and testing of embedded boards, sensors, cameras, etc and simultaneously developed their software, making sure they were compatible with vehicle(s) being developed. Fig. 3 shows students working on various parts of autonomous LTA vehicle development.

(a)

(b)



(c)

Figure 3: Photos of student progress during various phases of development: (a) vehicle material selection, (b) vehicle development, and (c) computer vision development.

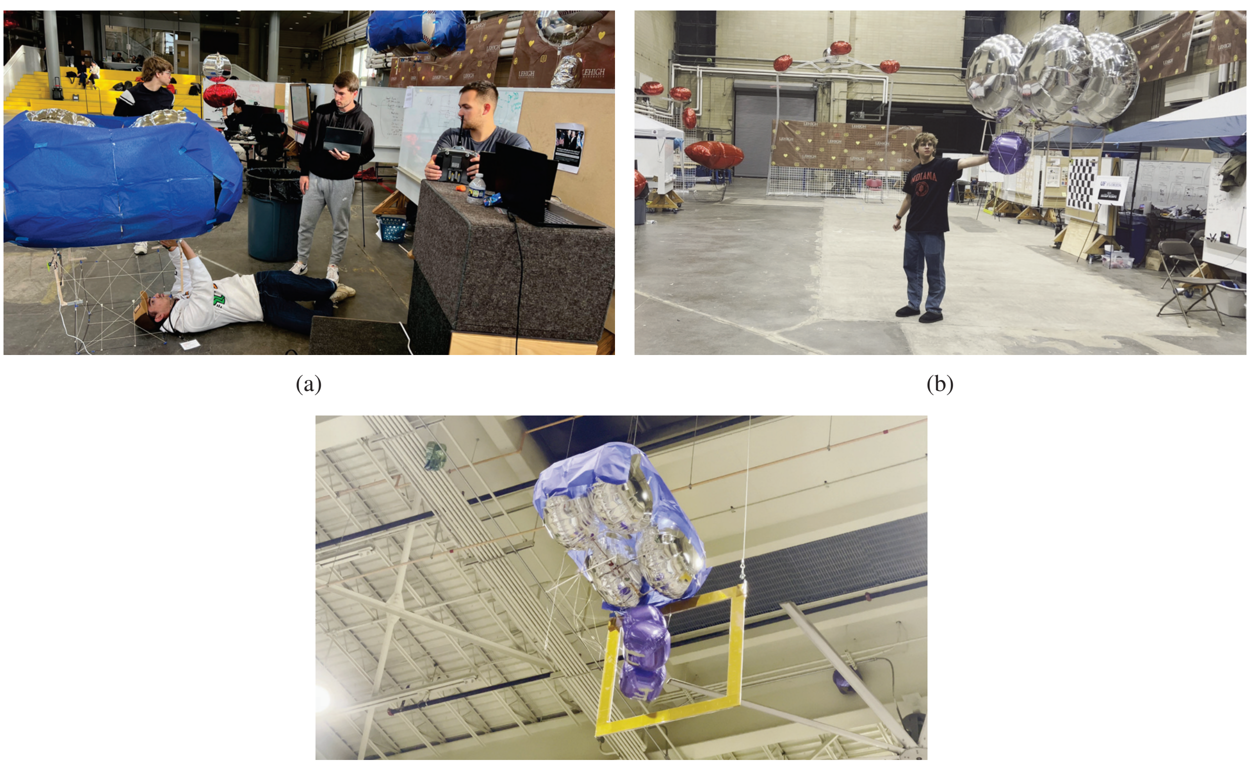
As with typical capstone courses, weekly check-in meetings were held with each of the teams to provide feedback and guidance as well as enable structured grading.

Certain systems engineering elements were also integrated into the course. For example, one of the lead students was appointed as a program manager to keep track of all student tasking. Due to the scale of the project and level of freedom allotted, students would often become stuck merely because they were waiting for someone else to finish a task even if it was not a dependency. Thus, this program manager student was assigned to manage overall schedule, task assignment, and personnel using a Gannt chart. This brought in a unique edge not seen in other “Defend the Republic” teams.

