Session 2023

Design and Construction of a Lighter than Air Robot Blimp

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Abstract

This paper describes the design and construction of a lighter than air robot blimp (LTARB). The blimp has both shared autonomy and fully autonomous modes. The blimp is designed to fly indoors and play a game called *Defend the Republic*, and it is sponsored by the United States Department of the Navy, Office of Naval Research. In this game, blimps fly around and capture floating balloons. The blimps then score by finding a goal and putting the balloons through the goal. The blimps' major sub-components, described in this paper, include: 1) Airframe, 2) Buoyancy, 3) Propulsion, 4) Balloon capture and scoring, 5) Avionics, and 6) Guidance and Control. This project has been integrated into multiple Baylor University engineering courses.

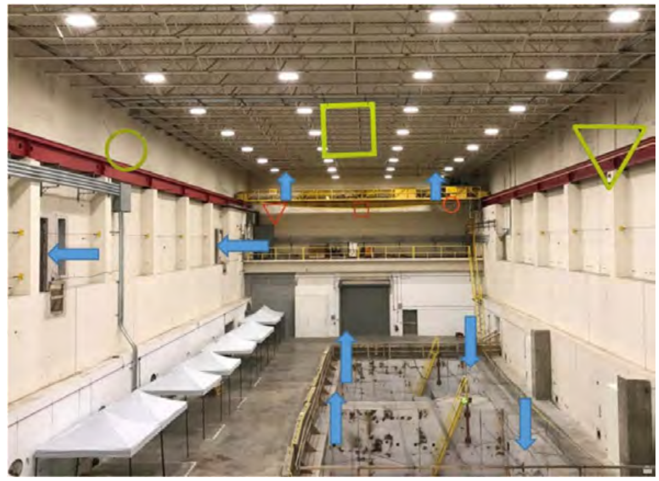
Introduction

This paper describes the design and construction of a lighter than air robot blimp (LTARB), Figure 1a. The blimp has both shared autonomy and fully autonomous modes. The blimp is designed to fly indoors and play a game called *Defend the Republic*. In this game, there are triangle, square, and circle goals on each end of the arena. Each team's blimps fly and capture floating round green balloons. The blimps then identify their respective goals, fly to them, and score by pushing the green balls through the goals. This project has been integrated into a Baylor University capstone design course ("Senior Design") and an embedded systems engineering course. It has also been used as an example in a Baylor University automatic control systems course, and as a project in a special projects engineering elective course. Work on the project started in the Embedded Systems course and continued into the Senior Design course. The project has seen continued work after the Senior Design course involving a team comprised of undergraduate and graduate students.

This paper first describes how this project was integrated into four Baylor University courses. Then, more details of the blimps' major sub-components are described. Sub-components include: Airframe, Buoyancy, Propulsion, Balloon Capture & Scoring, Avionics, and Guidance & Control.

This work relates to Department of Navy award N000142212190 issued by the Office of Naval Research.

a)



b)

Figure 1. Images from the Spring 2022 competition venue at Indiana University a) Image of a Baylor University Lighter Than Air Robot Blimp (LTARB) Flying Towards Balloons for Capture and b) Game Space at Indiana University [1]

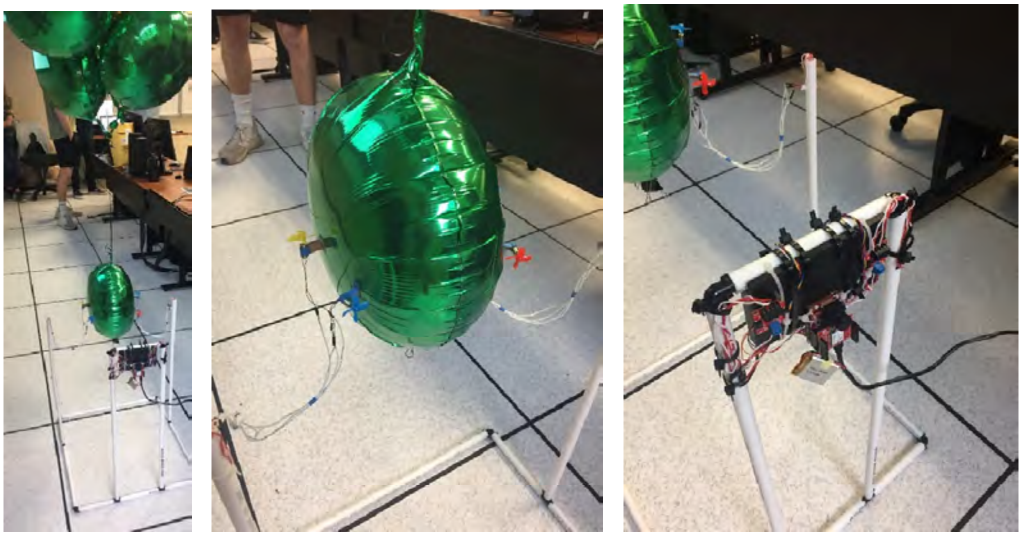
Course Involvement With the Project

The project has been integrated into multiple Baylor University courses: an embedded systems course, a senior design course, a feedback controls course, and an independent study special projects course. The integration into each of these courses is briefly described in the following sections.

