Practical Construction Methods For A Lighter Than Air Autonomous Robot: An Independent Study Report

Mitchell Kain

I. Abstract

Lighter than air robots present unique challenges in construction, sensing, processing, actuation, and propulsion. The reason for this is simple, we have a very limited amount of weight we are capable of lifting per unit volume. For a helium-based blimp this works out to be approximately 1 gram per liter under ideal conditions. This meant we needed to devise the lightest possible methods in order to create a functioning robot and that would not require a massive lifting volume. The end goal was to have a robust platform from which to conduct experiments on the performance in air of novel propulsion systems and control surfaces.

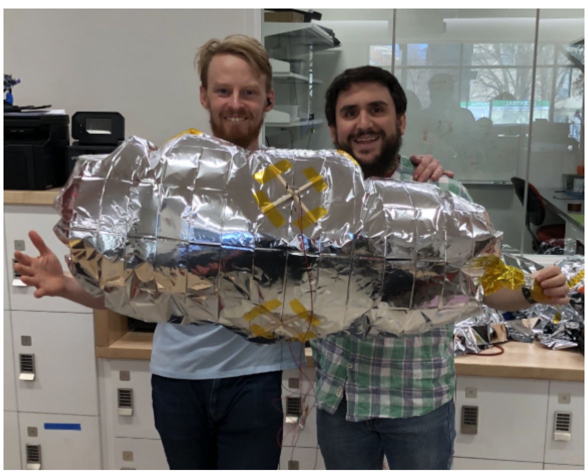

Fig. 1: A completed free floating prototype, George Knight Left, Mitchell Kain Right

II. Blimp Design Considerations

The biggest consideration for every design decision is weight. It is amazing the effect any dense object has on the blimp's buoyancy. It is a key point of discussion in all of the following categories.

A. Materials

1) Skin: The first question to answer was what material to construct the blimp lifting envelope out of. A material was needed that was capable of holding in a lifting gas, preferably for a long period of time, and that would not be too difficult to form into a desired shape. It also could not be too fragile or too heavy for flight. Many of the thermo-plastics commonly used in our lab were light enough to be used, but helium and similar gasses are molecularly small and permeate such materials quickly. The standard material for party balloons, Mylar, was selected. It is light, strong, loses helium slower than latex, and is readily available in large sheets in the form of space blankets.

2) Structure: In order to hold our electronics package and to support control surfaces and propulsion elements, the structure had to be rigid enough to keep the propulsion elements stable for flight dynamics calculation and controllability. Here, the biggest difficulty was, again, weight. We could not do a full ring support as we had originally intended as it was far too heavy, regardless of several considered materials; including balsa wood, cardboard, and rigid plastics. Instead, we were forced to use local x-shaped supports that would prevent the propellors from changing angle by pressing against the skin of the blimp, which when pressurized is relatively rigid.

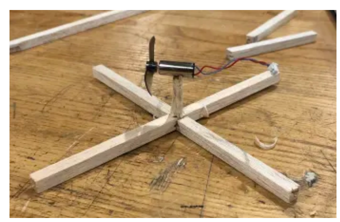

Fig. 2: Propellor mounted on x-shaped support

3) Lifting Gas Selection: It rapidly became clear that our choices for lifting gasses were limited from the beginning to just two options.

- Hydrogen: The most abundant and lightest element in The Universe, and can be produced via electrolysis. Has a tendency to explode.
- Helium: Has a lifting force of 1 gram per liter. Although expensive, it is still readily available for purchase and is completely inert.

Hot Air seemed like an interesting option, at first. It is free, but has the worst performance. Heating the air is a fire hazard and could melt the skin and structure of the lifting envelope. Additionally, unlike the other two options, additional equipment to keep the gas hot would need to be carried, as it does not lift at room temperature.

The lifting force, or net buoyancy force, associated with each gas can be calculated, per unit volume as follows:

$$\frac{F_{Lift}}{Volume} = (\rho_{air} - \rho_{gas}) * F_{gravity}$$

where ρ represents the density of the gases and F represents the indicated forces. Conducting this calculation for each of our candidate gasses we get the results shown in the following table.

It quickly became clear that despite its slight advantages over Helium using Hydrogen would not be worth the effort required to produce it and the safety risks involved with it exploding. Even given the reduced effectiveness of the not completely pure, helium-air mixture readily available.

	Hydrogen at 20°C	Helium at 20°C	Air at 121°C
Density [kg/m^3]	0.0827	0.1634	0.896
Force/Volume [N/m^3]	10.99	10.21	3.021
Volume to lift 50g [m^3]	.0045	.0049	.01655

TABLE I: Calculated values for lifting gases compared to air density at 20°C, $\rho_{\text{air}} = 1.204$ kg/m^3 [1].

