User Based Design and Evaluation Pipeline for Indoor Airships

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Abstract—Designing a controllable airship for non-expert users or preemptively evaluating the performance of desired airships has always been a very challenging problem. This paper explores the blimp design parameter space from the aspect of the user by considering various distributions of thrust, combinations of propulsive mechanisms, and balloon shapes. We provide open-source modular hardware and reconfigurable software design tools that allow inexperienced users to design a custom airship in a short time. Based on these design parameters, this paper develops a more engineering-focused evaluation system that can characterize the performance of different indoor blimps. An analytical comparison and some case studies that consider various points in the design parameter space have been conducted to prove the feasibility and validity of our design and evaluation system.

I. INTRODUCTION

Due to their ability to neutrally float in the air, lighter-than-air vehicles (LTAVs) had been widely studied and used as research and military platforms for aerial robotics over the last century. As a branch of LTAVs, the indoor airship is gaining increasing attention due to its promising potential for many applications \cite{1}. In the past 20 years, indoor blimps have been developed for infrastructure inspection \cite{2}, environmental data collection \cite{3}, indoor localization and mapping \cite{4}, education and research platforms \cite{5}, vision-based human-robot interaction \cite{6}, and other activities. While these tasks may also be conducted using unmanned aerial vehicles (UAVs) such as quadrotors, their flight duration time is generally only between 20 to 30 minutes, restricted by the power required for them to hover in the air. Quadrotors can also cause safety concerns when they operate in indoor environments with humans due to their relatively high operating speed and high-speed rotating blades.

In recent years, several research projects have focused on developing techniques related to indoor airships, and oftentimes, such projects focused on the controller design for a particular blimp developed by the authors. This has been observed with respect to PID altitude control \cite{7}, fuzzy logic control \cite{8}, neural network control \cite{9} and other controllers with various applications \cite{10,11}. These controllers only apply to their specific scenarios and particular airships, however, and are not accessible to ordinary users interested in implementing a novel design in user-specific scenarios such as a big warehouse or supermarket.

Among papers that deal with blimp design and application, Biju et al. described their blimp design subsystem and conceptual design method. Their blimp was very large in size, however, and difficult to scale to a miniature blimp \cite{12}. In contrast, \cite{5} presented a low-cost open-source miniature indoor airship for research and education applications, but its fixed structure makes it hard to extend its capability. The authors of papers \cite{13} and \cite{14} presented GT-MAB, a class of indoor miniature blimp designs, and a method to identify its model parameters. This approach is only applicable to a saucer-shaped balloon, however, and the fixed gondola complicates extending the concept to other configurations.

The research presented in this paper focuses on the design and evaluation aspect of indoor airships as shown in Fig. 1. We provide a user-based blimp design pipeline that allows inexperienced users to design and evaluate custom blimp designs. The modular design tools allow users to customize their hardware and electronics, and the reconfigurable control software allows users to change their control method under different configurations from the software level. The design evaluation system can help users check whether their design meets the motion and payload criteria, in addition to outputting an estimated performance of their designs.
blimps. The modular design tools are open-source and can be easily fabricated using 3D printers. To help users have a better understanding of designing custom indoor blimps, our work explores the blimp design parameter space from the user perspective by considering different configurations that users may care about, i.e., different thrust distributions, different propulsion combinations, varied balloon shapes, and the weight distribution.

Using user-based design parameters as inputs, our evaluation system then checks that these configurations can successfully generate basic motion primitives while estimating the payload capacity to ensure lighter-than-air travel. If the design from users passes these motion and payload checks, the evaluation system will output the blimp performance, defined as the maximum horizontal and vertical velocity the blimp can achieve (for a detailed explanation, see section II).

In summation, the main contributions of our paper are the following:

1. We create a modular design tool that allows users to design their own custom blimp, along with a software configurable motion control panel that can correctly interpret user-defined hardware electronics connections, such as motors to a controller board.

2. We propose a custom-blimp-design evaluation system that takes in design parameters, checks configuration feasibility, then provides as output the steady-state performance of the blimp design.

