Miniature Autonomous Blimps for Indoor Applications

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Miniature autonomous blimps are autonomous lighter-than-air vehicles that offer a variety of benefits over other existing flight platforms. In particular, blimps offer long flight times, soft envelopes that are resilient to collisions, and friendly human-robot interaction opportunities. As such, these platforms are well suited for indoor applications and human-cluttered environments as catastrophic or life-threatening collisions are far less likely. In this abstract, we detail some of our ongoing efforts to enable autonomous behaviors for lighter-than-air platforms through various sensing, actuation, and swarming efforts.

I. Introduction

Autonomous aerial vehicles have become a strong focus in the research community. The three-dimensional (3D) flight capabilities of such platforms offer a wide variety of navigation and agility opportunities that ground vehicles constrained to two-dimensional (2D) mobility are unable to access. As such, various platforms have been proposed by the community to explore these aerial capabilities. Multi-rotor platforms, such as quadrotors, are widely popular platforms that are capable of highly agile flight [1, 2] and have been used for various applications ranging from search and rescue to infrastructure inspection [3, 4]. However, these platforms typically have low flight times (~25 minutes) and are dangerous to operate around humans. Alternatively, fixed-wing UAVs are able to fly long distances, are capable of highly agile flight [5, 6], and can be used to carry large payloads [7]. These platforms though are unable to achieve vertical takeoffs and are generally unable to make tight turns making indoor use very difficult. In addition, both of these platforms typically require a personal safety operator who is able to take control with manual piloting in case of emergencies. This may inhibit the use of these platforms for swarming research as each agent requires a personal operator. Alternatively, autonomous blimps have become a popular research platform due to their long flight times and safe characteristics.

Blimps are lighter-than-air vehicles that rely on soft helium-filled envelopes to achieve low-effort flight. As a result, these platforms enjoy extensive flight times and require lower energy requirements to navigate through 3D space. These systems are in particular amenable to indoor applications and swarming research as they can collide safely with humans, obstacles, and other blimps and therefore do not require safety operators. In addition, various actuation configurations and methodologies can be designed for these platforms that allow for higher maneuverability or higher speeds, allowing for application-specific designs. For example, in the literature, differing platform configurations have been used to explore bio-inspired propulsion methods [8] and distributed source-seeking strategies [9, 10].

This abstract focuses on our joint design and development of miniature autonomous blimps as new aerial platforms capable of being used in a wide variety of indoor and swarming applications. In particular, we discuss our ongoing efforts to enable blimp autonomy via various actuation and sensing methodologies, and swarming strategies. In Section II, we discuss our development efforts across various robotic blimp platforms, including both propeller-based and

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bio-inspired flapping fin-based actuation systems. We discuss, in Section III, the use of these platforms in swarming applications and conclude with observations on our current progress in Section IV.

II. Actuation Designs

Various actuation configurations for miniature autonomous blimps can offer differing benefits to both flight performance and safety. For this work, we discuss two actuation styles: **i)** propeller-based designs and **ii)** flapping fin-based designs. Propeller-based propulsion offers faster and more consistent flight, allowing for easier modeling of the system dynamics [11] while flapping-based propulsion offers safer, quieter, and more energy-efficient flight, allowing for better loitering capabilities.

A. GT-MAB 2.0

The Georgia Tech Miniature Autonomous Blimp 2.0 (GT-MAB 2.0) utilizes a small gondola with six propellers located at the bottom of a helium envelope to achieve omnidirectional planar motion. As seen in Fig. 1, the platform is also equipped with a Raspberry Pi-based sensing package that streams measurements from an onboard BNO055 IMU and images from a Raspberry Pi Camera v2 over 2.4GHz WiFi. Due to the concentrated weight of the gondola, the