Embedded Systems Design class (ELC 4438):

In Baylor University's Embedded System Design class, students design and implement embedded computer systems using microcontrollers, sensors and data conversion devices, actuators, visual display devices, timers, and applications specific circuits. Students perform software design using microprocessor cross-development systems and learn real-time operating system principles. In the Fall 2021 semester, as their final project, a team of six students designed, constructed, and demonstrated the robot shown in Figure 2. The students were tasked with creating a lighter than air robot vehicle that would track a moving object and move the vehicle to point at the moving object. Figure 2.a. shows the completed prototype. The robot is buoyed by balloons as shown at the top of the picture. The robot is tethered to a polyvinyl chloride (PVC) plastic tube test stand to constrain the robot's movement. Figure 2.b. shows the robot and three of the four motors. Two motors and propellers point up, and two motor and propellers point forward. Figure 2.c. shows the embedded control system and battery. The avionics would have been too heavy to mount on the balloon in this prototype, so it was mounted on the PVC test stand. This allowed the team to test the main computing aspects of their design.

The team of six students split into three pairs to accomplish three major objectives of this project. Two students researched the OpenMV microprocessor/camera module. They implemented color recognition to identify a green balloon and also worked on feedback control to the motors. Two other students worked on the four brushed motors and the two motor drivers. They did all the hardware wiring and researched how to drive the blimp's motors. Finally, two students researched wireless networking so that different parts of the blimp could communicate with one another and potentially other blimps. They set up a Mosquitto broker for MQTT publishing and subscribing over wifi.



a) b) c)

Figure 2. Embedded Systems course Robot Blimp Prototype
a) Entire System showing a bundle of balloons at the top to provide buoyancy and a white PVC tubing test stand fixture b) motors on the body of the "robot" and c) microcontroller hardware
The microcontroller and battery were not mounted on the robot because this was out of scope for the embedded systems project.

Engineering Design II class (EGR 4390):

Engineering Design II (informally known as *Senior Design*) is a capstone design course that emphasizes learning and applying decision-making processes used by practicing engineers. Students learn to apply the basic sciences to optimally use resources to meet stated objectives. The lighter than air robot blimp team consisted of six students, of which four were mechanical engineering (ME) students, and two were electrical and computer engineering (ECE) students. The team was first presented with the blimp project's goals and constraints, and one of the team's initial design exercises was to generate ideas using tools such as morphological charts and function means trees. Figure 3 shows eight design alternatives developed by the team over the course of the Spring 2022 semester. The team created the design shown in Figure 1.a.

Automatic Control Systems class (ELC 4332):

In an Automatic Control Systems class, students learn to analyze and design linear feedback control systems. They learn to apply concepts of Laplace transforms, transfer functions, electrical and mechanical system modeling, system stability, time-domain response, root-locus method, and compensator design. The instructor was able to use this blimp project as an in-class example of both modeling and feedback control system design. Future work may include using blimp hardware to further illustrate and teach feedback control concepts.

	Important Objectives	1 : Fish Near Wing	2 : Prop Wide Wing	3 : Large Size Prop	4 : Donut Fish	5 : Donut Prop	6 : Fishtail Gondola	7 : Manta Ray	8 : Basic Gondola
1	Unique Function	4	8	7	3	1	5	2	6
2	Unique Design	5	7	4	1	2	6	3	8
3	Scoring Vehicle	4	1	3	7	5	6	8	2
4	Defending Vehicle	6	4	1	2	7	3	8	5
5	Manual Operation	3	1	4	6	7	5	8	2
6	Autonomous Operation	3	1	4	6	7	5	8	2
7	Maneuverable Vehicle	5	1	3	6	7	5	8	2

Design Alternatives (by Name)

** All design decisions will operate within design competition rules and will therefore abide by all constraints.

Decisions	
Standard	2 : Prop Wide Wing
Innovative (for client)	1 : Fish Near Wing
Super Innovative (for client)	4 : Donut Fish

If Client Prefers...	Characterisitcs...
2: Prop-Wide Wing, 8: Basic Gondola, 3: Large Size Prop	Easiest Manufacturing. Proven Concept. Quicker Manufacturing time. Requires less testing. Reasonable and can perform all objectives.
1: Fish Near Wing, 2: Fishtail Gondola	Difficult manufacturing. Mostly Proven Concept. Moderate Manufacuring time. Requires significant testing. Unique functionality.
4: Donut Fish, 5: Donut Prop	Very difficult manufacturing. Not a proven concept. Slow manufacturing. Requires significant testing. Unique funtionality AND design.
7: Manta Ray	Very difficult manufacturing. Mostly proven concept. Slow manufacturing. Requires significant testing. Unique funtionality AND design. Not practical for our purposes.