B. Control

1) Sensors: In order to keep the blimp as light as possible as much data processing and sensing as possible needed to be kept external to the blimp. Any other choice would require much more lifting force due to additional power requirements leading to increased battery weight in addition to the weight of the sensor itself. For this reason the blimp was intended to work with the motion capture equipment in the RASTIC MOCAP room. This would provide position information for the control algorithm, drastically cut down on the sensors that would need to be carried on the vehicle, and would provide more objective data.

2) Motor Controller: A motor controller was needed that was capable of receiving instructions from and sending flight data information to an external computer. Two-way communication was important in order to capture telemetry data for calculation. We wanted to have only the lightest components onboard, so a small Inertial Measurement Unit being connected to our board would be ideal as it would reduce the calculations necessary from motion capture. An off the shelf drone control board was used to get a response from the propellors for initial testing. The off the shelf board has built in safety's and controls that turn off propellors if the drone board tilts too much. A sensible precaution for a consumer drone, but not suitable for our specialized needs.

Our own control system is currently being designed and built using a low latency communication protocol called ESP-NOW. It is a low power system that transmits information from one ESP32 to another without using WiFi. This gives us the ability to quickly send instructions from an external computer running the control algorithm and collecting data from the ESP32 onboard the blimp and the MOCAP room output. The ESP32 devices are also smaller and more power efficient than the drone boards and as large a battery as weight permits can be attached.

3) Propulsion: The blimp was initially intended to be used as a testbed for a novel propulsion method, designed by Pranav Sultania and Professor Tommaso Ranzani in the Morphable Biorobotics Lab. We instead had to switch to simple brushed motors as the propulsion source as we developed the testbed, as the new technology was not ready for widespread testing. Drone motors were selected as they are exceptionally light and had low power requirements. Future versions will hopefully be able to use this exciting new technology.

4) Control Surfaces: Fins are generally required to keep a blimps or any other flying object's orientation consistent. They needed to be connected rigidly to the structure of the ballon. We had intended to develop morphable or bistable control surfaces to give the robot more maneuverability, however weight and time constraints limited our ability to apply these on this version of the robot. The research conducted is briefly summarized in a later section.

III. Construction Methods

A. Lift Envelope

The most difficult part of the assembly process is the construction of the lifting envelope. The shape of the envelope is based on the work of Atyya et. al. and their paper detailing the optimal shape of an airship [2]. Constructing the envelope, however, required a lot of trial and error to avoid leaks and achieve a level of symmetry that would allow for stable flight.

We were lucky enough to find instructions from a skilled hobbyist who makes blimps for recreational competitions [3]. The method recommended involves using a UHU glue stick and a clever folding method to ensure as air tight a seal as possible. The process is as follows:

1) Cut two mylar blankets into the outline of the blimp using a soldering iron to quickly cut the material with no frays. One should be an inch (half an inch on all sides) larger than the other.
2) Center the smaller sheet of mylar on top of the larger and glue underneath the smaller so that about half an inch of the smaller sheet is glued down all the way around the edge. Weigh down the center of the small sheet with heavy items to keep it from blowing away and keep it stretched taught.
3) When the first gluing has dried glue around the outer half an inch on top of the smaller sheet.
4) Fold the larger sheet over the top of the smaller one, adding glue as you go to ensure that the seam is as sealed as possible. Repeat until completely sealed.

This gives us a single, complete envelope. Practice is essential in making this envelope without leaks. Kapton tape was used to seal as best as was possible any breaches in the vessel.

Fig. 3: Completed Lift Envelope with Luer Lock fill spout.

It is also necessary to create a fill spout through which we can fill the blimp with helium. Several techniques were tried, the most successful being the addition of a mylar flap rolled into a flattened tube. The main envelope is cut and the tube is placed in that cut. The resulting seam is then sealed with Kapton tape, as is the spout after filling. Attempts to use Luer fittings resulted in leaks as the lock are not air (or helium) tight. Better results could likely be achieved with a more appropriate valve.

B. Control System

The ESP-NOW based control system currently being developed seems to be the most promising way forward. The drone boards used to this point require specialized knowledge of RC systems for interfacing with the boards, and the board themselves are not well documented.

ESP32s, however, are very well documented and a standard for this kind of prototyping. The Xiao-Seeed ESP32-S3s [4]selected for this project are particularly small, and feature full WiFi and motor controller capability. They are also capable of being programmed in the widely used Arduino IDE and with a light version of the python language. Additionally, the ESP-NOW communication protocol does not require a WiFi network to function. Sample code for this protocol is provided in detail by ESPRESSIF the ESP32s manufacturer on their website [5]. The figure below lays out the general architecture of our proposed control system.