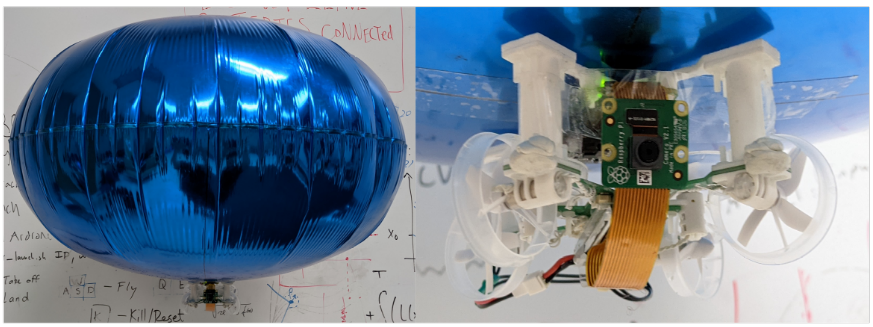

Fig. 1 The GT-MAB 2.0 propeller-based platform utilizing 6 propellers to achieve omnidirectional planar flight. Left: full platform with helium envelope, Right: close-up of gondola.

GT-MAB 2.0 is susceptible to heavy roll and pitch oscillations. As such, we designed a set of PID controllers to stabilize oscillations and track desired roll and pitch angles. By using a set of outer loop PID controllers, we can compute desired roll and pitch angles to achieve velocity tracking for the GT-MAB 2.0. The velocity tracking performance of the proposed control scheme for the GT-MAB 2.0 is shown in the left of Fig. 2. This velocity tracking controller also allows the GT-MAB 2.0 to achieve accurate waypoint tracking, as seen in the right of Fig. 2. For additional details, the reader is directed to the work in [12].

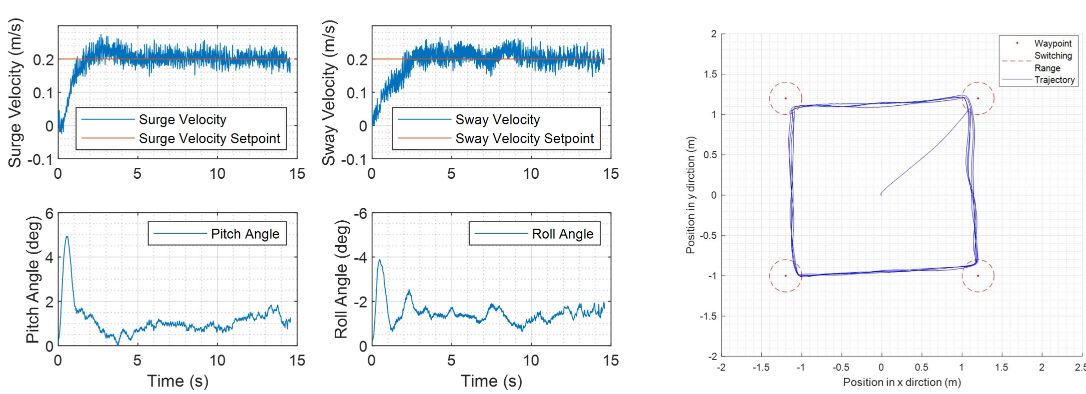

Fig. 2 Left: velocity tracking of the GT-MAB 2.0 given a desired velocity of 0.2 m/s. Right: position control of the GT-MAB 2.0 for four desired waypoints. Figures adapted from [12] with author permission.

We leverage a motion capture system to provide us with accurate pose estimates of the blimp to perform autonomous flight. However, in scenarios where a motion capture system is unavailable, we have also explored alternate localization methods using monocular images and convolutional neural netwrks (CNN) to estimate the 2D pose of the blimp (2D position and a heading angle). Our proposed approach leverages a collected image-pose dataset of the test environment where a set of images is labelled using the original pose of the camera (as measured via a motion capture system). Examples of images from the dataset used in this work and collected at the Georgia Institute of Technology are shown on the left in Fig. 3.