Figure 3. Example list of prototype design ideas generated by the Senior Design team for a client meeting

<u>Special Projects in Electrical or Computer Engineering (ELC 4V97)</u>:

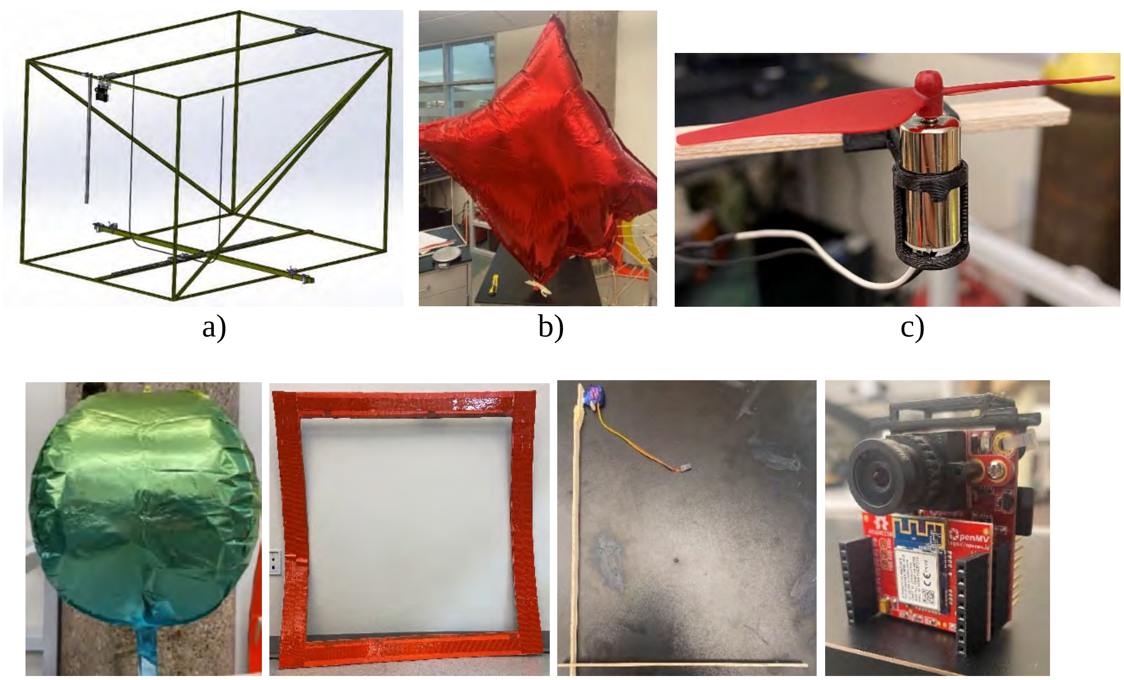
This Special Projects course is typically a one-on-one course where students work with a professor to pursue advanced topics and/or special project activities in electrical or computer engineering. In Fall 2022 one student, who was previously on the Senior Design blimp team, chose to continue the design and development of the LTARB vehicles.

Major Blimp Sub-components

The robot blimp can be separated into six categories: 1) Airframe, 2) Buoyancy, 3) Propulsion, 4) Balloon Capture and Scoring, 5) Avionics, and 6) Guidance and Control. Each of these categories are briefly described below.

1) AIRFRAME
   A rigid airframe composed of balsa wood strips constructed into a hollow square body is used [2], Figure 4.a. Balsa wood is used for its ease of procurement, low-cost, lightweight and is simple to use for construction.
2) BUOYANCY
   The aerostats used are custom made Mylar balloons filled with helium and attached to the airframe to provide buoyancy [2], Figure 4.b. Neutral buoyancy is desired which can be achieved through the adjustment of helium volume and weight of the robot blimp. Mylar is used because of its lightweight and able to be constructed into complex shapes.

3) PROPULSION
Four brushed DC motors are used for propulsion, two motors for horizontal propulsion and two motors for vertical propulsion, Figure 4.c. The motors are connected to the robot blimp via three dimensional (3D) printed motor mounts which slide onto the balsa wood strips, allowing modular installation and removal.
4) BALLOON CAPTURE and SCORING
The airframe of the robot blimps is hollow to allow space for the captured balloons to sit inside securely, Figure 4.a and Figure 4.d. A micro servo motor with a balsa wood rake at the face of the robot blimp allows the balloons inside, keeps the balloons contained, and allows them to be released for scoring, Figure 4.f. A second micro servo motor within the airframe is used to knock the balloons out of the airframe for scoring on goals. Figure 4.e. shows a square goal.
5) AVIONICS
The avionics used are a microprocessor, camera, altimeter, and proximity sensor. The hardware used is the OpenMV H7 R2 microprocessor system, Figure 4.g. The OpenMV controls the system using I2C, color detection to identify balloons for capturing and color detection to identify goals for scoring.
6) GUIDANCE and CONTROL
A proportional derivative (PD) controller is used for the autonomous control, tracking and guidance of the robot blimp [3][8].