II. USER BASED DESIGN PARAMETERS SPACE

Basically, for normal users who would like to customize their own airship for some particular scenarios, there are three aspects that are required to consider in their designs: thrust distribution, propulsion system, and balloon shape. Our design parameters are also derived from these three aspects.

A. Thrust distribution

In many indoor blimp designs, different thrust distribution is the main difference between the different designs. In thrust distribution, what users should care about is the position of their thrust. In order to enable the airship to have complete space exploration capability, the thrust distribution should be designed to satisfy three motion primitives:

- Maintaining forward speed. The blimp should be able to maintain a desired constant forward speed while having zero vertical speed and zero yaw angular speed.
- Changing altitude: The blimp should be able to ascend or descend to the desired height.
- Changing orientation: The blimp should be able to spin in place so that its yaw angle can be stabilized at any desired value.

B. Propulsion system combination

The propulsion system that we talk about in this paper is limited to only the "DC motor + propeller + servo motors(optional)" combination. Motors propellers have been studied for more than centuries. And they are dynamically stable, reliable, easy to design and control [15].

One benefit of using DC brushed motors is that the relationship between motor voltage $V_{motor}$ and thrust $\tau$ generated by propellers is a fixed function as shown below:

$$V_{motor} \xrightarrow{\text{load propeller}} \tau$$  \hspace{1cm} (1)

By changing the PWM signals from the control board, we can control the voltage outputs of the motor and thus control its thrust.

C. Balloon shape

In this paper, we only discuss the balloon envelope made of Mylar material, which is a polyester film made from stretched polyethylene terephthalate (PET). This material is chosen because it is used for its high tensile strength, chemical and dimensional stability, transparency, reflectivity, gas and aroma barrier properties, and electrical insulation [16]. Based on most of the literature, in our paper, we only discuss three common shapes: sphere, saucer, and oval shape balloon. Different shapes of balloons have different 3D dimensions and aerodynamic properties which will affect the performance of the designed airship.

D. Design parameters

In the design parameters space, we considered two types of design parameters that are user-friendly: hardware design parameters that are used for designing gondolas and support materials, evaluation design parameters that can be fed as inputs into the evaluation system.

For hardware design parameters, we need to consider:

- Propeller diameter: $d_p$
- Motor length: $l_m$
- Motor diameter: $d_m$
- Dimension of the selected control board: $l_{c_x}, l_{c_y}, l_{c_z}$

For evaluation design parameters, we need to consider:

- Thrust of propeller: $f_t$
- The position of each thrust component $i$ in the body frame: $p_i := [x_i, y_i, z_i]^T$ s.t. $i \in \{1...N\}$, $N$ is the total number of thrust vectors in the system.
- The orientation primitives of each thrust component $i$: $K_i = [k_x, k_y, k_z]^T$ s.t. $k_x, k_y, k_z \in \{0, 1\}$, 1 means that this thrust vector is in line with the corresponding axis and 0 means that it’s not generating thrust on that axis.
- The cross sectional area (CSA) of the inflated balloon: $A_{x}, A_{y}, A_{z}$.
- Mass of electronics, balloon envelope, support materials, and payload: $m_{elec}, m_{envelop}, m_{sup}, m_{payload}$

Look at the design of indoor blimps in recent years, miniature indoor blimps actually have a relatively simple design framework that contains several necessary components. The fundamental difference between different designs is the configuration of thrust, propulsion system, balloon shape, and weight distribution of sensors and other components.
Fig. 2. The user-based parameters should mainly consider thrust distribution, propulsion system and the balloon shape.

Fig. 3. (a) centralized reconfigurable gondola design. (b) decentralized reconfigurable gondola and motor support design.

E. Modular hardware and reconfigurable design

The purpose of the modular re-configurable hardware and design tool is (1) to help users to allocate their own thrust distribution (2) to provide suitable support materials that fit the dimension of the chosen propulsion system.

