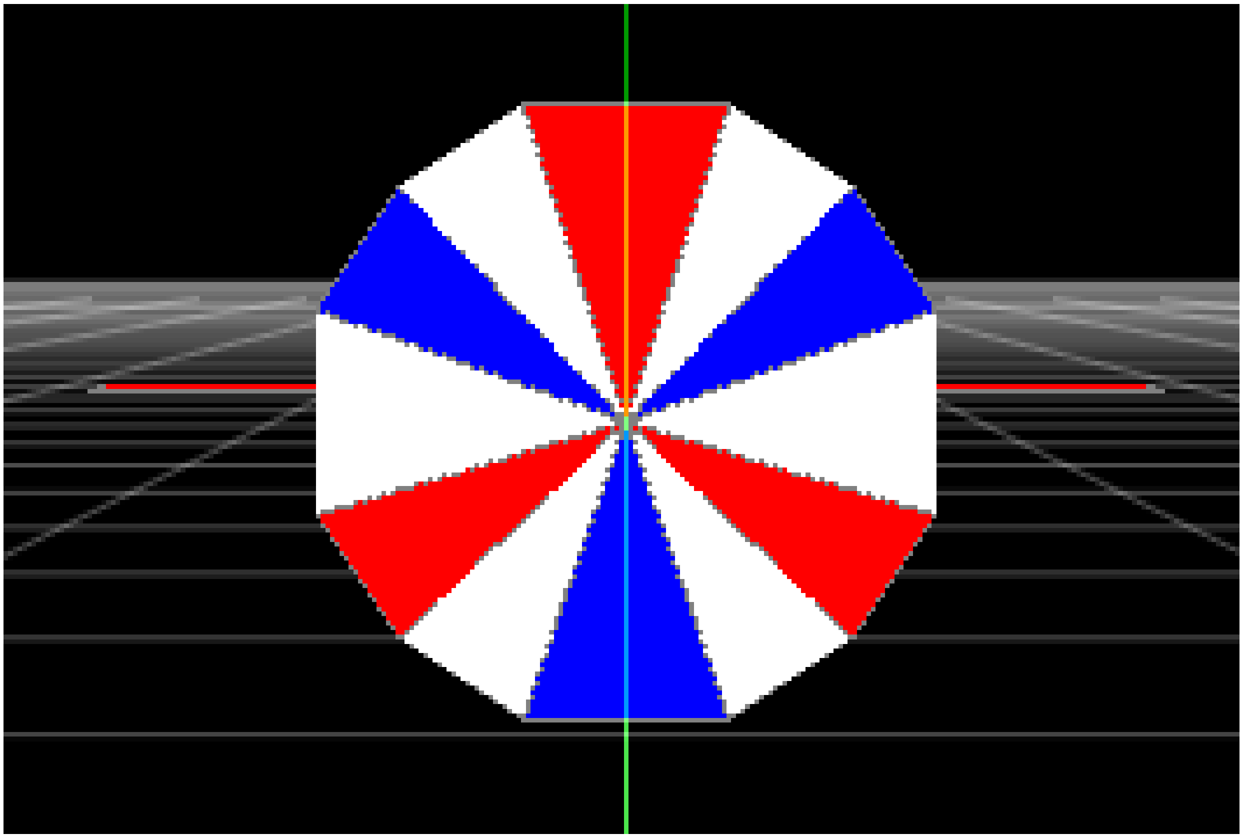

Final Project: Team Blimp

USS Aquafresh

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Abstract

For our final project in ECE 163, we decided to implement a buoyant UAV design. Using a blimp model, buoyancy could be varied in order to reach a target altitude. To do this, we changed the UAV's aerodynamic model with the introduction of buoyancy forces and moments. The buoyancy was then controlled by changing the helium lift bag volume using open loop control. The control implementation was able to successfully reach and hold target altitudes by altering lift bag volume. The main struggle of the blimp design was its wide turn radius, due to the buoyancy moments counteracting other control forces. To fix this shortfall in the future, we would get rid of the ailerons and add an additional propeller. The dual propellor design would allow for the blimp to make sharper turns by having differential thrust—this turning method would not have to fight against the buoyancy moments like the ailerons would. Overall, we consider this project a success as we were able to implement a buoyancy force that behaved properly and was able to be controlled in order to achieve a specific altitude.

