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TADPOLE: Tiny Autonomous Detection Platform for Off-Board Lightweight Edge-computing

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The deployment of autonomous capabilities on ultra-lightweight lighter-than-air (LTA) platforms is fundamentally constrained by a rigid trade-off between onboard computational power and available lift. Traditional autonomous architectures frequently rely on single-board computers that exceed the payload capacity of single-balloon vehicles, necessitating larger, multi-balloon configurations that compromise agility. This paper presents TADPOLE (Tiny Autonomous Detection Platform for Off-Board Lightweight Edge-computing), a novel systems architecture designed for the Defend the Republic (DTR) competition. TADPOLE utilizes a high-speed, low-latency UDP communication pipeline to offload computationally intensive vision processing and control logic to a centralized ground station, allowing the flight hardware to remain under a total mass of 75 grams. The system leverages an ESP32-S3 microcontroller to facilitate 10 Hz JPEG stream fragmentation and multi-modal telemetry acquisition. Experimental results demonstrate that this off-board provides stable autonomous navigation and target detection while preserving a significant buoyancy margin. This research validates a scalable pathway for high-level autonomy in SWaP-C constrained aerial swarms where individual vehicle cost and mass are minimized.

I. Introduction

As mission profiles for Unmanned Aerial Vehicles (UAVs) grow in complexity, these platforms increasingly require real-time autonomy to perform sophisticated obstacle avoidance, sustained navigation, and autonomous decision-making without reliable human oversight. This independence is especially challenging for lightweight aerial platforms operating in adversarial, dynamic environments with tight limitations on size, weight, power, and processing capability (SWaP-C). Traditional methods relying on GPS-based navigation and manual piloting often break down under these constraints, as observed in historical competitive frameworks.

The collegiate Defend the Republic (DTR) competition[1,2] provides a unique opportunity to explore these system design challenges by tasking teams with deploying lighter-than-air (LTA) UAVs that must autonomously locate, collect, and deliver neutrally buoyant goal balloons in a contested airspace.[3–12] Successful execution of these tasks requires robust perception pipelines, including vision-based object detection, which historically presents a significant engineering dilemma. While advanced machine learning techniques offer superior performance over traditional vision algorithms, their high computational cost typically necessitates an increase in the platform's power and weight capacity.[13]

For lighter-than-air vehicles, this perception-compute tradeoff is especially restrictive because the available lift margin is limited and directly coupled to vehicle maneuverability and endurance. Prior approaches have mitigated the computational demands of vision-based autonomy through onboard computing; however, physical implementations have often relied on quad-balloon configurations to support standardized compute hardware, power-regulation circuitry, and associated payload mass.[14,15] Although these software-driven architectures provide flexibility, they do not fully resolve the hardware-level challenge of deploying robust autonomy on the smallest viable LTA platforms.

A significant gap therefore remains: achieving vision-based autonomy on a single 36-inch Mylar balloon platform without compromising thrust-to-weight ratio, maneuverability, or flight endurance. Existing modular systems, while robust, also introduce larger cross-sectional areas that increase vulnerability to aerodynamic disturbances and defensive

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maneuvers encountered in DTR combat. Consequently, there is a critical need for a more integrated and minimalist hardware modality that reduces the onboard payload to the absolute minimum required for sensing, communication, and actuation.

To bridge this gap, this work introduces TADPOLE, the Tiny Autonomous Detection Platform for Off-Board Lightweight Edge-computing. TADPOLE deliberately shifts high-level perception and decision-making off board to a ground station server, preserving the flight dynamics of a single-balloon LTA vehicle. Rather than carrying heavy compute hardware, the onboard payload is reduced to a low-power, ultra-light sensing, communication, and actuation module based on the XIAO ESP32-Sense board. This board was selected for its compact form factor, image-capture capability, wireless communication support, and minimal onboard processing requirements.

In the proposed architecture, the ESP32 captures and transmits compressed image data to a ground station, where computationally intensive perception tasks are performed. The server processes the received data, calculates the required flight commands, and transmits those commands back to the vehicle for execution. While this introduces a dependency on the wireless communication link, it enables the use of computational resources far beyond what could reasonably be carried onboard, providing a capable perception pipeline without the associated mass, power, and cost penalties.[6] This approach builds upon existing research in reactive motion planning[16] and reinforcement learning for autonomous agents,[17] adapting these concepts to an ultra-low-mass hardware configuration.

