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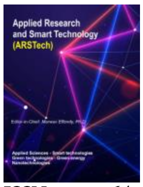

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Research Article

A remotely-controlled micro airship for wireless coverage

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ABSTRACT

This paper describes the design process and prototype development of a remotely controlled airship for wireless coverage. The airship is designed to be used as a platform to provide wireless coverage for rural areas. The design process follows a systematic design process for lighter-than-air vehicles, modified to impart slight heaviness to the vehicle. A remotely-controlled, thrust-vectored electric propulsion system offsets the slight vehicle heaviness. The electric propulsion system comprises two tilting rotors for takeoff, cruise, hovering, and horizontal manoeuvring. A rudder-less, rotor-less, cruciform fin design was implemented. A reduced-scale prototype of the airship was developed to prove the design concept. The airship prototype was successfully tested in an indoor environment. It was discovered that propeller tilting enables the dynamic thrust vectoring demanded by the various flight manoeuvres. If the airship can fly, no one will have to handle its flight when it is needed for wireless coverage.

1. INTRODUCTION

No country has full wireless network coverage over its entire land. Building wireless network infrastructure requires huge costs, equipment, and many working days. Governments and mobile service providers allocate their resources to areas of high population. Therefore, it is not an uncommon experience to have many areas with no or weak wireless coverage, especially remote areas with no or very limited number of inhabitants. Direct satellite wireless coverage is possible, but it requires special receiving devices and is offered at an unaffordable cost to the main users. In addition, there are several global and local events, such as Formula One and similar racing competitions, which witness hundreds or thousands of people gathering for a few days in rural areas which may fall outside the skirts of the existing mobile networks [1].

Providing mobile services for the participants in such limited-time events by working on a "coverage on-demand" strategy poses a challenge for mobile service providers [2-4].

Another need for temporary wireless coverage arises after the destruction of the wireless network infrastructure following a natural disaster or an act of war. A prominent and emerging solution to the problem of lack of wireless networks is to employ flying vehicles to transmit signals to users on the ground when needed. Temporary airborne wireless network stations can alleviate the disconnection problem of rescue workers and affected populations without waiting for ground-based towers' costlier and time-consuming construction [3,5]. Airships or aerostats have been proposed as low-cost alternatives for high-altitude platforms (HAPs) operating in the stratosphere (up to 22 km) to provide communication facilities for the delivery of future broadband wireless communications [2,6]. Airships are proposed as a platform to provide wireless coverage. The airship can carry a base station and an antenna, providing LTE coverage over certain regions for specified periods. The design features and attributes that an airborne wireless transmitter platform possesses can help to provide wireless coverage seamlessly and efficiently. Airborne wireless coverage may also help rural regions transition from poor, unreliable, sluggish service to ultrafast, cutting-edge 4G and 5G networks. A typical HAPs mobile network architecture is shown in Figure 1.

Low-altitude aerostats have also been proposed as a platform for cost-effective wireless communication as an alternative to fixed tower networks to fill the digital gap in rural areas. Aerostat platforms carrying wireless communication equipment at altitudes of few-hundred-meters can establish last-mile wireless over a radius of around 10 km. The Lighter-Than-Air Systems Laboratory of the Indian Institute of Technology Bombay designed, fabricated, and tested a low-altitude aerostat for wireless coverage [7]. The United States-based company Altareos has developed autonomous, tethered aerostats which can be used for wireless coverage flying for a few days at altitudes of a few hundred meters (an example is shown in Figure 2. [8].

The principle of operation of lighter-than-air (LTA) vehicles such as an airship is the same. An LTA vehicle displaces a volume of air which has greater mass than the total mass of the lifting gas (a gas of less density than air, such as helium), the total vehicle structure, the fuel (if any), and the useful payload – which generates an aerostatic lift according to Archimedes' principle. It will float when buoyant gas forces are in perfect balance with the overall vehicle weight. When lift forces exceed gravity forces, the vehicle will climb; when the opposite happens, it will descend. Aerodynamic lift and propulsive forces may also assist buoyant or aerostatic lift. Airship buoyant lift is nearly independent of flying altitude as long as the pressure altitude of the airship is not exceeded, and the lifting gas may expand within the boundaries of the gas envelope [9].