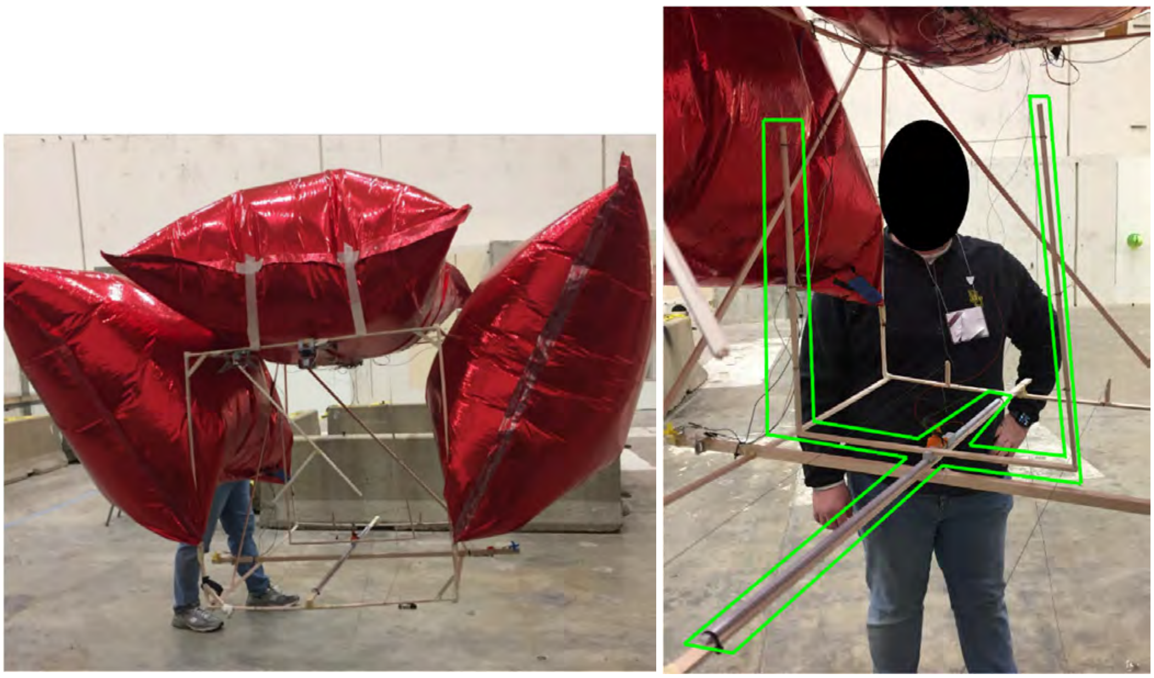
a) b) c)

d) e) f) g)

Figure 4. Major Sub-components of the LTARB and competition
a) Three dimensional (3D) model of airframe [4] b) Inflated Mylar balloon which was constructed inhouse c) One of four DC Brushed Motor used for propulsion d) Green balloon that the robot blimp tries to capture and put through goal for scoring e) One of three uniquely shaped goals on which the robot blimp is trying to score. f) Servo motor with balsa wood rake attached to open and close face of robot blimp. h) OpenMV microprocessor used to control the robot blimp

LTARB Senior Design Version

The first full system of the LTARB iteration was completed in the Baylor University Engineering Design II (*Senior Design*) engineering course. The design goal of the project was to develop a LTARB swarm that could participate in the Office of Naval Research sponsored *Defend the Republic* competition by the end of the course. The competition involves teams of LTARB swarms competing in matches against each other. Figure 5 shows the final robot blimp designed during the Senior Design course. The LTARB is capable of autonomous capture, scoring as well as manual operation. An OpenMV is the on-board computer used for motor control, balloon capture and scoring. A servo motor opens and closes the face of the LTARB using a balsa wood rake. A proximity sensor placed at the face is used to detect balloons entering the airframe which triggers the rake to close. The opening and closing of the face allow balloons to be captured and released. A rack and pinion inside of the airframe pushes captured balloons outside for scoring, Figure 5.b.



a) b)

Figure 5. The LTARB Senior Design Final Version [1]. a) the blimp at the competition, b) the green lines identify the rack and pinion system used to push the captured balloons out of the vehicle.

During the capture and scoring process, color detection is used to identify the goals and balloons. The balloons and goals are different and distinct colors which allow identification through color possible. Four brushed DC motors are used for the vertical and horizontal propulsion. The PD controller is used to adjust the motors to maintain a certain height or to track an identified object. The OpenMV camera can detect the center of an identified object and how far its center is from the camera's center of view. The distance from the camera's center of view to the center of the object is used for proportional aspect of the controller, Figure 6.

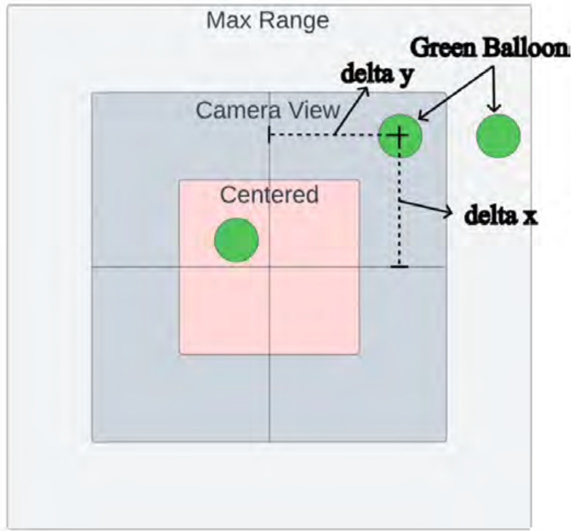


Figure 6. Image of OpenMV Measuring Distances for PD Controller Calculations

The derivative feedback control uses values calculated from the error of the current distance and previous distance from the center of the balloon. These two values, shown as *delta x* and *delta y* in Figure 6, are used to calculate the direction the motors spin and the speed of the motors [8]. Three Mylar balloons are used for buoyancy, two large balloons secured to the sides and one small balloon secured to the top. A method, which will be discussed later in the paper, has been developed so that the custom Mylar balloons can be constructed at Baylor University.