This paper details the design and systematic evaluation of the TADPOLE off-board computation architecture. The system is assessed against key DTR mission requirements, including size, weight, power consumption, communication range, detection image size, and latency. The resulting platform demonstrates that strategic off-board computation can enable vision-based autonomy under a mass budget that would be infeasible for comparable onboard computing solutions. In doing so, this work establishes a design methodology for achieving high-level autonomy in severely SWaP-C constrained aerial platforms by balancing the risk of communication dependency against the substantial benefits of a minimal flight payload. Figure 1 displays the completed platform, nicknamed Tadpole.

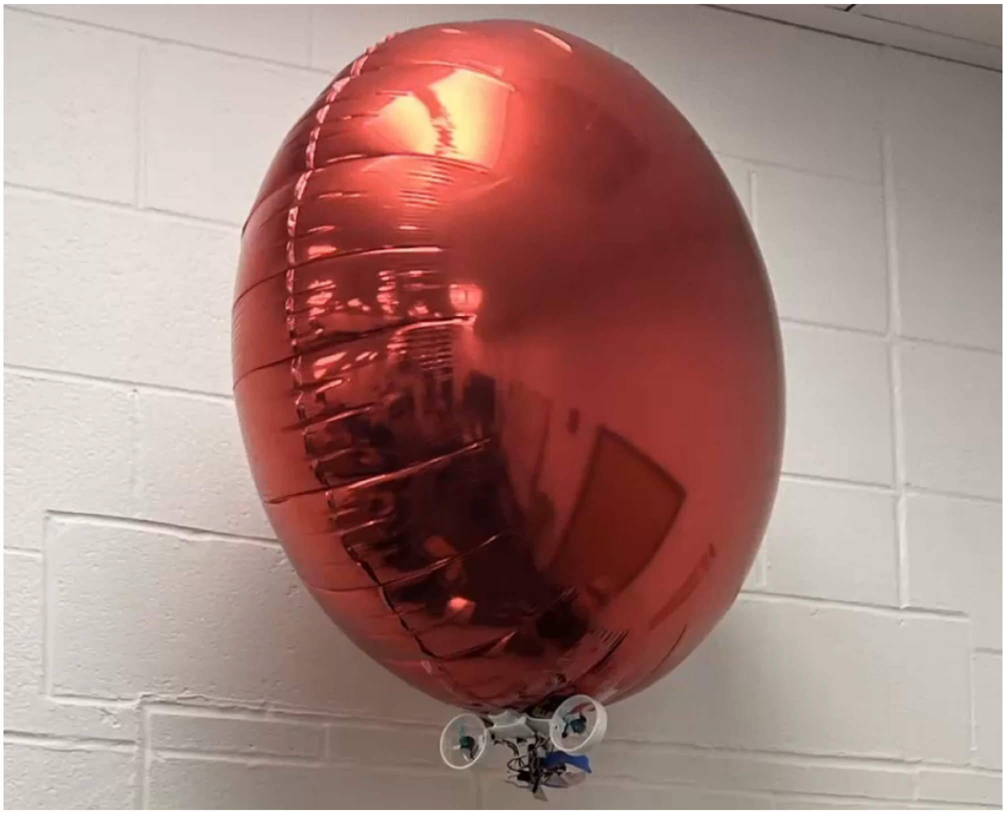

Figure 1. The 70 g TADPOLE LTA vehicle platform.

This work is organized as follows: Section II establishes the operational requirements and hardware constraints derived from the competition mission profile. Section III details the technical development of the TADPOLE platform, focusing on the custom low-latency communication stack and the integrated sensing suite. Section IV evaluates the experimental results, providing a quantitative analysis of system latency, mass budgeting, and flight stability. Finally, Section V summarizes the key contributions of this research and outlines future trajectories for swarm-based autonomy in lighter-than-air vehicles.

II. Requirements

The design requirements for the TADPOLE platform are dictated by the rules of the DTR competition and the physical constraints of LTA flight. These requirements are categorized into sensing, communication, and physical payload limitations to ensure compatibility with existing university fleets.[1,2]

A. Sensing and Perception Requirements

For effective state estimation, the system must acquire absolute orientation and relative altitude at a minimum frequency of 50 Hz. This data is essential for maintaining stability in the face of the nonlinear dynamics characteristic of blimp-style UAVs. Furthermore, the vision system requires a camera with a minimum horizontal field of view of 75° and a resolution of 320×320 pixels to ensure reliable target detection at ranges exceeding 5 meters.

