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Enhancing Experiential STEM Learning in Secondary Schools: Utilizing the Tadpole Unmanned Aerial System as a Modular Educational Tool

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This paper presents the development and initial implementation of a high-school outreach program centered on the Tadpole lighter-than-air unmanned aerial system (LTA UAS), a low-cost, modular educational platform designed to introduce secondary-school students to aerospace engineering, robotics, and autonomous systems. The program extends Indiana University's collegiate Defend the Republic (DTR) autonomous blimp competition into a developmentally appropriate high-school format, allowing students to build, configure, test, and operate indoor aerial vehicles in a safe, low-speed environment. The Tadpole kit mirrors the major subsystems of collegiate autonomous LTA vehicles while reducing system complexity, enabling students to engage with vehicle architecture, buoyancy, propulsion, embedded control, wireless communication, and iterative design. The paper describes the Tadpole platform design, kit components and cost considerations, guided assembly resources, and pathway from manual operation toward assisted and autonomous flight. It also presents the high-school DTR competition structure, including navigation, lift-and-deliver, and wrecking-ball-style challenges, and connects these activities to engineering design, physical science, and computational thinking standards. Initial outreach outcomes from events held in November 2024 and February 2026 indicate that the platform is feasible for recurring high-school STEM engagement, with 49 total participants across multiple schools and learning environments. Informal feedback suggests strong student interest in continued participation, while early implementation highlighted the need for additional flight practice time, structured pre-competition preparation, and formal assessment instruments. By documenting the Tadpole LTA UAS kit and high-school DTR model, this work provides a scalable framework for connecting K–12 STEM outreach with advanced collegiate autonomy education.

I. Introduction

The Department of Intelligent Systems Engineering at Indiana University (IU) offers undergraduate and graduate degree programs that emphasize the application of computing, machine learning, artificial intelligence, and systems engineering to real-world challenges. As part of its broader effort to develop student expertise in real-time autonomous systems, the ENGR-E 399/599 Autonomous Sports course was recently redeveloped into a capstone-like, project-based experience centered on the design, fabrication, and deployment of autonomous lighter-than-air (LTA) aerial vehicles.[1,2] In this course, student teams design and operate autonomous blimps for the inter-university Defend the Republic (DTR) competition.[3,4]

The collegiate DTR competition provides an engaging and technically challenging environment in which teams field autonomous LTA vehicles in a robotic, Quidditch-inspired game. Vehicles must navigate the arena, capture helium-filled game objects, and score them in opposing goals while operating under practical constraints on sensing, actuation, computation, and real-time decision making. As a result, the competition requires students to integrate concepts from vehicle design, fabrication, embedded systems, feedback control, motion planning, computer vision, and systems engineering. Figure 1 shows an example of the DTR competition, where IU LTA vehicles are competing against Baylor University vehicles during a match.

The Autonomous Sports course serves as an advanced experiential-learning opportunity for upper-level undergraduate and graduate students, allowing them to synthesize engineering, physics, mathematics, and computing knowledge through the implementation of real aerial robotic systems. This learning model aligns with the Luddy School's emphasis on experiential education by enabling students to learn through authentic design, testing, and competition.[?] However,

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Figure 1. Indiana University's DTR LTA fleet (blue) autonomously navigating during a collegiate DTR match.

while the collegiate DTR challenge successfully supports university-level design learning objectives, its long-term educational impact can be strengthened by introducing related engineering concepts earlier in the student pipeline.

To address this need, IU has developed a complementary high-school implementation of DTR designed to serve as an accessible first point of engagement for pre-university learners. This outreach effort adapts the core elements of the collegiate competition into a developmentally appropriate, standards-aligned format for secondary-school students. Rather than requiring students to begin with fully autonomous, research-grade systems, the high-school version emphasizes foundational aerospace and robotics concepts, including vehicle assembly, buoyancy, propulsion, control, sensing, teamwork, and iterative design.

Central to this initiative is the Tadpole LTA UAS: a cost-effective, modular unmanned aerial system platform engineered for inquiry-driven STEM learning. The Tadpole kit enables high-school students to build, configure, and operate functional indoor aerial robots within a constrained and safe environment. Through this process, students gain practical exposure to vehicle design, actuator and sensor integration, guided teleoperation, and potential extensions toward autonomy. These activities connect directly to high-school engineering and technology learning objectives while promoting engineering identity, confidence, and readiness for post-secondary STEM pathways.