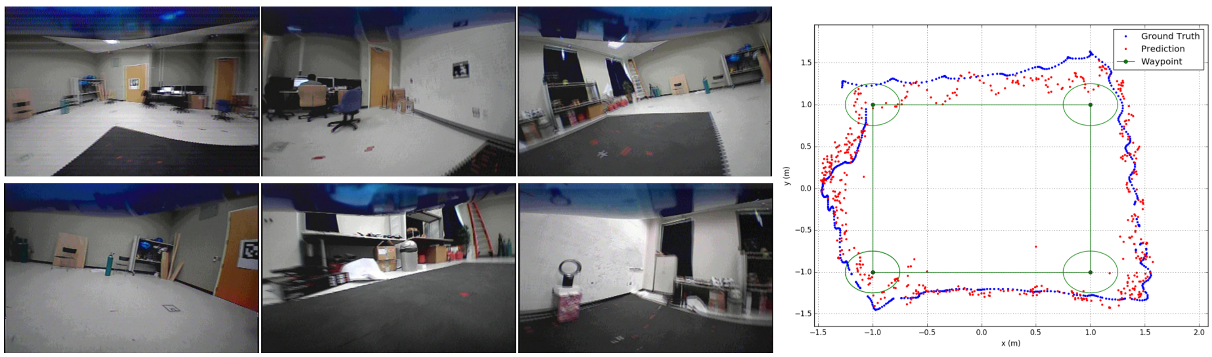

Fig. 3 Left: image-pose dataset samples collected using the GT-MAB 1.0. Right: waypoint tracking performance of the GT-MAB using the CNN for pose estimation. Figure adapted from [13] with author permission.

The image-pose dataset can then be used to train a convolutional neural network (CNN) using the approach outlined in [14] to both estimate the 2D pose of the blimp and enable 2D waypoint tracking. The performance of the waypoint tracking using the GT-MAB 1.0 [15] (a precursor to the GT-MAB 2.0) is shown on the right in Fig. 3. Notice that the true trajectory of the blimp is able to roughly follow the intended square trajectory. Additional details are provided in [13].

Propeller-based platforms, like the GT-MAB 2.0, offer nice advantages in the form of simpler dynamics and more consistent flight. However, propellers can require larger batteries and are still possible areas where a human operator could be injured. Wing-based propulsion, therefore, is an alternative method of propulsion that may boast improved energy performance, quieter operation and better safety.

B. Flapping-Wing Designs

Miniature blimps occupy a unique functional regime that can potentially meld a number of features of aquatic and aerial locomotion i.e. swimming in air. This affords opportunities to seek inspiration from natural systems such as fish that are exceptional at locomotion and need to cater to similar operational demands including: miniature size, buoyancy control, high manoeuvrability and passive stability. Small fish are passively stable due to their body shape, highly maneuverable, yet adept at station-holding and thus can be considered as model platforms for miniature blimp design. However, due to the vastly different fluid conditions and design pressures, biological systems may be considered as an operationally emulatable platforms and not as prototype for robotic blimps.

Following this approach, the UNSW-C Finned Blimp (FB) is equipped with bio-inspired propulsion and flight control systems. UNSW-C FB is a miniature blimp platform consisting of a spherical envelope (0.5m diameter) with a triangular fin attached to the front, back and two sides along the midplane, see left on Fig. 4. The fins are connected to tiny servo motors (1.6gms) that enable each of them to be oscillated at various frequency and amplitude, individually or in combination with others. Similar to fish, oscillation of the fins produces propulsive thrust.

In this design, the horizontally oriented front and back fins can be flapped individually to move the blimp backwards or forwards, respectively. Alternately, both can be offset downwards or upwards and flapped in order to move the blimp up or down, respectively. Left and right movement as well as yaw can be controlled in a similar fashion using the vertically oriented side fins. To simplify design and controller complexity UNSW-C FB cannot perform roll or pitch rotations. Similar to the propeller driven GT-MAB, a gondola carrying the controller (right on Fig. 4), communication module and battery is attached to the bottom, which increases pendulum stability of the platform.