B. Communication and Computation Constraints

A defining requirement of this architecture is the off-boarding of perception tasks. Consequently, the communication link must support a bidirectional, low-latency UDP stream with a reliable range of at least 50 meters to cover the competition arena. The bandwidth must be sufficient to maintain a 20 Hz down-link of JPEG-compressed images and binary telemetry. This frequency is derived from standard requirements for autonomous surveillance and reactive coverage.[16]

C. Physical and Economic Constraints

To maintain neutral buoyancy using a standard 36-inch Mylar balloon, the total flight payload—including batteries, sensors, and propulsion—must not exceed 80 grams, with a design target of $\leq$ 75 grams. This mass limit is significantly more restrictive than those of typical quadrotor platforms, necessitating the use of highly integrated micro-controllers over heavier single-board computers.[13] Finally, to support swarm research and fleet scalability, the total Bill of Materials (BOM) cost per unit must be strictly capped at $100 USD for practical reasons.

Table 1. TADPOLE System Requirements and References

Requirement Name	Target Specification	Source/Context
Sensor Acquisition Rate	$\geq$ 50 Hz	Navigation Stability[18]
Image Resolution (Min)	$\geq 320 \times 320$ pixels	Perception Accuracy[?]
Transmission Link	UDP $\geq$ 50 m Range	DTR Arena Rules[2]
Minimum Linear Speed	$\geq$ 2 m/s	Competition Agility
Maximum Flight Time	$\geq$ 5 minutes	Mission Profile[19]
Payload Capacity	$\leq$ 75 grams	Single-Balloon Lift
Kit Total Cost (BOM)	$\leq$ $100 USD	Fleet Scalability

III. Development

The technical development of the TADPOLE platform centers on a top-down systems engineering methodology where the central processing unit's capabilities dictate the integration of all auxiliary sensing and propulsion subsystems. By prioritizing a minimal physical footprint and high-performance wireless throughput, the architecture achieves a total flight-ready mass that remains compatible with the lift constraints of a single 36-inch mylar balloon. This development focused on the optimization of the sensor-to-server-to-actuator control loop, ensuring that the inherent latency of off-board computation does not compromise the stability of the vehicle's lighter-than-air dynamics. A photo of the developed TADPOLE platform that is attached to the mylar balloon is shown in Figure 2.