To reinforce these learning objectives, IU is planning to host high-school DTR competitions annually. These events provide authentic design challenges that parallel the collegiate DTR experience while remaining appropriate for introductory learners. By working in teams to construct vehicles, test design alternatives, and compete in structured mission tasks, students engage in creative problem solving, real-time decision making, and the engineering design process.

This paper presents the design, implementation, and evaluation of the high-school DTR program. Specifically, it describes the Tadpole LTA UAS education kit, the high-school competition rules and mission structure, curriculum alignment with engineering and technology standards, and outcomes from the November 2024 and February 2026 high school DTR outreach events. By documenting this vertically integrated educational model, the paper contributes a scalable framework for connecting K–12 STEM outreach with advanced collegiate autonomy education and for strengthening the future engineering talent pipeline.

This paper is organized as follows: Section II introduces the Tadpole LTA UAS education kit, including its design requirements, vehicle architecture, component-level cost breakdown, student assembly process, build documentation, and progression from manual control toward assisted and autonomous operation. Section III describes the high-school Defend the Republic competition format, including the mission challenges, rules, and learning objectives that structure the student experience. Section IV presents the curriculum alignment between the Tadpole/DTR activities and relevant high-school engineering, physical science, and computational thinking standards. Section V summarizes the outcomes of the first two high-school DTR outreach events that occurred in November 2024 and February 2026. Finally, Section VI concludes the paper with a summary and future work.

II. Tadpole LTA UAS Education Kit

The Tadpole lighter-than-air unmanned aerial system (LTA UAS) education kit was developed to provide an accessible entry point into autonomous aerial systems for secondary-school students. The kit is intended to support the high-school implementation of the Defend the Republic (DTR) educational ecosystem by enabling students to build, configure, test, and operate a functional aerial robot in a safe, low-speed, indoor environment. In contrast to conventional multirotor aircraft, the lighter-than-air vehicle architecture substantially reduces kinetic-energy risk while still exposing students to authentic aerospace and cyber–physical system concepts, including buoyancy, propulsion, actuation, control, sensing, wireless communication, and iterative vehicle design.

The Tadpole platform was intentionally designed to mirror the major subsystems of the collegiate DTR vehicles[5–8] while remaining appropriate for high-school outreach activities. In this way, the kit serves as a scaled and scaffolded version of the university-level autonomous blimp platform: students encounter the same broad system categories–airframe, lift generation, propulsion, embedded computation, software, and mission-specific mechanisms–but at a level of complexity suitable for introductory STEM engagement. A representative assembled Tadpole vehicle is shown in Fig. 2.

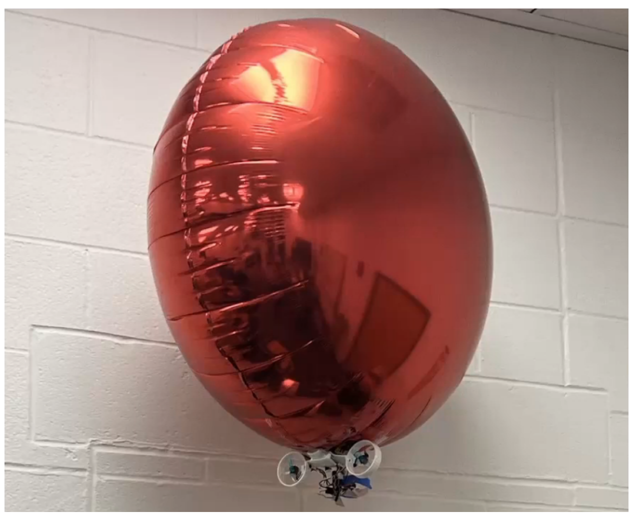

Figure 2. A photo of a full assembled Tadpole LTA UAS.

A. Design Requirements and Educational Objectives

The Tadpole kit was developed around four primary design requirements. First, the vehicle must be sufficiently low cost to allow multiple high-school teams to participate with modest outreach or classroom funding. Second, the vehicle must be safe and robust enough for repeated indoor operation by novice users. Third, the kit must be modular, allowing students to modify or extend selected subsystems without requiring a complete redesign of the aircraft. Fourth, the system must provide a pathway from manual operation toward assisted or autonomous behaviors, thereby supporting a progression from introductory vehicle operation to more advanced computing and control topics.