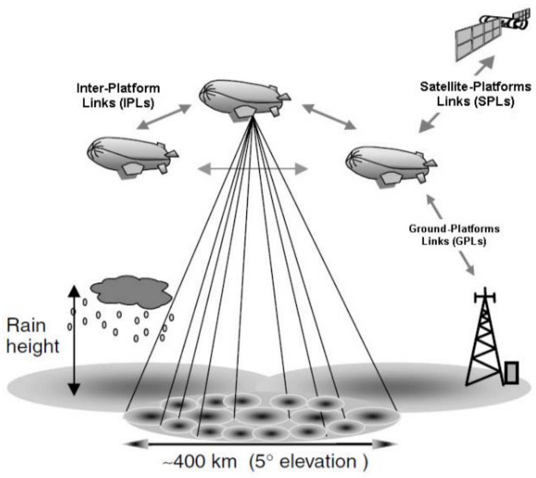


Figure 1. Typical HAPs mobile network architecture [6].

Figure 2. Altareos ST-Flex tethered aerostat [8].

This paper describes the design, fabrication, and testing of micro airships that can be flown at low altitudes (below 100 m AGL) and provide temporary wireless coverage over relatively broad areas. This micro airship is developed as a proof of concept for using airships for wireless coverage. The airship's structure is a non-rigid airship or blimp with no internal structural framework. The airship is powered by an electric propulsion system and is controlled remotely by an operator on the ground. The payload is the communication equipment needed for wireless coverage. A suitable power source, such as rechargeable batteries or fuel cells, must also be carried to provide power to the payload and the electric propulsion and flight control systems. This research aims to create an energy-efficient airship capable of extended periods of hovering without recharging or refilling. Another goal for the airship's design is to make it available cheaply.

2. AIRSHIP DESIGN

2.1. Performance analysis

There are three main established structural design concepts for airships: rigid, non-rigid, and semi-rigid [9, 10]. We select a non-rigid design (formerly referred to as blimp or dirigible; the term dirigible is rarely used now). The internal gas pressure of the non-rigid airship keeps its hull shape. Typically, a non-rigid airship design consists of one or more flexible bags (also called ballonets) placed inside the main envelope of the non-rigid design. The function of the flexible bag is to keep the pressure difference constant because the density, pressure, and temperature of the lifting gas are continually changing [9, 10]. We select for our airship a non-rigid structural design with no ballonet. This design concept was selected for its more straightforward design, less weight, and lower cost compared to the other design concepts.

2.2. Airship mission and performance

The mission of the micro airship is composed of four main phases: takeoff and climb, hovering, cruise, descent, and landing. All the phases will be analysed at constant speed since airships usually fly at a constant speed. The heaviness, H, of an airship is defined as the gross weight, W, minus the buoyancy or aerostatic lift, B, or

$$H = W - B \tag{1}$$

The buoyancy lift is calculated from

$$B = \left(\rho - \rho_g\right) Vg \tag{2}$$

where ρ is the atmospheric density, ρ_g is the density of the lifting gas, V is the volume of the envelope, and g is the acceleration of gravity. The buoyancy ratio, BR, of an airship is defined as the ratio of buoyant lift to the gross weight of the airship, thus

$$H = W(1 - BR) \tag{3}$$

A conventional airship will have BR more than 85% at takeoff and between 95% and 98% at landing, assuming weight reduction due to fuel consumption. The remaining heaviness is offset by aerodynamic lift, L, and/or any vectored thrust force, T. Bodies of revolution are not effective in producing aerodynamic lift. Therefore, vectored thrust is needed to offset the vehicle's heaviness [9]. The propulsion system selected for the micro airship is an electric propulsion system which is powered by rechargeable lithium-ion batteries [11]. This results in invariant vehicle weight, hence the buoyancy ratio. In order to alleviate the power requirement to offset the vehicle heaviness using vectored thrust, throughout all the phases, a buoyancy ratio of 97% is assumed.

The takeoff and climb phase begins with lift-off until the airship reaches the desired altitude. The rate of climb is determined by balancing the vertical upward forces and the downward vertical forces. In the hovering phase, the airship stays in the air at a fixed position. Propulsive thrust will be required to offset the heaviness of the airship. During the cruise phase, the airship moves horizontally from one point to another at a constant speed and angle of attack. The thrust will be assumed to make an angle γ with the horizontal.

The last phase is descent and landing, when the airship decreases its altitude, opposite to the climb phase. During this phase, the airship will fly vertically downward with constant speed. In this phase, the motors will be switched off, so the airship will descend solely due to its heaviness. The force diagrams for the performance analysis of the airship are shown in Figure 3.