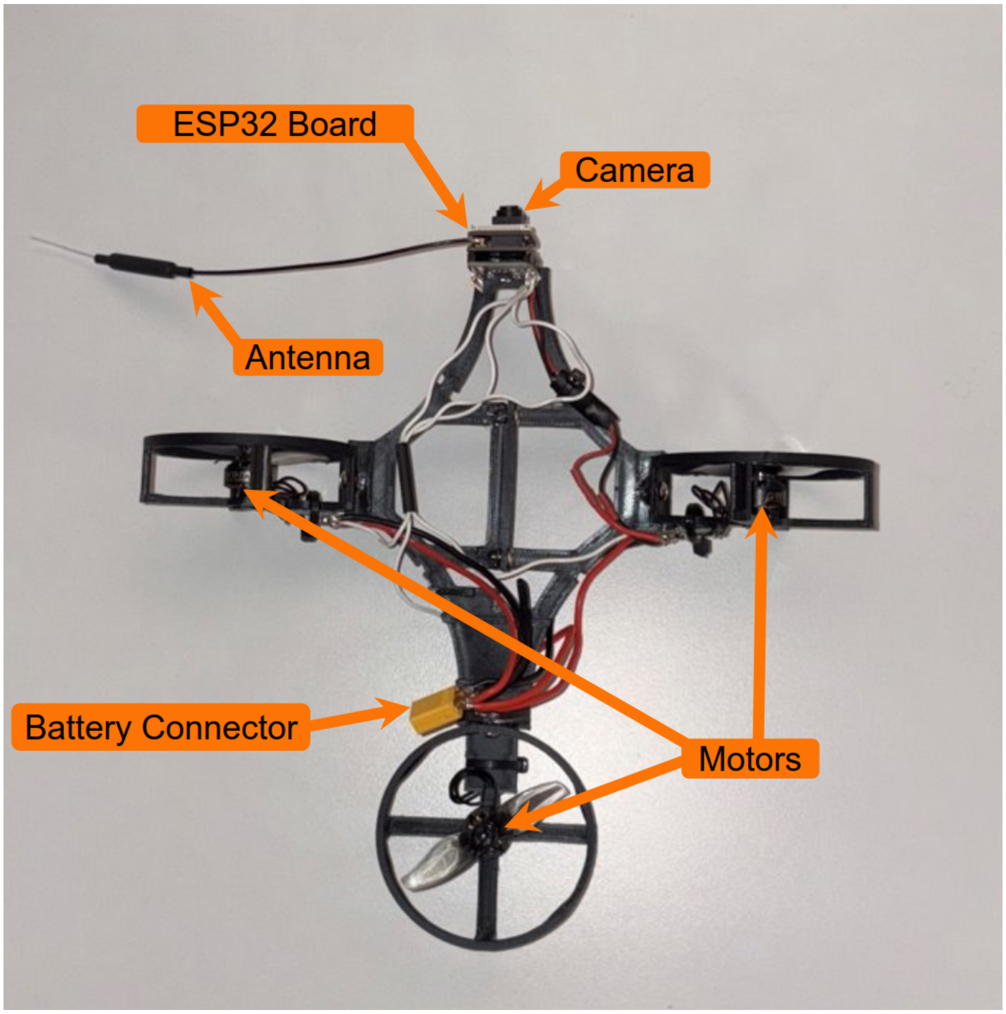

Figure 2. Top-down view of the experimental vehicle platform, not attached to mylar balloon.

A. Compute and Communication Hardware

The primary compute and communication hardware selected for this architecture is the Seeed Studio XIAO ESP32-S3 Sense, which serves as the consolidated node for image acquisition, inertial telemetry, and actuator command execution. This micro-controller is specifically chosen for its high frequency processing and large onboard memory size, which is essential for buffering high-resolution JPEG frames captured by the integrated OV2640 camera sensor. Unlike traditional Linux-based single-board computers, the ESP32-S3 operates on a real-time execution model that allows for near-instantaneous boot times and precise control over task scheduling. To support the platform's vision-based requirements, the hardware is configured to capture 320x320 pixel frames at a target rate of 10 Hz, providing a sufficient temporal resolution for ground-station detection algorithms while maintaining a manageable bandwidth footprint on the 2.4 GHz WiFi spectrum. Despite the high performance of the micro-controller, there is a significant tradeoff with compute power and system weight, as shown in Table 2

Table 2. Hardware Comparison: TADPOLE (ESP32-S3) vs. Radxa Zero 3W

Feature	TADPOLE (ESP32-S3)	Radxa Zero 3W
Mass (with Camera)	$\sim$4.5 g	$\sim$15–20 g
Operating Voltage	3.3V – 5V (Single Cell)	5V (Requires Regulator)
Power Consumption	0.3W – 0.5W	1.2W – 3.5W
Boot Time	$<$1 Second (RTOS)	30 Seconds (Linux)
Compute Locality	Off-board (via UDP)	Onboard
Cost (USD)	$\sim$ $15.00	$\sim$ $30.00

B. Software Architecture and Network Optimization

The software implementation leverages the user datagram protocol for WiFi communication the ESP32-S3. Given the dynamics of lighter-than-air flight, the system is designed to prioritize the most recent state estimate over guaranteed delivery; if a packet is lost due to RF interference, the ground station simply awaits the next update rather than initiating a costly retransmission, thereby maintaining a consistent and low round-trip time for the control loop.

C. Embedded Sensing and Multi-Modal Telemetry Acquisition

To satisfy the requirement for high-fidelity state estimation within the weight constraints of the TADPOLE platform, the system utilizes a tightly integrated sensing stack consisting of an Adafruit BNO055 9-DoF Inertial Motion Unit (IMU) and a BMP280 barometric pressure sensor. These sensors are interfaced via the Inter-Integrated Circuit (I2C) protocol, operating at a bus speed of 400 kHz to ensure minimal latency during data retrieval. The BNO055 is particularly advantageous as it features an onboard Bosch Sensortec digital signal processor that performs high-speed sensor fusion, providing absolute orientation in the form of Euler angles directly to the microcontroller. This offloads the computationally expensive task of quaternion-to-Euler conversion from the ESP32-S3, preserving CPU cycles for communication tasks.