The state diagram of the robot blimp is provided in Figure 7. There are six total states for the robot blimp and four of the six are used for its autonomous operation. The manual state allows control of the robot blimp via a controller.

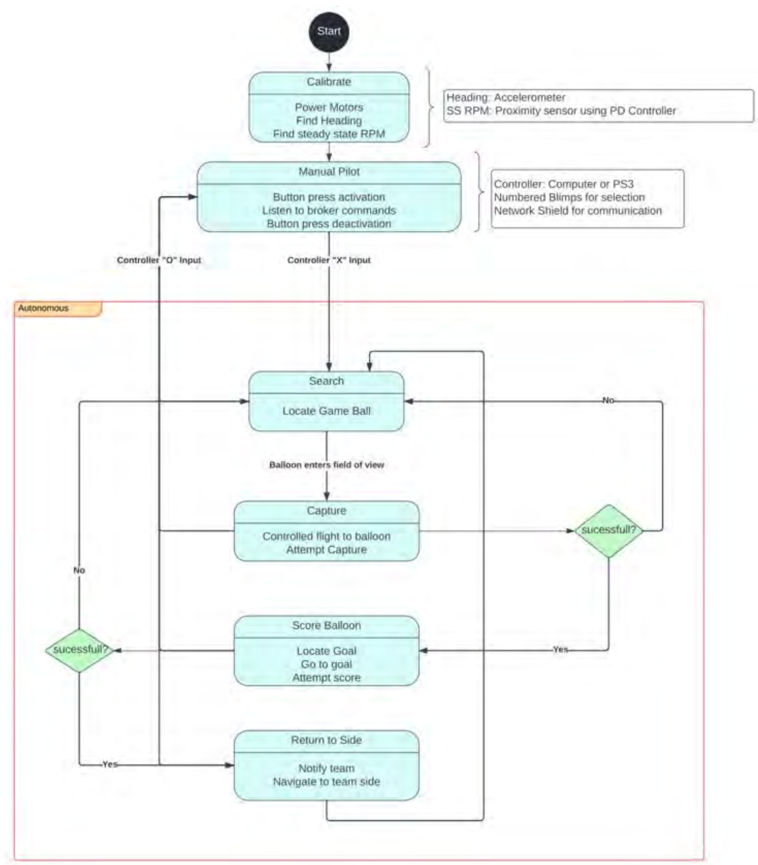


Figure 7. Senior Design LTARB State Diagram [4]

LTARB Updated Design

Since the completion of the Baylor University Senior Design engineering course, the robot blimp has been updated with new changes, Figure 8. A team of undergraduate and graduate students have continued developing the LTARB. A new smaller design was created, and work of the older design was continued. The smaller LTARB was designed with the capabilities to capture and score one balloon at a time. This was so the swarm could still participate in the scoring aspect of the competition. The larger LTARB from the senior design course was modified to only capture and contain multiple balloons. Since the design has changed to capture only, the rack and pinion was removed. The proximity sensor has also been removed to prevent false triggers from already captured balloons. The DC brushed motors have also been updated to more powerful motors. The motors were changed because the Defend the Republic match arena at Indian University has strong air currents which are difficult to overcome. The arrows on Figure 1.b show the areas in the arena where strong air currents are present. The OpenMV, guidance and control has remained the same. The airframe now uses lightweight string for tension which adds stability to the balsa wood and helps contain the captured balloons. The electrical system and airframe have been designed to be more modular to make assembly of the robot blimps easier and faster for the competition. The electrical system can be removed from the airframe without being disassembled and the airframe uses precut-to-length balsa wood. Three large Mylar balloons are used for buoyancy and all three are now attached to the top of the robot blimp.