We designed a reconfigurable 3D printed gondola which allows users to reconfigure their thrust distribution in the way they want by simply changing the position of the motor support as shown in Fig. 3(a). For decentralized design, we also provided separated support structures that allow users to place their control board, DC motors, servo motors, and propellers on any position of the balloon surface as shown in Fig. 3(b). Based on different design purposes and configurations, different types of gondolas and support materials can be easily fabricated using 3D printers or origami printers. Based on the user’s required hardware design parameters that were introduced before, all these support materials can be customized using our open source files provided in the git: https://github.com/zhz03/User_Based_Design_and_Evaluation_Pipeline

As for different dimensions of the propulsion system, our support materials could customize the diameter of motors between 4mm ~ 8.5mm. The shaft diameter of the propeller can support common types such as 1 mm and 0.8 mm on the market and it’s determined by the shaft diameter of the selected motors.

F. Reconfigurable control software design

In the blimp design, reconfigurable hardware is only one part of the design, the other part of it is to allow users to control their designed blimps in the right way. The purpose of reconfigurable software is to enable the operation of the control software to match the right wire connection between the control board and propulsion system after the modular hardware design meets basic motion primitives. In our design pipeline, we choose Adafruit ESP32-based Feather and its compatible 4-Channel DC Motor as well as 8-Channel PWM Servo FeatherWing as the main control circuit.

We choose Blynk APP as the control interface since it’s a freely available application that anyone could download online. As shown in the 4, our control panel contains two joysticks to control blimp movement(horizontal and vertical) and one slider to control all motors speed. Since the wiring of electronics will directly determine how to manipulate the custom blimp, our reconfigurable low-level program can handle the wiring and connection between the control board and propulsion system and allows users to re-map the control to the actual propulsion system they design through the terminal panel.
To find out the correct command that matches the mapping, users need to go over the following three iterations:

(Iter. 1) Initialization: Initial command "1F2B3U4DN" means that DC motor channel 1 is "forward" rotation, channel 2 is "backward" rotation, channel 3 is "upward" rotation, channel 4 is "downward" rotation, and the left and right direction is not confirmed.

(Iter. 2) Determine main horizontal and vertical channel: based on the actual propellers rotation and activation situation, use joystick to check if previous command is correct, if not, then change the command to determine the correct horizontal and vertical channel and rotation direction. Command after iteration example: "1F2F3U4DC1L2R". The last 5 digits means that horizontal and vertical channel are confirmed using DC motor and assume channel 1 to rotate left and channel 2 to rotate right.

(Iter. 3) Determine the rotation channel from previous command: if the previous command is correct then stop. If not, then switch the rotation channel, for example: "1F2F3U4DC2L1R".

III. EVALUATION SYSTEM DESIGN

In our evaluation system, the problems we could like to help users to solve are: (1) Whether the designed blimp can effectively move in the 3D space, which is to meet the three basic motion primitives. (2) Whether the designed airship can be effectively suspended in the air, that is, it can maintain neutral buoyancy in the air without activating the propulsion system. (3) What is the estimated maximum performance of the designed airship. In this section, we will discuss three main functions in the evaluation system: (1) Motion primitives checking, (2) Payload checking and estimation, (3) Steady-state performance estimation.

A. Motion primitives checking

When non-expert users use our modular design framework to design their own blimps, one notable design problem is that their custom design may not satisfy their needs of exploring the space, which is to satisfy the basic motion primitives as described before. Mathematically, motion primitives checking is defined as:

$$\begin{bmatrix} F_p \neq 0 \\ F_p \neq 0 \\ F_p \neq 0 \end{bmatrix}, \begin{bmatrix} M_p \neq 0 \\ M_p \neq 0 \\ M_p \neq 0 \end{bmatrix}$$

Where, $M_p$ is the moments generated by propulsion force. $F_p$ and $M_p$ can be calculated by Equ.

$$F_p = \sum_i f_i K_i$$

$$M_p = \sum_i a_i \times (f_i K_i)$$

B. Payload estimation and checking

Oftentimes, for users who choose a 2D envelope to make an airship, it's hard to tell whether their chosen 2D balloon envelope could offer enough buoyancy after it’s inflated. For indoor airship, the total lifting capacity can be divided into: electronics, balloon envelope, support materials and payload. Therefore, the total mass is calculated by:

$$m_{total} = \sum_i m_i = m_{elec} + m_{envelop} + m_{sup} + m_{payload}$$

To allow the designed airship to maintain neutral buoyancy in the air without activating the propulsion system. The payload checking criteria is: $m_{payload} \geq 0$.