The aerodynamic lift, L, and drag, D, on the airship are dominated by the envelope and the fins and are calculated from

$$L = qC_L S_{ref} \tag{4}$$

$$D = qC_D S_{ref} \tag{5}$$

where $q = 1/2\,\rho v^2$ is the dynamic pressure of the freestream, and v is the flight velocity; C_D is the drag coefficient of the airship; C_L is the lift coefficient of the airship; and $S_{ref} = V^{2/3}$ is the reference area of the envelope [12].

The equations of motion of the airship for the four phases are given by

Takeoff and climb:

$$T = W - B + D = H + D = W(1 - BR) + D \tag{6}$$

Hovering:

$$T = W - B = H = W(1 - BR) \tag{7}$$

Cruise:

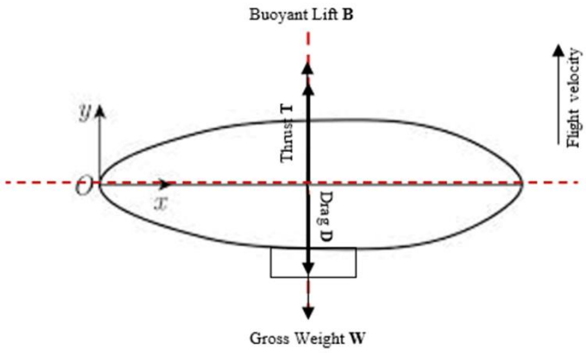
$$T \sin\gamma = W - B - L = H - L = W(1 - BR) - L \tag{8}$$

$$T \cos\gamma = D \tag{9}$$

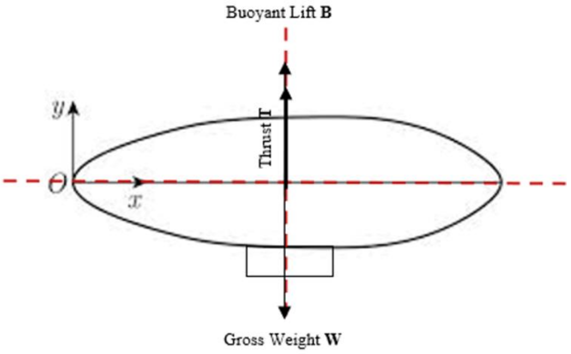
Descent and landing:

$$T = 0 \tag{10}$$

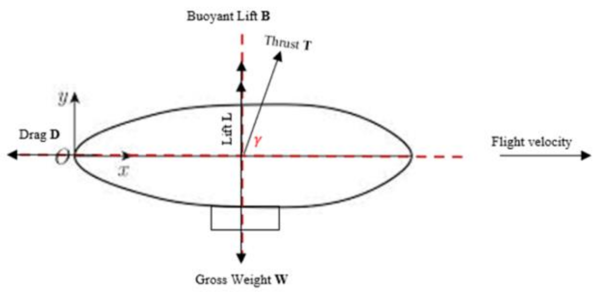
$$D = W - B = H = W(1 - BR) \tag{11}$$



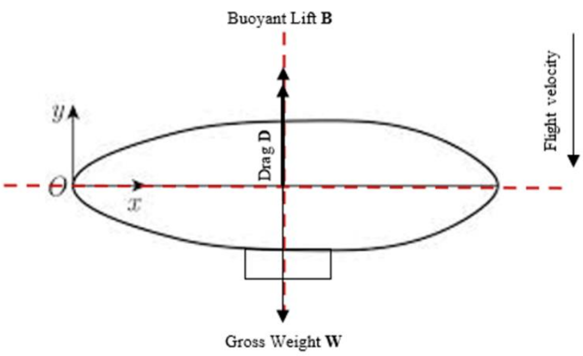
(a) Takeoff and climb



(b) Hovering



(c) Cruise



(d) Descent and landing

Figure 3. Force diagrams for the performance analysis of the airship.