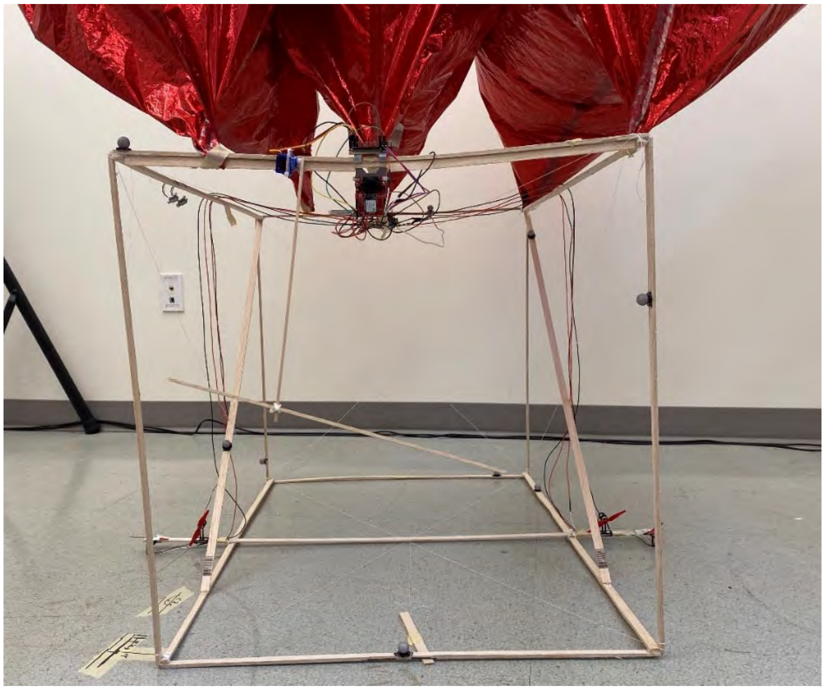


Figure 8. Image of LTARB Updated Design

The state diagram of the updated robot blimp can be found in Figure 9. There are four total states, the score balloon and return to side state have been removed, Figure 9.

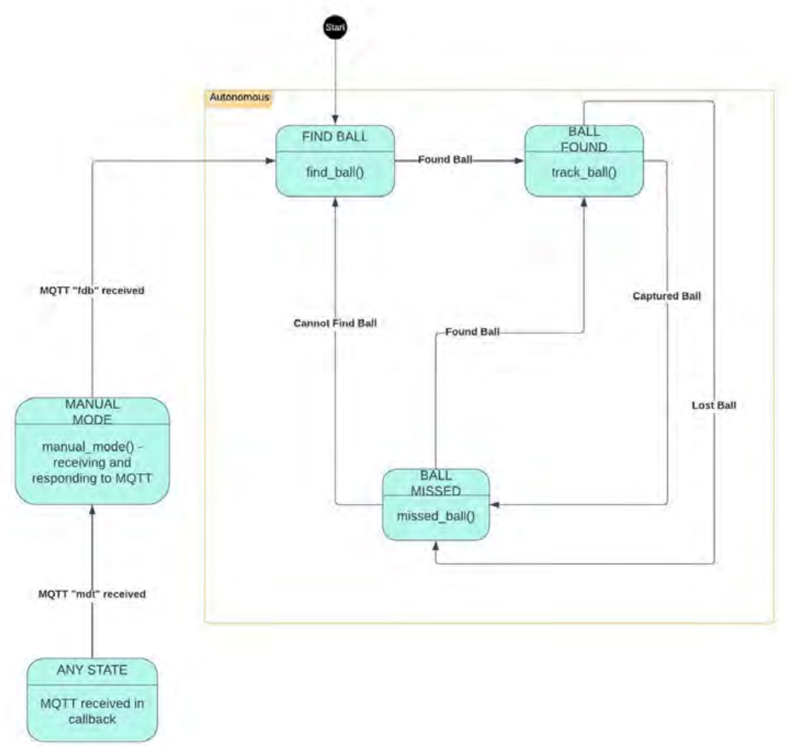


Figure 9. Updated State Diagram of LTARB

Mylar Balloon Design and Construction

The buoyancy of the robot blimp is achieved by using helium filled Mylar balloons, Figure 10.a. The Mylar used is a metallized film that is heat-sealable which makes it light weight and ideal for inhouse balloon construction. The weight of Mylar is 1.39 g / cm^3 which is considerably lighter than other materials considered [5] [6].

a) b)

Figure 10. Mylar used for buoyance. a) Image of Custom-Made Mylar Balloons, b) Outside Colored Lining and Inside Silver Lining of Mylar

The construction process of the custom Mylar balloons consists of cutting the Mylar, attaching a valve, and sealing the Mylar. The first step is to cut out two Mylar sheets of the same dimensions, the balloons in Figure 10.a. were cut to be 3x4 ft. Mylar has a silver-colored side, the silver end is what is used to create the seals between the two Mylar sheets with heat, Figure 10.b.

Once the Mylar has been cut, the second step is to acquire a premanufactured balloon that has a valve and a silver lining on the inside. The valve is cut from the premanufactured balloon so it can be used for the Mylar balloon. Half of the valve is sealed to one of the Mylar sheets and then the second half of the valve is sealed to the other Mylar sheet. The seal is created by using heat to melt the silver lining of the valve to the silver lining of the Mylar. A mini-iron with a flat tip is pressed down and run across the mylar to melt and seal the Mylar, Figure 11 and Figure 12.

Figure 11: Mini Iron Used for Sealing the Mylar

After the valve is securely attached to the two Mylar sheets, the sheets are then sealed together. The steps are as follows: With a large flat surface, tape one Mylar sheet flat to reduce creases while the silver lining is facing up. Then tape the second Mylar sheet with the silver lining facing down onto the other Mylar sheet. Secure the second sheet with tape, try to remove any creases, and align the two sheets as best as possible. Once this is done run the iron around the edges to seal the Mylar sheets to each other, Figure 12. During the construction process, damage to the work surface can occur and it is encouraged to add a protective layer. Specifically, when sealing the Mylar, the colored side of the Mylar will melt off onto the work surface. Cutoff any excess Mylar that is not needed to remove any unnecessary weight.