The buoyancy $F_B$ can be calculated using Archimedes’ principle and is equal to the weight of helium and all other components:

$$F_B = \rho_{air} V_{envelop} g = \rho_{air} f(L_x, L_y, L_z) g = (m_{helium} + m_{other}) g$$

where $\rho_{air}$ is the density of air and $V_{envelop}$ is the volume of the envelope, which is the function of 3D geometry dimension $f(L_x, L_y, L_z)$.

In this paper, the balloon shapes we discussed are sphere-shaped, saucer-shaped, oval-shaped, and non-regular oval-shaped. All of these four different shapes can be characterized and using the ellipsoid 3D geometry model to calculate their volume.

According to Equ.(5), the payload is calculated:

$$m_{payload} = V_{envelop} (\rho_{air} - \rho_{helium}) - (m_{elec} + m_{envelop} + m_{sup})$$

However, $L_x, L_y, L_z$ are the dimension after the balloon is inflated. To tell directly from 2D deflated envelop, we need to map the dimension of the 2D deflated balloon to $V_{envelop}$.

Since the elasticity of Mylar is very small, by using the principle of entropy increase, we can assume that the surface area of 2D envelope $SA_{2D}$ is similar to the surface area of 3D inflated balloon $SA_{3D}$: $SA_{2D} \approx SA_{3D}$. Therefore,

$$SA_{3D} = 4\pi r_{3D}^2 \approx SA_{2D}$$

$$r_{3D} = \sqrt[3]{\frac{SA_{2D}}{4\pi}}$$

$$V_{envelop} = \frac{4\pi}{3} r_{3D}^3$$

C. Steady-state performance estimation

The kinematics and dynamics of our blimp system can be divided into a linear component and an angular component. We first show how we modeled the linear part, then we present a steady-state maximum speed calculation, which is a critical performance metric.

$$\begin{bmatrix} F_p \neq 0 \\ F_p \neq 0 \\ F_p \neq 0 \end{bmatrix}, \begin{bmatrix} M_p \neq 0 \\ M_p \neq 0 \\ M_p \neq 0 \end{bmatrix}$$
TABLE I
TWO CASE STUDY USING MODULAR HARDWARE AND RECONFIGURABLE SOFTWARE DESIGN TOOL

| Case | Circuit diagram | Thrust dist. | Motion Checking | Iter. 1 | Status | Iter. 2 | Status | Iter. 3 | Status |
|------|-----------------|--------------|----------------|---------|--------|---------|--------|---------|--------|
|      |                 |              |                |         |        |         |        |         |        |

1) **Modeling:** The linear system dynamic in the world frame is:

\[
\begin{align*}
    \dot{v}_x &= \begin{bmatrix} 0 \\ 0 \\ mg - F_B \end{bmatrix} + R_{wb} \begin{bmatrix} F_X - f_x(v_x, body) \\ F_Y - f_y(v_y, body) \\ F_Z + f_z(v_z, body) \end{bmatrix} \\
    \dot{v}_y &= \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}
\end{align*}
\]  

(11)

Where \( m \) is the total mass of our blimp, \( F_B \) is the buoyancy, \( R_{wb} = R(\phi, \theta, \psi) \) is a rotation matrix that captures the controller-governed attitude with a roll \( \phi \), pitch \( \theta \), and yaw \( \psi \), \( F \) is the net propulsion provided by motors, and \( f \) being the drag, which is a function of velocity in the body frame.

2) **Steady-state Solution:** We observe that our drag model is in fact a mapping from speed to drag force [17]. So if we can calculate what the terminal drag force is, we can infer what the terminal velocity should be.

To calculate the terminal drag force, we set the acceleration on all 3 axes to be equal to 0, that is: \( \dot{v} = 0 \).