Introduction

Background Information

The inspiration for this project stems from our Capstone project for ECE 129 where the four of us, along with two others, plan to make a buoyant drone with the addition of a controllable helium bag on the drone. With this buoyant component, the drone can rely less on the motors for controlling and maintaining altitude, which will both prolong the drone's flight time and provide minimal interference for any payload devices it carries.

Why Blimp?

Although our final design for capstone will be more in the shape of a quadcopter, a blimp design was a good starting point as it reused elements from the work we did in ECE 163, while also incorporating new components of our future design. A blimp design, like our own drone design, would be stable without need for extra vertical force, capable of flying for long periods of time, and have low sensor interference for any payloads.

Goals

Our ultimate goal for the project was to create a functioning blimp model that adjusted the volume of the helium bag to reach the desired altitude and attitude. First, we would need to change the model of the blimp and its attributes, then factor in buoyancy to the model in the form of an upward force and a resulting moment, and then finally change that buoyancy to reach a target height.

Team Composition

Dylan Arius Harootunian - This team member primarily worked on implementing the physics needed for this project, including redesigning gravity forces into a lift forces function, adding new control inputs, and implementing the barometric formula. This member also did much of debugging needed to get the GUI for the simulations working.

George Hernandez - This team member worked out some of the early physics and math for the drone forces and moments, added the volume control to the control files, edited a few classes, such as control inputs, to incorporate buoyant properties, and helped design some of the physical limitations of the drone, such as maximum and minimum volumes.

Leonid Shuster - This team member worked on tuning the gains for the blimp and testing its stability and convergence over time, as well assisting in controlling the bag volume.

Isaac Szu - This team member designed the model for the blimp and worked on VPC to write in values needed for other functions in VAM and ClosedLoopControls. He also spent time helping to research and debug various errors.

Theory

Physics

Total lift force was calculated from the buoyancy and gravity forces. These calculations use attributes of the blimp, including the volume of the lift bag, the air density, and the mass of the blimp. The buoyancy force is first calculated in a similar manner to gravity forces. These are combined to give the total lift force. The moment for this force is calculated by adding the cross products of the gravity and buoyancy forces with the center of gravity and center of buoyancy respectively.

$$F_{gravity} = R^T \begin{pmatrix} 0 \\ 0 \\ mg \end{pmatrix} \qquad F_{lift} = -R^T \begin{pmatrix} 0 \\ 0 \\ B = \rho \cdot Vol \cdot g \end{pmatrix}$$

$$M_s = \overline{NG} \times F_{gravity} + \overline{NC} \times F_{lift} \qquad \tau_s = \begin{pmatrix} F_{gravity} + F_{lift} \\ \overline{NG} \times F_{gravity} + \overline{NC} \times F_{lift} \end{pmatrix}$$

[1]

NG and NC represent the center of gravity and center of buoyancy, respectively. And the tensor τ_s represents the force moment being returned by the new lift forces function.

Air density is calculated using a simplified scaled down version of the barometric formula:

$$P = P_0 e^{\left(-\frac{Mgh}{RT}\right)}$$

Parameter	Symbol	Value	Unit
Average sea level pressure	P_0	101,325	kPa
Gravitational acceleration	g	9.807	m/s^2
Molar mass of Earth's air	M	0.02896	kg/mol
Standard temperature	T	288.15	K
Universal gas constant	R	8.3143	(N*m)/(mol*K)

$$P(h) = 101.325 \cdot \exp\left(-\frac{0.02896 \cdot 9.807}{8.3143 \cdot 288.15} h\right) = 101.325 \exp(-0.00012\, h)\ [\text{kPa}],$$

[2]

This was altered by using VPC.rho as average sea level pressure and doubling the exponential coefficient to -0.00024; h is the altitude value. This alteration was made so that the changes in air density would have a significant effect on the lift force being created from the bag volume in the simulation.

Geometry (Physical Design)

Because of the buoyant moments and forces, the center of buoyancy must be above the center of mass. If not, the buoyant moments will force the blimp to violently turn upside down in order to stabilize the forces. The design is otherwise similar to the drone designed in class, and uses many of the same VPC values, with any changes noted throughout the report.

Advantages/Disadvantages

Blimps have many advantages and disadvantages, so they are great options in some areas, but terrible in others.

One advantage is that the moment created by the lift force is self-righting, so it is very hard to flip the blimp, and if it does flip it will try to turn itself upright. This is great for stability. Another advantage is that blimps use relatively low fuel due to its buoyancy and lower reliance on motors.