The blimp is controlled by a Matek F405-STD flight controller that runs open-source autopilot ArduPilot. For autonomous control, the blimp uses velocity and position input derived from a motion capture system (VICON) and two

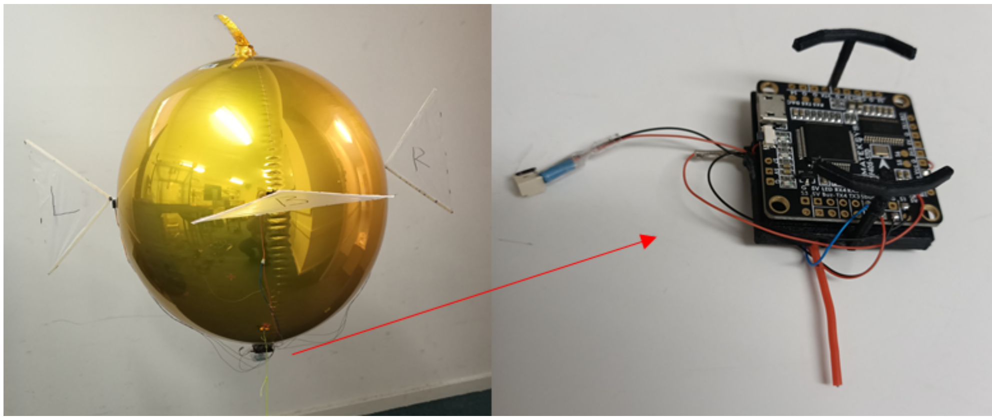

Fig. 4 (a) Image of the UNSW-C Finned Blimp. (b) Closeup image of the gondola containing the Matek flight controller, battery, WiFi module, RC receiver and voltage converter.

nested PID controllers. The on board autopilot receives position information from VICON system that is then passed through an EKF before being passed to the controllers. The position PID controller takes the target position and current position and outputs a target velocity. This is passed to the velocity PID controllers which takes this along with the current velocity and outputs XYZ and Yaw directions. Preliminary tests reveal good position hold capability (Fig. 5).

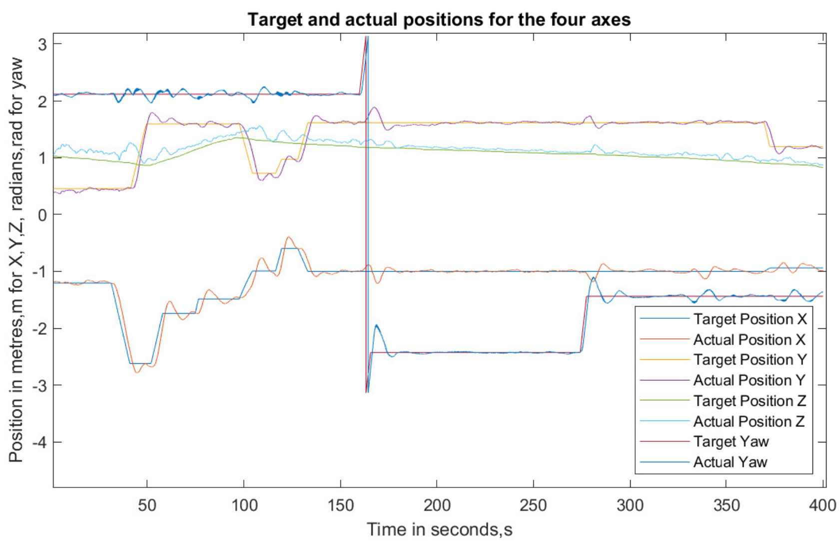

Fig. 5 Sample data from a flight test. The desired position from the controller is presented against the position of blimp obtained from the motion capture system.