Another the unique aspect integrated into the course was students needing to requisitioning desired materials while mitigating supply chain limitations. Since the course had been redeveloped, most of the existing course materials available were not compatible with the proposed designs and implementations the students proposed. Therefore, a significant amount of vehicle frame, propulsion, computational, and vision components had to be purchased in real time. In order to accomplish the project within the semester and competition timelines, students were limited to what could be sourced, which also factored in their proposed designs and implementation. These constraints mirror the challenges faced by engineers working on short-term projects in industry, therefore providing an real-world educational experience.

IV. Competition Results

The ENGR-E399/599 Autonomous Sports class developed multiple LTA vehicles and several other prototypes over the course of the semester, which are detailed in related work.[3] The final vehicles, which were brought to the competition, all had common structure, propulsion, and control affector layout, which made the development of later aircraft easier. In order to create LTA vehicles that were competitive, the students competition needed to be technically strong yet highly-flexible to quickly adapt to change and succeed. Fig. 4 shows students performing additional development and adaptation of their LTA vehicles at the competition.



(a) (b) (c)

Figure 4: Photos of student progress during the ”Defend the Republic” competition: (a) avionics development, (b) control scheme tuning, and (c) scoring practice.

Two completed vehicles were brought to the competition with a handful of spare parts and frame parts, and during the competition, the team realized that a key to success would not only being able to score, but rather also being able to counter the other teams they were competition against. Thus, the Indiana University team designed and developed a 3rd vehicle at the competition venue — a ”Defense” vehicle using the common vehicle architecture previously developed, specifically to counter the strategies of the other teams competing. This was a demonstration of the learning and adaptive mindset repeatedly instilled over the semester. Figure 5 shows the ”Defense” vehicle successfully pushing multiple adversary team vehicles during a match.

Figure 5: The Indiana University onsite-built ”Defense” vehicle (red) pushes away multiple adversary team vehicles (blue) from the playing field.

Three final LTA aircraft were used by the Indiana University team at the ”Defend the Republic” competition: (1) an autonomous LTA vehicle,[3] (2) a completely manual LTA aircraft, and (3) the aforementioned ”Defense” vehicle, which was semi-open loop control.[4] During the competition, the team demonstrated technical strength, creativity, and highly adaptability, which led to the Indiana University team winning the Fall 2023 “Defend the Republic” competition in the round robin tournament, with 7 other collegiate teams.[5] A photo of the student team, faculty mentor/instructor (paper author), and scoring vehicles is shown in Figure 6.

Figure 6: Indiana University ”Defend the Republic” team photo with scoring vehicles in background.

V. Lessons Learned

Over the course of the Fall 2023 ENGR-E 399/599 Autonomous Sports course and through November 2023 Defend the Republic competition, several important realizations were made:

- **Vehicle Design Iterations:** The course allowed students to make several iterations of their LTA vehicles over the semester. About a dozen concepts were initially explored by the vehicle design team, with several concepts being tested, and finally one being chosen and built. These design iterations also affected the sensing, control, and communications team and the computer vision team. Allowing students to conceive and test several concepts provided them real-world education on design, specifically that design is not finite, but rather improves with iterations and also has downstream impacts.
- **Flexible Mindset:** The DTR competition demonstrated the advantage of teaching students to be flexible and adaptive to their conditions. By adopting a flexible mindset, the IU team was able to quickly adapt to the challenges presented at the competition and ultimately win.
- **Course Structure:** Students sometimes struggled with the lack of direct course structure presented over the semester. Unlike a typical course with rigid assignments and clear desired outcomes, students were given lots of flexibility in their design process with gentle weekly nudging by the instructors. Some students flourished while others struggled. Upon presenting the students a survey at the end of the semester, students were split between maintaining the current flexibility and requesting more structure.
- **Time Management and Planning:** Due to the nature of the starting off with a clean sheet design and having to requisition most components and materials in real time, students learned about real-world design constraints faced during a short term project. This aspect also presents the question of how the course should be structured in the future - supply chain limitations, design iteration cycles, and unknown development timelines, not only impacted and challenged the students but also affected the course schedule, which the instructors had to continually modify.

References

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[3] Taylor, C. and Dantsker, O. D., "Lighter-Than-Air Vehicle Design for Target Scoring in Adversarial Conditions," AIAA Aviation Forum 2024, Las Vegas, Nevada, Jul. 2024.

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