These engineering requirements are directly connected to the educational goals of the high-school DTR program. Through the kit, students are expected to practice the design–build–test cycle, identify system-level constraints, evaluate trade-offs among mass, stability, maneuverability, and payload capability, and connect design choices to measurable competition outcomes. The platform also supports later curricular alignment with engineering design standards by giving students an authentic artifact around which they can define criteria, decompose subsystems, test alternatives, and justify design decisions.

B. Vehicle Architecture

The baseline Tadpole vehicle consists of a lightweight mylar envelope, a 3D-printed structural frame, propulsion units, a lift fan, an embedded controller, a battery, and optional sensing modules. The mylar envelope provides buoyant lift, while the frame serves as the central mounting structure for propulsion, electronics, and mission-specific attachments. A differential-drive propulsion configuration provides horizontal maneuvering, and an additional lift fan enables vertical control authority. This configuration allows students to observe how thrust, drag, buoyancy, mass distribution, and actuator placement affect vehicle response.

The embedded control system is built around an ESP32-S3 miniature computer with integrated Wi-Fi and Bluetooth capability. This controller provides a low-cost interface for motor commands, wireless communication, and future sensing extensions. Optional sensors, such as an inertial measurement unit (IMU) and barometer, may be incorporated to support assisted-flight or autonomous behaviors. The baseline configuration emphasizes reliable manual control, while the extended configuration enables students and mentors to introduce topics such as sensor feedback, state estimation, altitude control, or rule-based autonomy.

C. Kit Components and Cost Accessibility

A central motivation for the Tadpole platform is cost accessibility. The kit uses commercial-off-the-shelf components where possible, combined with 3D-printed structural parts that can be fabricated using common educational makerspace equipment. This approach reduces the per-vehicle cost relative to many aerial robotics platforms while preserving meaningful student interaction with both mechanical and electrical subsystems. Table 1 summarizes the baseline bill of materials, including components, quantity, and unit cost. 3D-print files have been made available to other schools and outreach programs.

Table 1. Tadpole LTA UAS kit component and cost breakdown (as of January 2025).

Component	Qty.	Cost Each [USD]
Mylar balloon	1	5
3D-printed frame	1	5
ESP32-S3 controller	1	8
BetaFPV 1102-18,000kV motors	3	11
Gemfan 2015 props	3	2
FLASH Hobby 7A ESCs	3	12
1S 750mAh Lipo Battery	1	4
Wiring and connectors	1	6
USB charger	1	3
USB cables and hub	1	13
XBox controller	1	27
Total	–	146