III. Swarming Strategies

Due to their soft envelopes and slow dynamics, autonomous miniature blimps are safe to use around humans and in swarms. As such, we detail some of our efforts in designing swarming applications for miniature blimps, including visible light communication (VLC) for swarms, multi-agent path-planning, and relative sensor-based swarming. Many of the efforts detailed in this section utilize the LTA^3 platform [16] derived from the GT-MAB 1.0.

A. VLC for Swarms

VLC is a light-based communication protocol that transfers data via high frequency pulsing light [17]. Compared to RF-based communication strategies, these strategies also allow for fine-tuned group communication including private messaging (i.e., VLC can be directed to specific targets) and broadcast messaging (i.e., VLC can be spread over a wide domain). These benefits may be particularly useful for large group interactions as overwhelming the network with broadcast messaging (as is the case in RF-based communication) may lead to overall lower throughput. In this work, we investigate the use of VLC for agent-to-agent swarm communication and relative localization (azimuth and altitude estimation) on the LTA^3 platforms in order to enable intra-swarm communication via LEDs and digital cameras.

The proposed strategy of this work uses LEDs blinking at different frequencies to communicate shared information received by a camera. While our initial results using VLC between two agents show that only slower frequency light pulses can be detected, we can improve the data rate by segmenting the camera frame with Regions of Interest (ROI) as shown on the right in Fig. 7. As a result, multiple ROIs allow the VLC data rate to scale as the number of agents captured in an image increases. Incorporating various color LEDs can also be used to distinguish between various types of data. Aerial experiments with the LTA^3 platform were conducted at the Naval Research Laboratory and showed that agents could detect different frequencies using Frequency Shift Keying (FSK). FSK is a frequency modulation scheme where over a sequence of time intervals, different blinking LED frequencies are able to transmit binary information. An example of this technique is shown in Fig. 6. Leveraging FSK, we were able to achieve bit-error rates of 4.83% for 1

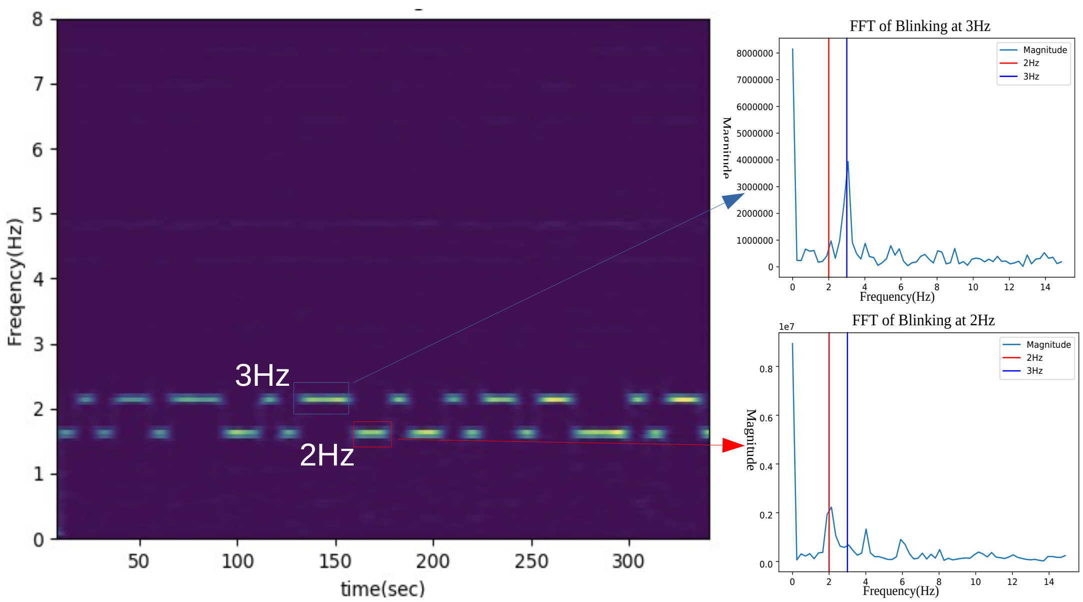

Fig. 6 An example of the FSK scheme used to transmit binary information via VLC.

agent, 4.44% for 2 agents, and 6.32% for 3 agents. These tests were performed using the setup shown on the left in Fig. 7. This work was presented at DARS-SWARM 2021.