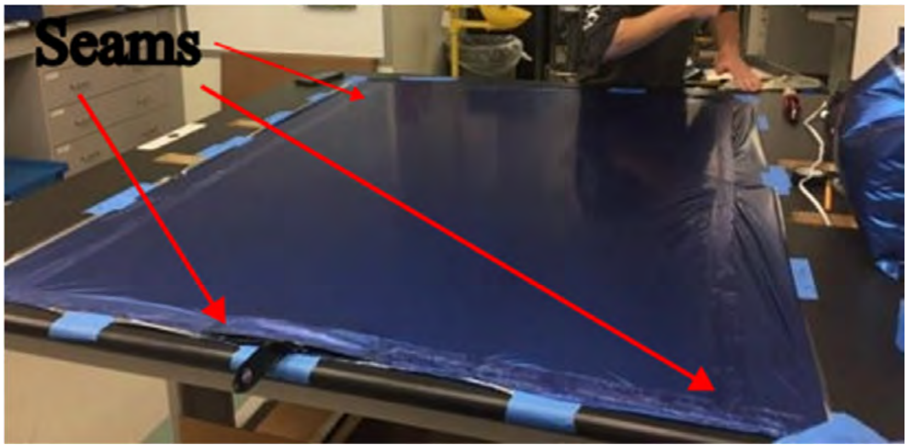


Figure 12. Image of Custom Mylar Balloon Construction [4]

For the Defend the Republic matches, there are rules limiting the amount of helium used total for the swarm and for each individual robot blimp. Due to these rules, a method was devised to estimate the volume of helium the 3x4 ft constructed Mylar balloons could hold. Figure 13 and equations (1) to (6) describe the first method used involving a cylinder and half spheres.

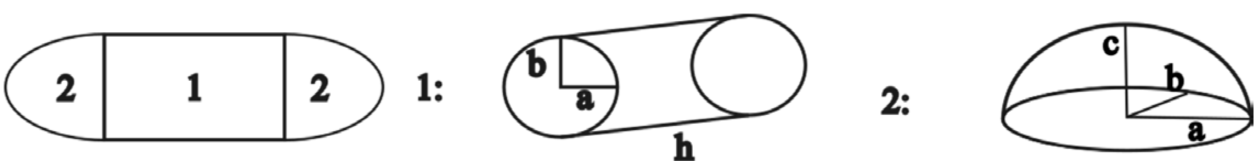


Figure 13: Volume Calculation with Cylinder and Half Sphere Method

$$V_{Cylinder} = \pi abh \tag{1}$$

$$V_{Cylinder} = \pi(15\ in)(9\ in)(28\ in) = 11875.2\ in^3 \tag{2}$$

$$11875.2\ in^3 = 6.872\ ft^3$$

$$V_{HalfSphere} = \left[\frac{4}{3}\pi abc\right]\frac{1}{2} \tag{3}$$

$$V_{HalfSphere} = \left[\frac{4}{3}\pi(15\ in)(9\ in)(8\ in)\right]\frac{1}{2} = 2261.95\ in^3 \tag{4}$$

$$2261.95\ in^3 = 1.309\ ft^3$$

$$V_{Total} = V_{Cylinder} + 2V_{HalfSphere} \quad (5)$$

$$V_{Total} = 6.872\ ft^3 + 2(1.309\ ft^3) = 9.49\ ft^3 \quad (6)$$

To help confirm the accuracy of the volume calculations, a second and more conservative method was used. This second method used a cube and triangles, and it is described in Figure 14 and equations (7) to (12).

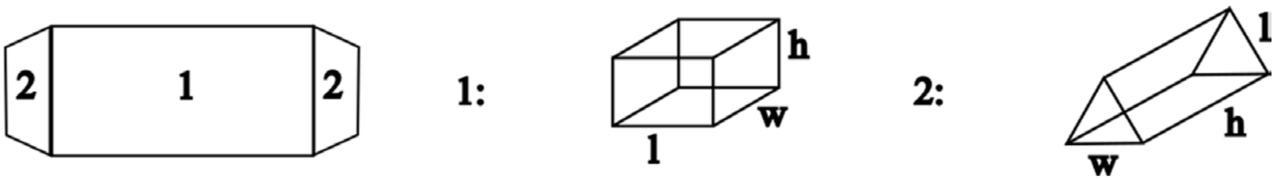


Figure 14: Volume Calculations with Cube and Triangle Method

$$V_{Cube} = wlh \quad (7)$$

$$V_{Cube} = (30\ in)(28\ in)(18\ in) = 15120\ in^3 \quad (8)$$

$$15120\ in^3 = 8.75\ ft^3$$

$$V_{Triangle} = \frac{1}{2}bhl \quad (9)$$

$$V_{Triangle} = \frac{1}{2}(30\ in)(8\ in)(18\ in) = 2160\ in^3 \quad (10)$$

$$2160\ in^3 = 1.25\ ft^3$$

$$V_{Total} = V_{Cube} + 2V_{Triangle} \quad (11)$$

$$V_{Total} = 8.75\ ft^3 + 2(1.25\ ft^3) = 11.25\ ft^3 \quad (12)$$

Robot Blimp Image Processing Testing and Results

The robot blimp needed to be tested to determine autonomous capabilities of identification. The OpenMV comes with multiple programs already developed, and one of them is color detection. Identification testing of the balloons and goals is done by using color detection. If a green balloon is successfully identified by the robot blimp, a live feed image from the OpenMV will have a white box surrounding the balloon, Figure 15. The same testing process is used for goal identification. A white box will appear on the goal with it is successfully identified by the robot blimp, Figure 16.