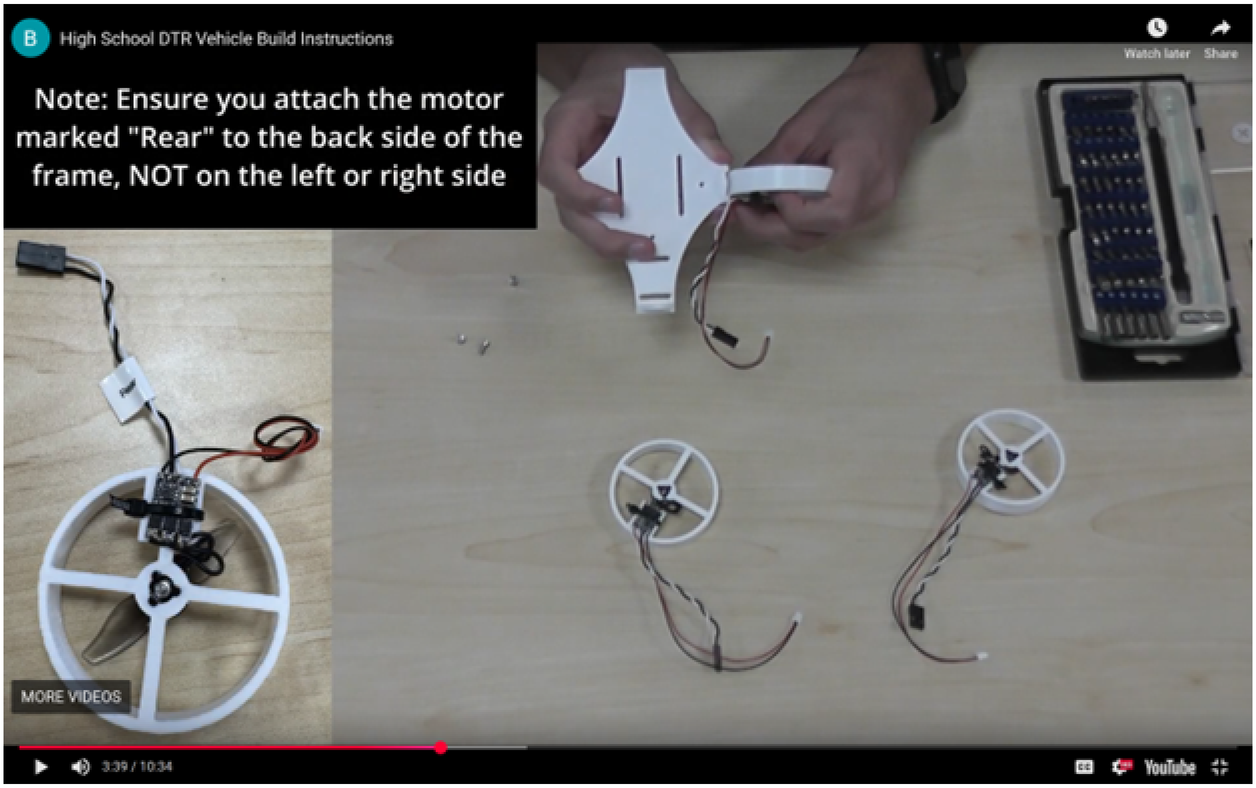

Figure 3. Screenshot from the Tadpole LTA UAS build-instruction YouTube video used to guide high-school students through kit assembly.

D. Kit Assembly and Build Video

The Tadpole kit is designed to be assembled by high-school students using guided documentation and mentor support. The build process includes frame preparation, actuator mounting, wiring, controller installation, battery integration, balloon attachment, software flashing, and initial system checks. This sequence allows students to encounter the vehicle as an integrated engineering system rather than as a preassembled product.

To reduce the burden on teachers, parents, and outreach volunteers, the kit is supported by step-by-step video instructions. These materials show students how to assemble the vehicle, connect the electronics, attach the balloon envelope, and prepare the system for flight. A screenshot from the instructional video sequence is shown in Fig. 3.

E. Manual Control, Assisted Flight, and Autonomy Pathway

The baseline Tadpole system supports manual operation so that students can quickly connect vehicle design decisions to flight behavior. Manual flight is especially valuable during early outreach events because it provides immediate feedback: students can observe how changes in vehicle trim, payload mass, fan orientation, or effector design influence maneuverability and stability.

The same hardware platform also provides a pathway toward assisted and autonomous operation. With the addition of onboard sensing (e.g. using a BNO-055 IMU and BMP-280 barometer ESP32 backpack), students may explore feedback-based behaviors such as heading stabilization, altitude regulation, or simple mission sequencing. These extensions are not required for initial high-school participation, but they allow the Tadpole platform to scale with student experience and teacher resources. This progression from manual operation to autonomy mirrors the broader DTR educational pipeline, in which introductory high-school activities prepare students for more advanced university-level work in embedded systems, controls, perception, and autonomous vehicles.

III. High School Competition Format

To translate the collegiate Defend the Republic experience into a scalable and developmentally appropriate K–12 format, the high-school competition focuses on three core mission challenges. Each challenge emphasizes one or more foundational aerospace and cyber–physical learning objectives while ensuring safe and engaging game play. Collectively, they promote operational competency, system design iteration, spatial awareness, and fundamental principles of force and motion.

A. Navigation Challenge

The Navigation event evaluates the controllability of student-designed Tadpole UAS platforms by requiring teams to traverse a three-dimensional obstacle course under time pressure. A series of vertical poles and soft structures, positioned at heights between approximately 3 and 8 feet, define a five-point slalom-style trajectory. Teams must complete the course as rapidly as possible while avoiding collisions with both obstacles and arena boundaries. To penalize imprecise control, each obstacle or boundary contact incurs a three-second time penalty, encouraging stability, actuator tuning, and pilot skill development. This event reinforces concepts of thrust vectoring, aerodynamic drag, and dynamic response in light indoor flight environments.