B. Multi-Agent Path-Planning

Synchronized multi-agent path-planning is an important behavior to ensure swarming agents can safely fly along desired trajectories. In this work, we designed a synchronized A^* path-planning method that could be easily and safely tested using the blimp platforms. Using an estimated model of the blimp dynamics, our A^* strategy was able to generate dynamics-compliant trajectories that satisfied target waypoints. Agent paths were re-computed occasionally in the event that the agents drifted too far from the desired trajectory.

As seen in Fig. 8, the synchronized A^* strategy was able to generate trajectories for three agents that enabled the spelling of NRL with synchronized starting and ending times. For additional details, the reader is directed to the work in [18]. These platforms were also deployed in a large swarm test of 25+ LTA^3 agents to follow predefined trajectories. State information for both of these cases were provided via motion capture system and ultrasonic ping sensors mounted on each platform. For more details, the reader is directed to the work of [16].

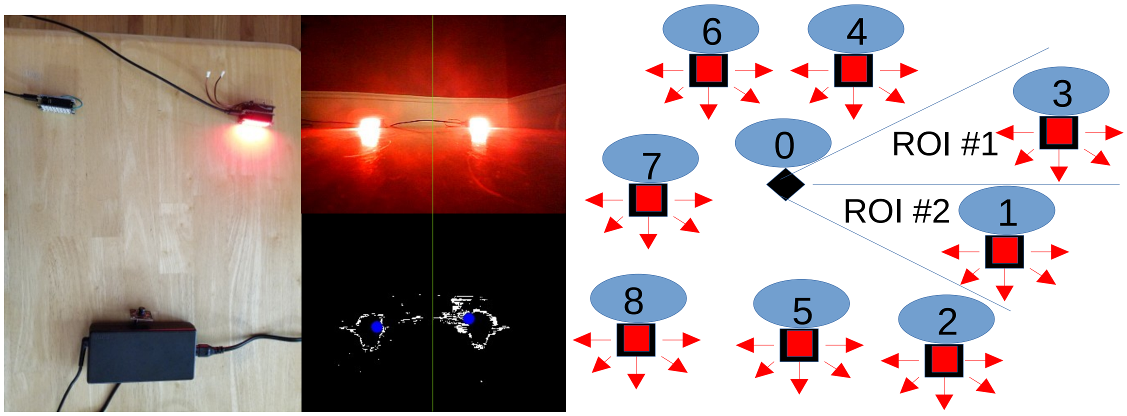

Fig. 7 Left: A series of pictures describing VLC and what the camera sees during VLC. This test setup simulates 3 agents, two agents communicating simultaneously to the camera posing as an agent. Right: A diagram showing how VLC would use ROI to receive information from multiple agents at once.