To optimize the telemetry downlink, the firmware implements a custom serialization scheme. These values are bit-shifted and packed into a compact UDP payload. By reducing the telemetry packet to a raw byte stream, the system significantly decreases the wireless bandwidth required, effectively reducing the likelihood of packet collisions in the high-density RF environments characteristic of the DTR competition.

D. Propulsion and Actuator Interface

The vehicle movement subsystem is designed around a three-motor differential configuration, utilizing BETAFPV 4pcs 1103 11000KV brushless motors to achieve the necessary thrust-to-weight ratio for agile maneuvers. Significant effort has been done to explore ideal propeller-motor combinations.[20] These motors are driven by dedicated FLASH HOBBY 7A BLHeliS Electronic Speed Controllers (ESCs) that interface with the ESP32-S3 via a stable 50 Hz Pulse Width Modulation (PWM) signal. The firmware maps incoming UDP command packets from the ground station—representing the x, y, and z thrust vectors—directly to the duty cycles of the respective pins.

The vertical motor is dedicated to altitude maintenance, while the two horizontal motors provide both forward translation and yaw torque through differential thrust.

E. Ground Station Integration and Vision Processing Pipeline

The off-board component of the TADPOLE architecture is hosted on a high-performance ground station designed to process the incoming fragmented UDP stream and generate real-time control responses. The receiver software utilizes a non-blocking socket architecture to reassemble the 1024-byte image fragments into a complete JPEG buffer. By monitoring the image number and image part values embedded in each packet, the ground station can identify if a frame is incomplete. To maintain the lowest possible latency, the pipeline is configured to drop incomplete frames immediately rather than attempting a request for retransmission, ensuring the autonomy engine never processes "stale" visual data.

Once a frame is reassembled, it is passed to a vision processing pipeline utilizing the OpenCV library and a lightweight object detection model. The detection logic is tuned to identify high-contrast targets, such as the competition goal balloons, within the 320×320 pixel coordinate space. The resulting centroid coordinates are then compared against the desired setpoint to calculate the error values for the control loop. These errors are processed through a Proportional-Integral-Derivative (PID) controller, which computes the necessary x, y, and z thrust vectors. These commands are packed into a 6-byte control packet and transmitted back to the vehicle. This closed-loop cycle, from image capture to motor command execution, is designed to operate with a deterministic frequency, providing the stable "edge-computing" performance required for autonomous LTA navigation.

IV. Results and Discussion

The performance of the TADPOLE platform was evaluated through a series of controlled bench tests and active flight trials within a simulated competition environment. These evaluations were designed to quantify the reliability of the off-board control architecture and verify that the platform's mass and power profiles remain within the operational envelope dictated by the LTA vehicle's lift capacity. Figure 2 shows the entire vehicle suspended by a single 36 inch mylar balloon.

A. Latency Characterization and Network Reliability

The primary metric for validating the TADPOLE architecture is the cumulative Round-Trip Time (RTT), which encompasses image acquisition, network transit, ground-station inference, and command execution. As the distance approached the 50-meter requirement, the latency increased to an average of 70 ms due to minor packet re-ordering at the router level. However, the use of the custom UDP fragmentation protocol ensured that the "latest-is-best" data priority was maintained, preventing the control loop from experiencing the exponential delay increases common in TCP-based streams.

Analysis of the packet success rate indicated that while individual 1024-byte fragments were occasionally dropped in high-interference environments, the ground station successfully reassembled over 90% of total frames. The deterministic 100ms update window (20 FPS) provided by the ESP32-S3 proved to be significantly faster than the mechanical dynamics of the 36-inch Mylar blimp, effectively masking any network-induced jitter during autonomous station-keeping maneuvers.

B. Mass Budget and Buoyancy Analysis

In lighter-than-air robotics, mass and displaced volume are the most significant constraints on autonomy and performance. A detailed mass breakdown of the TADPOLE flight hardware is provided in Table 3. The total flight mass of 70 grams was achieved through the strategic use of direct-soldered "stack" configurations and minimal wire lengths.