B. Lift and Deliver Challenge

The Lift and Deliver event introduces introductory manipulation and task-level planning. Teams are provided with ten soft foam "X-shaped" game elements stored at a ground-level depot. Within a three-minute match period, students must attach and transport as many elements as possible to an elevated target container approximately 8 inches in diameter and positioned 1-2 feet above the ground. Success in this challenge rewards careful control of lift margins, mass distribution, and simple grasping or attachment mechanisms. The task fosters an understanding of payload constraints, mission optimization, and the interaction between vehicle performance and structural design decisions.

C. Bowling / Wrecking Ball Challenge

The third event incorporates a playful but educationally meaningful test of kinetic interaction. Each Tadpole system includes a below-hanging effector—a lightweight mechanism constrained to remain within specified dimensional limits to ensure safety and fairness. Teams must navigate their vehicle down an 8-foot-long "alley" to displace as many upright game elements as possible using the swinging or glancing motion of the effector. This challenge encourages experimentation with momentum transfer, pendular dynamics, and precise trajectory control in confined spaces, reinforcing STEM concepts in an intuitive physical format.

Together, these mission elements structure the high-school Defend the Republic competition as a progressive design-learning experience: students observe the influence of their mechanical and software choices on measurable scoring outcomes, perform rapid iteration between match rounds, and gain practical exposure to the engineering design cycle within an engaging robotics context.

IV. Curriculum

Studies suggest that real-world experiential learning reinforces understanding in advanced STEM topics by situating abstract concepts within authentic problem-solving contexts. Similar to previous work that have generate real-world learning experiences in a challenge format,[9–13] the Tadpole LTA UAS platform was intentionally designed to support alignment with the Next Generation Science Standards (NGSS), particularly within the Engineering Design (HS ETS1-1, HS-ETS1-2, and HS-ETS1-3) strand,[14] while also enabling extensions into physical science and computational thinking domains.

For each of the following standard intrinsic to the Tadpole platform/Challenge model, activities within the challenge that directly align with the standard are listed. Further, potential deliverables that assess that standard are also recommended.

A. HS-ETS1-1.

Analyze a major global challenge to specify qualitative and quantitative criteria and constraints for solutions that account for societal needs and wants. Students begin by analyzing each of the competition challenges (Navigation, Lift and Deliver, and Wrecking Ball) as constrained engineering problems. For each challenge, they must:

- Identify performance criteria which could include maneuverability, payload capacity, or scoring efficiency
- Define constraints which could include weight, safety limitations, and competition rules

Students may work in teams to outline these criteria and constraints in the form of a design review. They could also deliver extended criteria and constraints for effectors that are needed to be designed/added to the vehicle (Lift and Deliver and Wrecking Ball).

B. HS-ETS1-2.

Design a solution to a complex real-world problem by breaking it down into smaller, more manageable problems that can be solved through engineering.

For these challenges, the students must break down the overall UAV system into manageable subsystems. These can be articulated initially during the building/construction phase. Subsystems include:

- Structural frame and buoyancy system
- Propulsion and movement
- Control interface (manual or autonomous, if applicable)
- Payload/effector mechanisms

Students may work in teams to iterate designs/prototypes for a specific subsystem (e.g., the lift effector in Lift and Deliver) before integration with the structural frame. Subsystem design and integration plans would be valid deliverables.

C. HS-ETS1-3.

Evaluate a solution to a complex real-world problem based on prioritized criteria and trade-offs that account for a range of constraints, including cost, safety, reliability, and aesthetics as well as possible social, cultural, and environmental impacts.

For each challenge, students evaluate their designs through test/redesign cycles. These tests have measurable outcomes such as:

- Timed trials in the navigation course (Navigation)
- Payload delivery success rates (Lift and Deliver)
- Efficiency in object displacement (Wrecking Ball)

Once these outcomes are understood, students can evaluate design decisions based on tradeoffs such as:

- Lift vs. payload mass
- Stability vs. maneuverability
- Simplicity vs. functionality of effectors

Test logs or documentation of these tests, as well as reflection on how tradeoffs affected the outcomes and final design, would be appropriate deliverables.

The Tadpole Kit/Challenge model also offers flexibility for adaptation to other standards or NGSS domains. Below are several standards that would work well within the kit design.