The terminal drag can thus be extracted from Equ. (12)

\[
\begin{align*}
    \begin{bmatrix} f_x(v_{x,\text{max, body}}) \\ f_y(v_{y,\text{max, body}}) \\ -f_z(v_{z,\text{max, body}}) \end{bmatrix} &= \begin{bmatrix} F_X \\ F_Y \\ F_Z \end{bmatrix} - R_{bw} \begin{bmatrix} 0 \\ 0 \\ F_B - mg \end{bmatrix} \\
    F &= \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}
\end{align*}
\]  

(12)

With our drag model, we can calculate the terminal velocity as in Equ. (13)

\[
f = \frac{1}{2} \rho v^2 C_D A \quad \Rightarrow \quad v_{\text{max, body}} = \sqrt{\frac{2f}{\rho C_D A}}
\]  

(13)

Where, \( C_D \) is the drag coefficient which can be calculated using the method provided in [9] or in our paper, we used CFD software – Ansys Fluent to approximate. The Ansys Fluent can calculate the result in half hours after the 3D model is designed and modified in our modular design.

**IV. CASE STUDY, EXPERIMENT AND ANALYSIS**

A. Designed blimp case study

To verify our design tools, we designed two different cases with different shapes and different numbers of motors and propellers. Both of them have passed our motion primitive checking since their thrust distributions meet three basic motion primitives requirements. Table I shows how to map the wiring with control software in a three-step iteration through commands. Eventually, after the adjustment through commands, the software can control the design airship to conduct the right horizontal, vertical, and rotation movement.

B. Balloon Volume estimation case study

**TABLE II**
COMPARISON OF MEASURED AND CALCULATED BALLOON VOLUMES

| Balloon | Actual Vol. (m^3) | Calc. Vol. (m^3) | % Error |
|---------|------------------|------------------|---------|
| White   | 0.0338664        | 0.0326159        | 3.834   |
| Silver  | 0.0139214        | 0.0152378        | 8.639   |
| Red     | 0.0963472        | 0.1261541        | 23.627  |
| Black   | 0.0721492        | 0.0947815        | 23.878  |

In this case study, we conducted measurement and comparison on 2 saucer-shaped balloons (Silver and Red), 1 oval shape balloon (Black), and 1 spherical shape balloon (White) in order to verify the theory from payload estimation. We measure their actual volume after inflated and we also calculate their theoretical volume using our theory. As shown in Table II all the mean error is less than 25%, which means that our calculation can be regarded as the upper bound of the payload estimation.

C. Experiment settings

We considered 3 groups of experiments to verify the impact of different design parameters. In order to verify the design evaluation system, we conduct performance testing under the Opti-track system and compared it with the results from the evaluation system.

In the 3 groups of experiments, We use the controlled variable method to change only one of the parameters and keep the other parameters unchanged each time as shown in
Table III. In experiment group (1), we use different thrust distributions and maintain all other high-level parameters as the same. In group (2), we choose two different propulsion combinations. In experiment group (3), we used two different balloons that have different shapes.

D. Results and discussion

According to the comparison results, as shown in Fig. 5, the evaluation system is able to predict the vertical and horizontal speed trend, and it can also predict the terminal velocity of the designed airship. Some of these predictions are even within the error range of real experiments, for example, the horizontal speed of group (2)(b) and group (3)(c), and the vertical speed of group (1)(d). Except for the Fig. 5 (f), the maximum prediction errors is less then 25%. Based on the experiment data from Fig. 5 (f), we have reason to believe that in the real experiments, the actually designed blimp didn’t reach its maximum velocity before the Opti-track system stopped recording. Some other observations from the experiments:

- In the group (1) experiments, although the thrust in the first configuration is twice the thrust in the second configuration, since the drag coefficient increases with the increase in speed, the terminal speed is not twice the relationship.
- Even though the thrust distribution is the same, different motor + propellers combinations will also cause a huge impact on the performance of the designed blimp. And change the propulsion system is actually the fastest way to change its performance.
- Balloons with different shapes may "accidentally" have similar performance, but due to different volumes, the payload could be very different.

V. CONCLUSIONS

This work provides a modular and reconfigurable design framework to help the non-expert user design their own custom blimps. By exploring the design parameter space, our design and performance evaluation system provides an end-to-end solution that will both build and characterize the blimp designed by users. Using a case study and comparison between experiments and predicted performance, we have proved the feasibility of the design and evaluation system presented in this paper.
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