As for disadvantages, the blimp is bad at making complex maneuvers since those same buoyancy moments are hard to counteract. Its turn radius is significantly larger compared to the UAV design we used throughout the class. In addition, wind compensation is more difficult due to having larger drag coefficients, so the blimp can be hard to navigate in harsher wind conditions. Also, the blimp’s bag requires large amounts of helium, a scarce resource. Temperature changes can also affect the density and pressure within the bag. Lastly, any punctures can be devastating to flight safety.

Vehicle Aerodynamics Model

The forces being applied to the blimp were modified in VAM based on new control inputs, and were simulated in a modified version of the chapter 4 simulator.

Design Considerations

The aerodynamics model should be able to solve for forces and moments caused by the center of buoyancy. The buoyancy should also be calculated based on the density and volume of the air displaced, as well as the blimp's mass.

Implementation

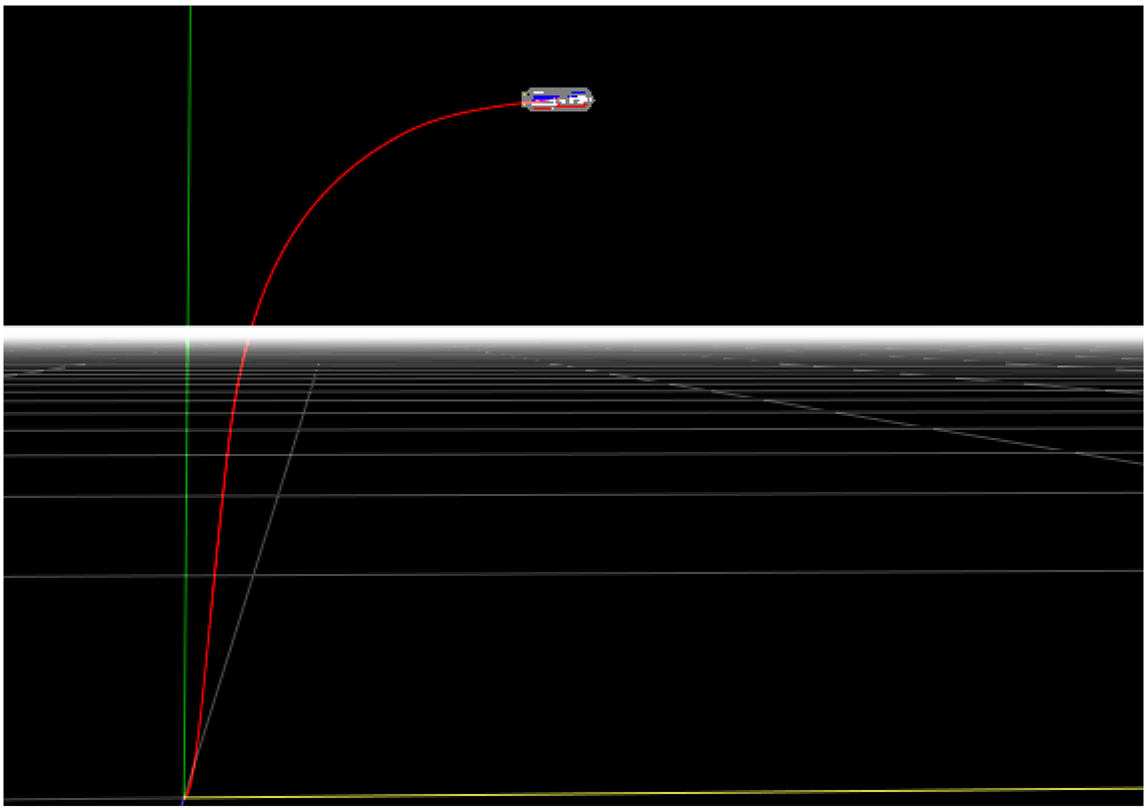
The changes needed to implement the aerodynamics of a blimp were done by first adding two new control inputs to the control Inputs class. The first was bagVolume which was initialized to 8.67371m^3, the volume of helium that would be needed to make the 11kg vehicle neutrally buoyant at the initial AirDensity. This would be the primary control for changing the buoyancy of the blimp. The second control Input was AirDensity which was initialized to 1.2682kPa which is the value for rho in VPC. Although air density is not an actuator, having access to it from a controlled Inputs class instance is very convenient for multiple purposes, such as making it easier to add as a slider, or making it a function of altitude later on in the ClosedLoopControl file. Vectors representing the coordinates for the center of gravity and center of buoyancy in the body frame, as well as a value representing the position on the z axis of the center of buoyancy relative to the center of mass were added to VPC. These new controls and vectors are used in the calculation of liftForces, a new force function in VAM which replaces gravity forces. This function would take in an Input controls class and a vehicle state. The rest of implementation of this function was done as described in the physics section. Once the lift forces function was written, test code was made to assure that the altering of these values produced the expected lift forces. The test code passes the function controls classes with various bagVolume and AirDensity values so that we could assess if the function was returning the expected forces and moments. After testing the function the new control inputs were added to the chapter 4 related files so that aerodynamics could be simulated with the new forces applied by the inputs. This included adding two new sliders for the forces so that they could be adjusted during simulation.