Figure 15 is a frame captured from a live feed image from the OpenMV when pointed at a green balloon. The white box surrounding the balloon means it was successfully identified.

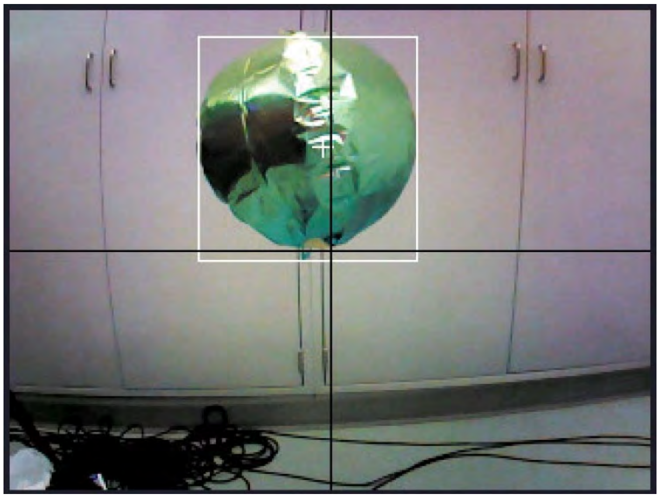


Figure 15. Image of OpenMV Balloon Detection

Figure 16 is a frame captured from a live feed image from the OpenMV when pointed at a goal. The white box on the goal means it was successfully identified.

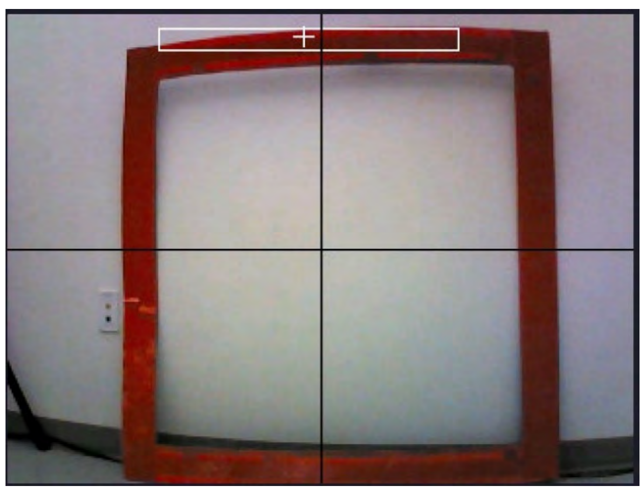


Figure 16. Image of OpenMV Goal Detection

Mylar Balloon Lift Testing and Results

The volume calculations for the Mylar balloons were validated by experimentally determining the total lift capabilities of the balloons. A known constant of 28.2 g / ft^3 for how much weight per cubic feet helium can lift was used to calculate the actual volume of the balloons [7]. The total lifting capabilities of the Mylar balloon is the weight of the deflated balloon and the lifting capability when inflated. A scale was used to determine how much weight the balloon can lift when inflated. Tape was used to secure the inflated balloon to the scale to allow measurements of the lifting capabilities. Figure 17 shows the test setup for measuring the lift of the balloon.

Figure 17. Experimental setup for testing the custom Mylar balloon's lift capability

Table 1 contains the summary of the test results. The Mylar balloon when not inflated weighed 69 g. The lift measured from the scale was 131 g. The total lift of the balloon was 200 g. The actual volume was then calculated and compared to the theoretical volume from the described calculation methods.

Calculation Method	Theoretical Volume	Mylar Weight	Measured Lift	Total Lift	Actual Volume	% Error
1	9.49 ft^3	69 g	131 g	200 g	7.09 ft^3	25.29%
2	11.25 ft^3					36.98%

Table 1. Summary Results of Mylar Balloon Lift Capabilities. This compares theoretical calculations to measured data

Test Analysis

The robot blimp has proven able to successfully identify the green balloon which is supposed to be captured during the match. It has also proven that the goal which is supposed to be scored on after the green balloon has been captured is identifiable. This suggests that with proper implementation of the PD controller and servo motors the robot blimp is capable of capture and scoring autonomously.

The Mylar balloon testing has shown that the two described volume calculations have error. Our calculation methods are still reasonable if the volume is being calculated for the Defend the Republic competition. The competition has rules limiting the amount of helium being used which means it is better to overestimate than underestimate the volume of helium. Depending on other purposes, the error can be considered high and an insufficient method.

Summary and Conclusions

Baylor University has successfully designed and constructed a LTARB through courses and special design teams. The LTARB project was first started in the Embedded Systems course then passed onto the Senior Design course. The robot blimp design has changed from capture and scoring to capture only through its design history. The Mylar balloon construction method has been proven to be a suitable means of creating custom balloons for LTARB. In addition, the volume calculation method for the custom Mylar balloons proved beneficial in estimating the volume capacity in certain applications of the balloons. In conclusion, with proper motor control an autonomously LTARB capable of participating in the Defend the Republic competition has been successfully designed.

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