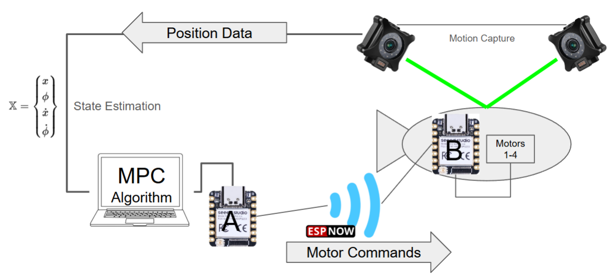

Fig. 4: Diagram of proposed control system under development

The intent is for the robot to be autonomous, and navigate from one position to another within the MOCAP room. An external computer will process all the position data the MOCAP room collects for each fedicial marker placed on the blimp and conduct state estimation. This produces a vector consisting of the blimps position, orientation, velocity, and acceleration vectors. This will be passed to the control algorithm, running Model Predictive Control (MPC) as outlined in [6] which will send control signals via ESP-NOW to the ESP on board the blimp. The Blimp will then follow those commands until it reaches the intended state.

IV. Control Surfaces Research

A. Bistable Deployment

Much time was spent looking at ways to efficiently use bistable mechanisms like those in [7] pictured below to deploy sail-like fins. The main difficulty here was, as in most things with the blimp, weight. The bistable needed a lightweight method of actuation, and was not feasible without making the blimp larger to support the added weight. Since space applications are also very weight sensitive using mechanisms designed for space applications was logical but there was still too much parasitic mass to make it viable.

Fig. 5: Bistable Mechanism from [6]

B. Bio-Inspired Batwing Designs

The Morphable Biorobotics lab is constantly looking for inspiration in the natural world that might apply to our designs. To that end several different animals provided inspiration to control surface and bistable fin designs we investigated.

1) From Literature: Bat wings stow down to an impressively small size and provide a large surface area to use for control and stability. The first version of the wing is a bistable design by [8] that was originally developed to transition a quad copter drone into fixed wing flight.

2) New Design: We also designed our own bat wing like actuator. It would rely on a rotating central hub which spreads spines out or folds them flush with the mechanism. When spread out a membrane would be stretched taught between the spines. When folded the membrane would hang loosely. In the image below the central hub is omitted to show that it can function when rotating around circular hubs of different diameters.

Fig. 6: A batwing mechanism, from left to right, undeployed, deployed around a small radius, and deployed around a large radius.

C. Grid Fins

Grid fins were considered as a steering method in place of the differential thrust method chosen. Most research seems to have been done at high speeds for missiles and spacecraft, but they should be effective at slower speeds. Possibly more effective than at high speeds. But, the dynamics, were difficult to calculate and it did not seem like the best use of resources in terms of time and weight. Also considered, was a form of grid fin that was skew morphable. It was determined that, despite being a novel idea, it would require too much mass for actuation as we would need to design a new, likely heavy, mechanism.

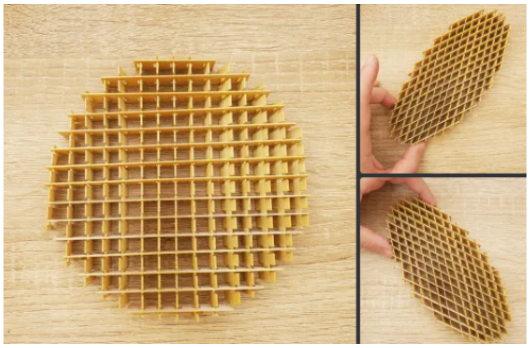

Fig. 7: Grid fin in unmorphed and skew morphed positions.

V. Future Work

The next phase in the development of the Blimp platform is the completion of the ESP-NOW control system. After that, testing can begin on control algorithms and propulsion systems. The main system to be tested is the bistable fluid jet developed in the Morphable Biorobotics Lab. It has already shown impressive performance in water testing, and the mechanism involved is also capable of functioning in air. Additional adjustments would need to be made, in order to support such a differently shaped system, and experiments would likely initially need to be conducted with tethered flight for power and signal considerations.

A flying wing design has been proposed for increased performance. The theory being that if the Blimp's lifting envelop produced lift from form in addition to being neutrally buoyant, we could gain more control over the blimps position and motion in the z-axis as well as pitch. This would also necessitate the use of control surfaces to prevent the blimp from rising in an uncontrolled manner every time it moved forwards. These additional requirements would require this version of the robot to have a larger lifting volume if it is to remain neutrally buoyant when not moving.

A toroidal design has also been proposed. This would move the propulsion system to the center of the lifting envelope, keeping everything on the central axis. The concept is to simplify the equations of motion and test the propulsion systems under simplified conditions. Difficulty arises in the construction of a toroidal lifting envelope, which is challenging to construct in more convention form factors.

The main target of future work should be making a blimp of slightly larger volume, capable of holding larger massed payloads and control and propulsion systems. The Blimp could be a very useful tool to measure thrust and performance once it can be made uniformly and its drag coefficients and equations of motion are well understood, the main barrier to this is the limited payload it can currently carry.

VI. Concluding Remarks

A floating blimp test bed would be a great step forward for the Morphable Biorobotics Lab at Boston University. It would allow detailed performance testing and rapid design iteration for novel propulsion designs. This platform is not without its own development challenges but could provide substantial value to research.

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