Functionality

While simulating the new forces in the newly modified chapter 4, we found that the new force allowed us to move almost directly vertically by adjusting the bag volume to produce a lift force that was in the negative pd direction. In order to have movement be almost purely vertical, initial speed was reduced to 0.5 in VPC so that we could vertically take off with little forward force. It was set to 0.5 because values smaller than that would result in forces that would push the blimp backwards which we did not want, so some forward movement was accepted so that the blimp did not move in unwanted directions during pure vertical flight.

Since the center of buoyancy was above the center of mass. It was observed that the blimp was now self correcting. The moment created by the position difference between the center of mass and buoyancy caused the blimp to try and keep itself upright at all times. This made controlling the blimp roll very difficult for the ailerons. The benefit to this however was that the blimp was almost impossible to flip over when buoyant. If the blimp was flipped over it would quickly reorient so the center of buoyancy was on top keeping the blimp upright.

The final thing we tested in the modified chapter 4 simulation was how the air density affects buoyancy. It was observed that the adjustment of the air density changed the lift force being applied to the blimp as expected. Changing the air density would change the required bag volume needed for neutral buoyancy; the higher the air density, the less volume needed.



The observations from the modified chapter 4 simulation confirmed that the physics applied in the lift forces function was performing to our satisfaction.

Vehicle Trim

Chapter 5 calculates the trim in order to tell the vehicle whether it needs to ascend or rotate to follow a line or turn.

Design Considerations

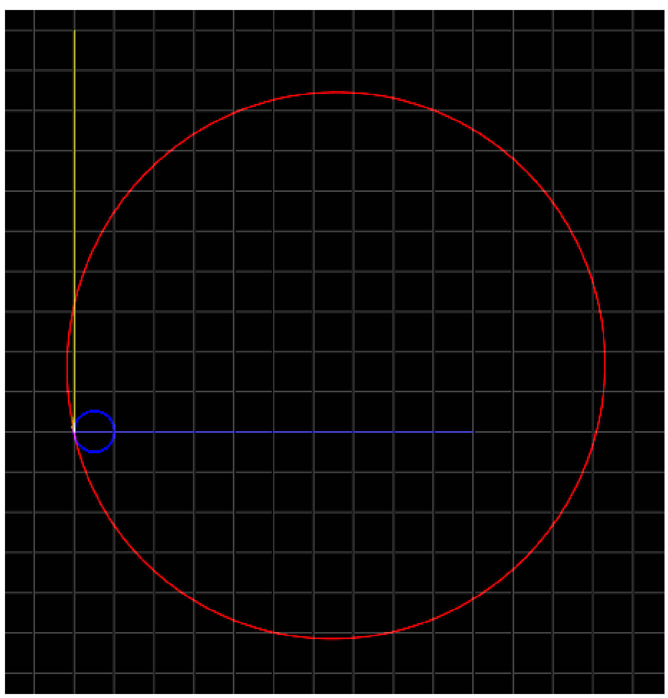
The matrices for the trim did not include effects of buoyancy. Since buoyancy adds both a force in the negative down direction, and moments about all three axes, it needs to be taken into consideration in order to achieve the desired action.

Implementation

The matrices used to calculate trim needed size adjustments to accommodate the buoyancy. These were added, and we included the neutral buoyancy volume at standard temperature and pressure (STP) as the starting point.