D. HS-ETS1-4.

Use a computer simulation to model the impact of proposed solutions to a complex real-world problem with numerous criteria and constraints on interactions within and between systems relevant to the problem.

Students could integrate sensor-based feedback (e.g., IMU data) that could support trajectory prediction or motion planning of the UAV's path. Students could develop simulations of drone path-planning models and validate them with measurable sensor data, for example.

Beyond engineering design, the Tadpole system naturally reinforces key physical science principles:

E. HS PS2 (Motion and Stability: Forces and Interactions) and HS PS4 (Waves and Information Transfer).

Concepts such as thrust generation, drag forces, force balancing, and wireless communication are embedded in this platform. Complementary activities that strengthen conceptual retention could be generated alongside existing lessons.

F. Computational Thinking and Technology Extensions.

The Tadpole platform also supports integration with computer science standards through programming a microcontroller, acquiring and analyzing data from onboard sensors, and implementing autonomous or rule-based control. These activities align with broader STEM competencies in algorithmic thinking, debugging, and system integration.

The Tadpole platform offers an opportunity for pre-collegiate students to hone key engineering and STEM-related skills in a measurable but engaging way. The platform is also designed for versatility such that it can be used co-curricularly as a real-world application of many theoretical concepts in core math, computer science, and physics classes.

V. Outreach Event Outcomes

The first high-school DTR outreach event was held in November 2024 and included 27 students from local South and Central Indiana high schools including: Bloomington High School North, Bloomington High School South, Loogootee High School, and Washington Catholic High School. The event served as an initial implementation of the Tadpole LTA UAS platform in a competition-based outreach setting, allowing students to assemble, operate, and compete with their vehicles in a structured environment. Overall, the event was well received by participants. Informal feedback indicated that students were interested in participating in similar activities again, suggesting that the DTR format was successful in generating engagement and enthusiasm for hands-on aerospace and robotics activities. Participants also noted that additional flight practice time would have improved the experience, as some challenges were difficult to complete due to the abbreviated time available for vehicle control practice.

Although formal assessment data was not collected during the initial event, several follow-on indicators suggest that the outreach model had a positive impact. One participant from the November 2024 drone event later enrolled at Indiana University in the Department of Intelligent Systems Engineering, and another participant registered for the follow-up DTR workshop held in February 2026.

The February 2026 event included 22 participants representing five schools and learning environments: Bloomington High School South, Edgewood High School, Spring Valley High School, Owen Valley High School, and homeschool participants. Together, these first two events demonstrate the feasibility of using the Tadpole LTA UAS platform as a recurring outreach activity for high-school students. They also highlight several areas for improvement in future events, including increased time for driving and flight practice, more structured pre-competition training, and the development of formal pre- and post-event assessment instruments to evaluate student learning, confidence, and interest in engineering pathways.

(a)

(b)

Figure 4. Photos from the (a) November 2024 and (b) February 2026 high school DTR events hosted at Indiana University

VI. Summary and Future Work

This paper presented the Tadpole LTA UAS education kit and its use as the foundation for a high-school implementation of the Defend the Republic outreach program. The platform provides a low-cost, modular, and safe indoor aerial robotics system through which students can engage with aerospace engineering, embedded systems, wireless control, vehicle assembly, and iterative design. By adapting the core structure of the collegiate DTR competition into navigation, lift-and-deliver, and wrecking-ball-style challenges, the program creates an accessible pathway for secondary-school students to experience authentic engineering problem solving. The first two outreach events, held in November 2024 and February 2026, engaged 49 total participants across multiple schools and learning environments and demonstrated the feasibility of using the Tadpole platform as a recurring high-school STEM activity.

Future work will focus on improving both the technical and educational implementation of the program. Event structure will be refined to provide students with additional flight practice, more structured pre-competition training, and clearer opportunities for design iteration before competition scoring. The Tadpole kit will also continue to be developed to support assisted-flight and autonomy extensions through onboard sensing, including IMU- and barometer-based feedback. In parallel, future outreach events will incorporate formal pre- and post-event assessment instruments to evaluate student learning, confidence, engineering identity, and interest in STEM pathways. These improvements will support continued expansion of the high-school DTR program and strengthen its role as a bridge between K–12 STEM outreach and collegiate autonomous systems education.

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