Table 3. Detailed TADPOLE Mass Budget

Component	**Mass (g)**
XIAO ESP32-S3 Sense (Microcontroller + Camera)	4.2
BNO055 + BMP280 Sensor Stack	3.1
1103 Brushless Motors (x3)	14.7
Electronic Speed Controllers (ESCs) and Propellers	12.5
Battery (300mAh 2S LiPo)	18.2
Airframe, Wiring, and Structural Adhesives	17.3
Total Measured Flight Mass	70.0

With a measured gross lift of 65 grams from a single helium-filled 36-inch Mylar balloon, the platform maintained a neutral buoyancy margin of 5 grams. This margin is critical as it allows the vertical thruster to operate at a lower duty cycle to maintain altitude, thereby extending the total flight duration. During testing, the 300mAh 2S battery configuration provided a continuous operational window of 25 minutes, which significantly exceeds the 5-minute round competition requirement and accounts for the power draw of the active WiFi radio and the three brushless motors. Figure 2 displays the vehicle frames with annotations for each part.

C. Detection Performance and Off-Board Control Stability

The off-board detection pipeline was tested against target goal balloons at varying lighting conditions and distances. Using a 320x320 pixel JPEG stream, the ground station achieved a detection confidence of 70% at ranges up to 5 meters. Because the detection was handled by a high-performance ground-station GPU rather than the onboard micro-controller, the system was able to utilize more complex feature extraction than what would be possible on an edge device.

The resulting PID control stability was observed during autonomous "approach and collect" trials. The most significant challenge observed was the "shutter lag" inherent in the OV2640 sensor during high-velocity yaw rotations; however, the low-latency command link allowed the ground station to dampen these oscillations effectively. This proves that for LTA platforms with slow physical dynamics, off-board edge computing provides a viable—and often superior—alternative to high-mass onboard processing.

Experimental results verified that the system meets all requirements for the Defend the Republic competition, including a reliable 50-meter communication range, and sufficient flight endurance, as well as a total bill of materials cost under $100 USD. The TADPOLE architecture provides a scalable and attritable pathway for deploying large-scale autonomous fleets where individual vehicle cost and weight must be minimized without sacrificing high-level mission performance.

V. Summary and Future Work

This paper presented the design and implementation of TADPOLE, a novel, ultra-lightweight sensing and autonomy architecture for LTA UAVs. By systematically offloading computationally intensive perception tasks to a ground-station server, the platform successfully overcomes the traditional trade-off between advanced autonomous capabilities and strict flight payload limits. The use of a low-cost, ESP32S3-based sensing module paired with an optimized UDP communication pipeline demonstrated that real-time vision-based control is achievable even on platforms with a mass of under 75 grams.

The current TADPOLE architecture transitions the paradigm of lighter-than-air autonomy from isolated, resource-constrained agents to a centralized, scalable intelligence model. By off-loading the primary computational burden, the platform effectively decouples the complexity of the mission software from the physical mass of the flight hardware. This shift introduces a novel modality in the Defend the Republic (DTR) framework: the ability to deploy heterogeneous swarms without a linear increase in onboard hardware costs or vehicle weight.

In this off-board configuration, the ground station functions as a centralized "hive mind," capable of multiplexing the perception and control loops for multiple agents across distinct UDP port ranges. While traditional LTA vehicles are often restricted to simple color-thresholding or basic proximity sensing due to the power-draw of onboard NPUs, a swarm of TADPOLE vehicles can leverage shared high-level vision models and global path-planning algorithms simultaneously. This multi-agent scaling is facilitated by the custom fragmentation protocol, which allows the ground station to prioritize the highest-confidence visual streams from the fleet to coordinate intercept maneuvers or defensive positioning. Ultimately, this approach moves the DTR competition away from single-agent survival toward sophisticated group behaviors, where the "intelligence" of the vehicle is limited only by the ground station's GPU throughput rather than the buoyancy of a single Mylar balloon.

Future work will focus on improving the robustness of the off-board link with closed loop angular PID controlled motion onboard the vehicle for smooth continous control. Additionally, the team aims to expand the ground-station software to support multi-agent coordination, allowing a single server to provide perception and control updates for an entire swarm of TADPOLE vehicles simultaneously. Further research will also investigate the integration of low-power UWB ranging for GPS-denied localization to augment the current vision-based navigation pipeline.[21]

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