Functionality

The trim was able to successfully calculate the buoyancy for climb angles. In fact, the expected trim climb angle was very close to the actual climb angle, but trim calculations involving turn radii were never met. Even though the blimp would eventually make the turn, the correcting moment from the buoyancy made it hard for the blimp to turn quickly, since the ailerons had trouble controlling roll. Our blimp was only able to make very wide turns around a factor of ten larger then the expected turn radius from the trim calculation.



The blimp's command was a 100m radius turn meant to be conducted at 25 airspeed with no climb angle; this is represented with the blue circle in the figures top down view of the simulator. The red circle is the actual turn of the blimp with around a 1300m radius. Since the moment created by the buoyant force is so strong, the blimp has trouble counteracting it with the current setup. This causes roll angles to be extremely limited, causing high radius turns. If the throttle speed is increased, the forces from the aileron, elevator, and rudder are increased, and make a tighter circle, but the turn radius is still limited.

Closed Loop Control

The closed loop control file is in charge of adjusting the positions of the aileron, rudder, and elevator, as well as the throttle and balloon volume.

Design Considerations

For the ClosedLoopControl file, we wanted to incorporate volume control of the lift bag. Since the buoyancy moments are high, the focus in adjustment is for the altitude control. Also, air density is adjusted as a function of height, so a simplified model of the barometric formula is incorporated. The volume should correct for buoyancy within a maximum and minimum volume.

Implementation

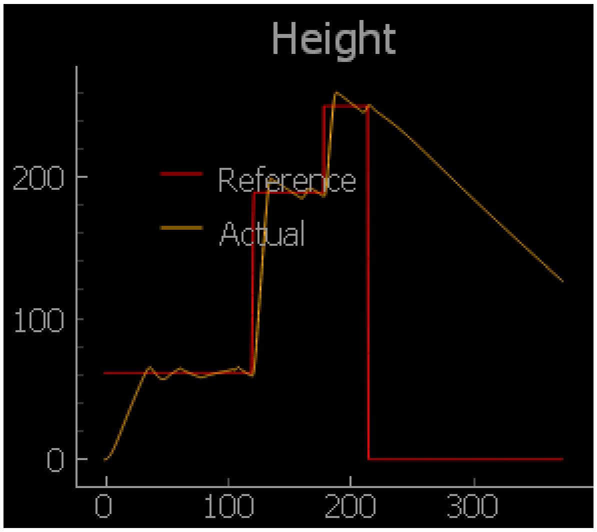
For the implementation of the blimp in chapter 6, a maximum and minimum value for bagVolume were added into VPC. These were used as the commanded volume in the ascending and descending altitude states in ClosedLoopControl. This was in order to get the blimp to the desired altitude. We also implemented the barometric formula discussed in the physics section in order to update the current air density based on the current altitude.

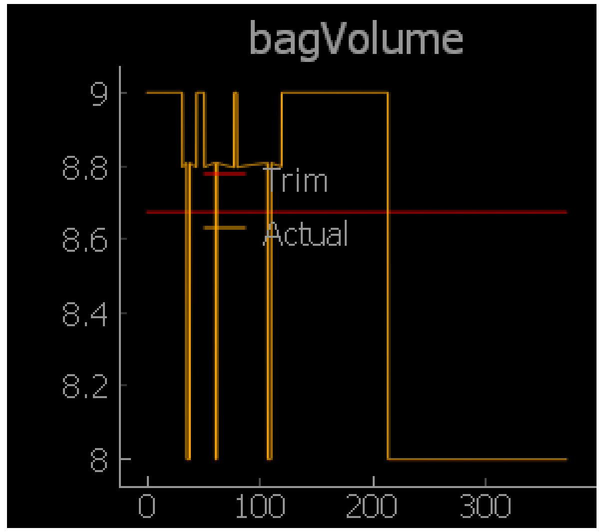
To find the volume range of the bag, we first calculated the volume needed for neutral buoyancy at STP, approximately 8.6 cubic meters. From there, a minimum and maximum volume were arbitrarily decided at 8 and 9 cubic meters, but the actual volume range would depend on physical design.