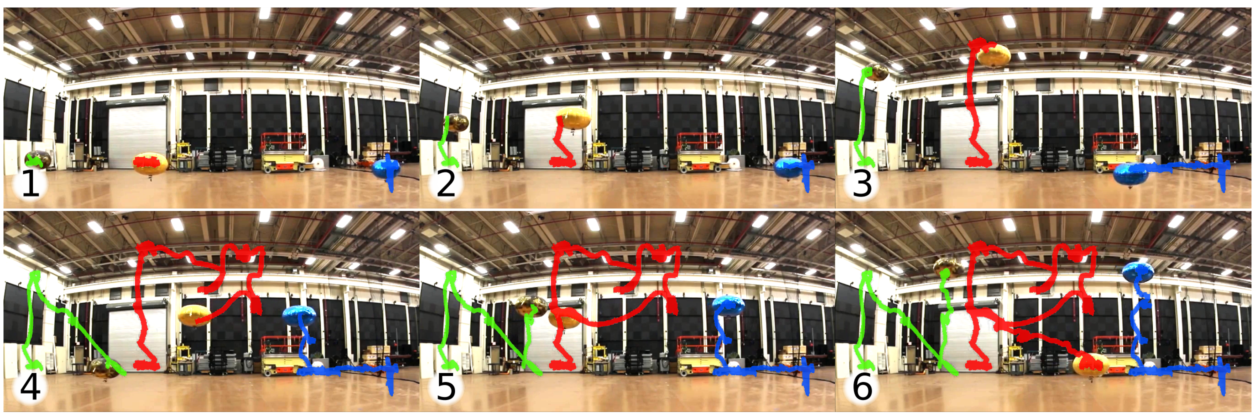

Fig. 8 Time-synchronized multi-agent A* path planning with 3 real-world LTA^3 agents spelling "NRL". Figure adapted from [18] with author permission.

C. Defense of the Republic

The "Defense of the Republic" is a blimp-oriented competition designed to thoroughly verify the strategies and methods used for blimp swarming autonomy in an adversarial environment. The competition is organized around two teams capturing and driving target objects (neutrally buoyant green balloons as shown on the left in Fig. 9) through designated hoops on the opposing side over a set amount of time. Competitors in the "Defense of the Republic" included teams from George Mason University (GMU), Penn State/ARL, University of California-Los Angelos (UCLA), and NRL/GT. Agents in the competition are permitted to have access to any autonomous sensing or computation available but are restricted by the environment. For example, due to the indoor nature of the environment, GPS signals are inaccessible but AprilTags [19] are mounted on goal hoops. The competition was hosted at Indiana University-Bloomington's MESH facility which included a large GPS-denied indoor space with a net-covered pit area that generated strong up and down winds. The competition environment is shown on the right in Fig. 9.

Platforms designed for this competition included a larger blimp with slower dynamics but high payload capacity to support computer vision detection of the game ball (using the CMU PixyCam) and a flat wide blimp for collecting game balls on the net-covered pit area. As shown in Fig. 10, these platforms were specialized to handle different aspects of the game environment. This competition is an ongoing effort with increasing levels of autonomy, starting from only tele-operation (phase 1 in August, 2020) to full autonomy (phase 4 in April, 2022) and will be detailed more in later publications.

Fig. 9 Left: various competition blimps fighting for the game ball. Right: game environment at the Indiana University-Bloomington's MESH facility.

Fig. 10 Left: "caterpillar" blimp design to achieve on-board ball tracking. Right: "crab" blimp design to scoop game balls off the net-covered pit.

IV. Conclusion

In this abstract, we have demonstrated that these platforms are capable of high-accuracy tracking control and swarming behavior when high-accuracy localization systems (e.g., motion capture) are available. In addition, these platforms are easily perturbed by small wind disturbances, making these platforms excellent for online wind-mapping applications which may also be useful for other airborne agents. Wind-rejection controllers and path-planners are also a new opportunity for these platforms to further improve tracking performance.

In cases where motion capture systems are unavailable, we have also demonstrated that waypoint tracking can be enabled using monocular cameras to provide pose estimates when an image-pose dataset is available. In view of the payload limitations of these platforms, we have also suggested possible future work in cooperative localization strategies which can help to mitigate these limitations by offloading computationally-expensive requirements to larger platforms capable of supporting these requirements at the sake of speed.

Finally, we have demonstrated that these platforms are also excellent for investigating new bio-inspired actuation strategies in which flapping motions can also be studied to emulate "swimming" through the air. Such strategies offer both energy-efficient and possibly omni-directional flight and improved safety in proximity to humans. While there are still various research efforts necessary to achieve wide-spread adoption of these platforms, the details we have provided in this abstract demonstrate that these platforms offer significant potential as future research or industrial aerial vehicles.

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