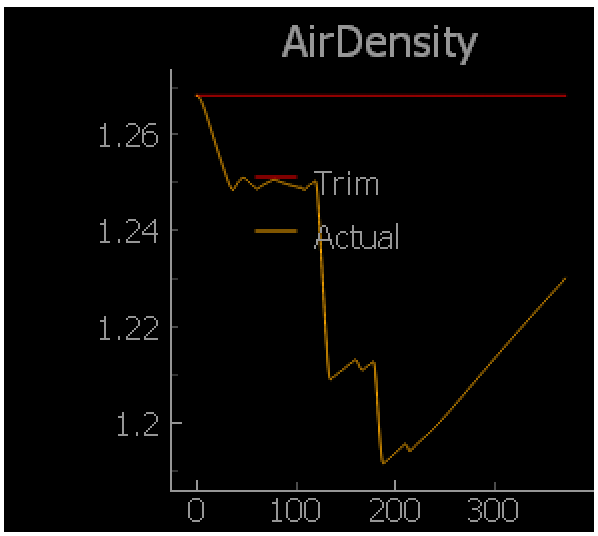
For the control, if the blimp was ascending, it would maximize its volume. If the blimp was descending, the volume would be minimized. If the blimp was in the hold zone, the volume to maintain neutral buoyancy is calculated based on the current air density and blimp mass. If the value is in the allowable volume range, the balloon volume is set to it, and if not, the balloon volume is set to its minimum value or the maximum value, whichever is closest. Since the buoyancy forces are very small when the blimp is near neutral buoyancy, a hold zone range is specifically added for the volume control. The hold zone range for the rest of the drone is set at 30m in the Vehicle Physical Constants file, but the hold range for the volume is set at 3m; this helps the balloon volume contribute more to stabilization of the drone, since the lift force automatically dampens as the drone approaches neutral buoyancy anyways.

Functionality

The altitude control works extremely well, and balances out quickly. The gain values were set at kp_pitch = -6.5, kd_pitch = -13, kp_alt = 0.042 and ki_alt = 0.021. The results are shown in the graphs below and show the drone increasing altitude in two steps, before dropping. The gains on the rest of the controls were not tuned in since the altitude control was our main focus, so the drone is pretty wobbly. The blimp could have a near vertical takeoff, and stable height control, but it is slow to dive.







As can be seen when the drone ascends, the bag volume is set to a maximum volume of $9m^3$. Then when it gets to the actual height, the neutral buoyancy volume is calculated and implemented, resulting in a small drop in volume. When the altitude is increased again, the volume is set to 9, but remains 9 at the hold state since the calculated neutral volume is higher than the max due to the lower air density. Then, when the blimp dives, volume is set to the minimum of 8. The controls for the altitude behaved properly and responded well.

Blimp Modeling

Design Considerations

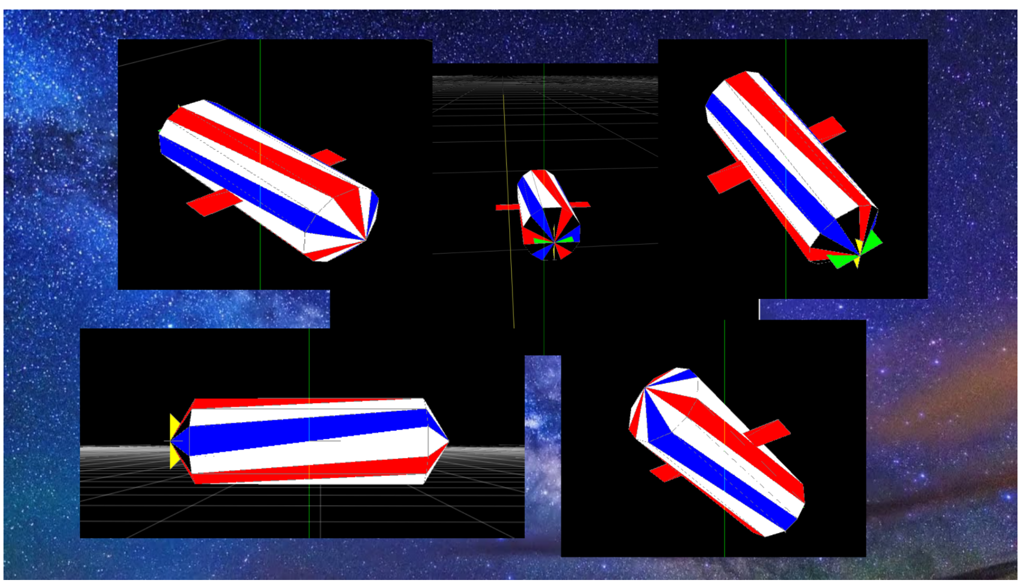
Our main focus was to design the blimp model similar to a blimp, and contain similar attributes to one.

Implementation

The model we've drawn is a dodecagonal front and back cone followed by 24 body triangles to connect the two polygons. The front tip is a single point surrounded by 12 other points to create 12 triangle faces and the same is done for the back end. Between the two cone faces are 24 triangle faces to connect the two ends. The rudder is mirrored and the elevator and ailerons that come with it are adjusted to the blimp's diameter.

Personality

This design draws inspiration from the classic barber shop pole with a focus on American colors. The green and yellow rudder and elevator finish on the back of our blimp help them stand apart from the rest of the aircraft. This handsome, stunning, and sleek design reminded the team of a tube of toothpaste earning the blimp design its name, USS Aquafresh.



Potential Areas to Improve

The project accomplished a lot of the goals we set out for, but it is not a complete blimp model.

Vehicle Aerodynamics

The file works extremely well and no areas for improvement were found. The file would be updated for future design changes to the blimp such as if alterations to the actuators are made.

Vehicle Trim

The model for trim and forces seems to work in the Vehicle Trim files, but the radius is limited by the physical design. The physical design would need to be changed in order to compensate for the buoyant moments. This can be done by manipulating some values in VPC, such as values for the rudder, or with model changes such as using a second motor propellor to generate moments about the z-axis.

Closed Loop Control

ClosedLoopControl appears to work well, and only the wobbliness of the blimp needs to be fixed, which would be done by dialing in the gain values in the GUI. A feature that would be helpful is gradual volume control. The current design assumes volume is changed instantaneously, which works well for the speeds it is currently able to move at, but if the blimp were able to change altitude at a faster rate, it would no longer be accurate. A maximum volume change rate would be helpful in further developing the design.

Beyond

Some of the future plans we'd like to implement with our code is to add a PI control loop for the air bag volume to change with altitude and air density. The blimp model would also be modified closer to a drone and simulate terrain tracking and obstacle avoidance. Finally, removing the ailerons and adding a second propeller could help decrease the large turn radius. Having a design where there are propellers on either side of the blimp would allow it to turn without needing to roll in the way that aileron turns do. This is important since the moment created by the difference between the center of gravity and the center of buoyancy causes the roll to diminish greatly from the moment being applied by the ailerons. The two propellor design would allow the blimp to turn simply by powering one propellor more than the other applying a yaw moment rather than a roll moment created by ailerons; this would not be countered by the buoyancy moment and could allow for sharper turns. The removal of the ailerons could also have additional benefits such as reduced weight and less forces being applied to the blimp during vertical takeoff, but this is to be determined and would need further research.

Conclusion

In the project, we set out to add buoyancy to the UAV design, and make it a blimp. We edited the Aerodynamics model, Visual Model, Vehicle Trim calculations, and Closed Loop Control to incorporate these changes. The Aerodynamics model calculated the forces and moments caused by buoyancy, as well as the magnitude of the buoyancy as determined by the lift bag volume and displaced air density, and functioned exactly as expected. The visual design was changed to look more like a blimp, and it looks great. The vehicle trim did run into some issues, but we believe the problems were related to the physical design of the blimp—the blimp as designed cannot make expected tight turns. This is due to the buoyant moments counteracting the moments caused by other flight controls. The simulated results showed the turn radius was off by a factor of 10 in multiple tests. The physical design of the blimp needs to be updated to allow better turning, but the simulation appears to be accurate and functional, and follows climb angles extraordinarily well. Volume control was added to *ClosedLoopControl* and modeled as instantaneous volume change, which is acceptable for the blimp since it has slow climb and dive rates anyways, but it is not a sufficient model for higher speeds. The way to adjust this would be to add a maximum volume change and calculate the volume based on that. The other gain coefficients were not calculated for in the simulations since we were focused on the volume and altitude control, resulting in wobble, but the altitude and volume control work extremely well and stabilize quickly. The project met all the goals we set out for, but we want to improve on a few areas, especially in changing the physical design. This project was chosen as a precursor to the buoyant drone design we want to incorporate in our capstone course, and we feel we learned alot about the physics and controls considerations for buoyant designs, and will be taking that knowledge into our capstone design. The project was extremely successful in meeting our assigned goals and preparing us for further buoyant drone design.

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