2.3. Envelope design

The airship design follows a systematic design process of an LTA vehicle [13]. For an LTA vehicle, the volume is a key geometric design parameter. To adjust the volume of the airship, we only need to change one geometric dimension—the largest diameter of the axisymmetric envelope—in our chosen geometric design. The design process of the envelope begins by selecting an initial diameter. The first step is to calculate the envelope's weight using the envelope material's surface. The envelope material must be chosen effectively to achieve sufficient strength, durability, low weight, low leakage of gas, and ease of fabrication and sealing [10]. Small airship envelopes are usually fabricated using single-ply fabrics that are made up of a single lamination or single sheet. Polyvinyl chloride (PVC), nylon, polyester, and Kevlar are some of the single-ply fabrics employed. Polyurethane (PU) and Polyvinyl Chloride (PVC) have excellent gas retention properties. However, PVC is far less expensive than PU; hence it is often used. Second, the aerostatic lift force of the envelope is calculated using the density of the lifting gas. The lifting gas is a gas of lower density than the surrounding atmospheric air. Hot air was used in early airships but soon proved ineffective, giving way to hydrogen and helium [9]. Hydrogen is more effective as a lifting gas compared to helium. However, it is very challenging to use it safely because it is highly flammable and chemically reactive. Therefore, helium, a noble gas, became the standard lifting gas for airships after the historical Hindenburg disaster [9, 14].

Next, the weight of the gondola, including all other necessary equipment for the airship operation (the flight controller, propulsion system, etc.) and the payload, are added to the weight of the envelope to obtain the vehicle's gross weight. The buoyancy ratio can then be calculated from

$$BR = B/W \tag{12}$$

A trade-off between aerodynamics and buoyancy determines the shape of the envelope. Aerodynamics demands a body of revolution with a high fineness ratio, FR, whereas buoyancy requires a spherical body. Non-rigid airship designs have body shapes with FR between 3 and 5. Higher FR is not possible with non-rigid airship designs [10]. Lower FR will be possible if the airship is designed to act as an aerostat.

We design the airship with a target buoyancy ratio of 97%. The envelope shape used is a modified GNVR shape. The GNVR shape consists of three sections, the front section is portion elliptic, the middle section is the arc of a circle, and the end section is parabolic [15].

The envelope's material is PVC-coated nylon with a density of 120 g/m^2 [16]. The maximum diameter is iterated until the target buoyancy ratio is achieved with a reasonable tolerance. The envelope fineness ratio of the envelope is taken as 2.26. A two-dimensional drawing of the envelope is shown in Figure 4 compared to the GNVR shape. The envelope's volume, surface area, and centroid are determined from a CAD model of the envelope created in CATIA using corresponding tools. The final envelope design parameters are given in Table 1. A US company fabricated the envelope specialised in manufacturing blimps used for advertisements.

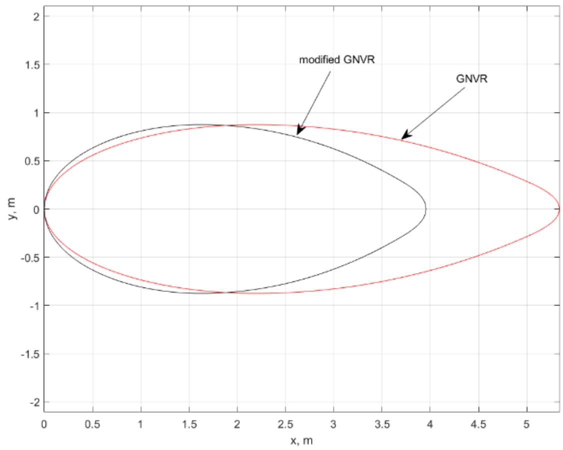


Figure 4. Modified GNVR envelope.

Table 1. Design parameters of the airship envelope.

Design parameter	Value
Length	3.96 m
Diameter	1.75 m
Shape	Modified GNVR
Fineness ratio (FR)	2.26
Volume	6 m^3
Thickness	0.18 mm
Mass	2.8 kg
Material	PVC
Density	120 g/m^2

2.3. Fin design

Airship envelopes are usually equipped with fins near the envelope tail. A vertical fin provides static stability about the airship's vertical axis (directional static stability), and a horizontal fin provides static stability about the lateral axis (longitudinal static stability). Moveable surfaces on the fins are sometimes employed to allow control of the airship's attitude. The vertical fin area is always equal to or less than the horizontal fin area.

The fin sizing of an airship can be done by considering a pair of opposing tail surfaces, including the area between the tails, to form a full-span surface equal to a typical aircraft wing. The tail surface's lift curve slope is calculated using a simple calculation based on the tail aspect ratio and sweeps angle from finite wing theory. Since fins have significance and that weight is located aft, it is important to minimise fin weight. Controlling the location is also vital for airships [9]. Two horizontal and two vertical fins of identical size were chosen for the airship. Lift is related to the square of flight speed, and since the airship is meant to travel at an insufficient speed, aerodynamic control will be ineffective.

Therefore, we employ thrust vector control rather than aerodynamic control, and the fins will not be equipped with moveable surfaces. This will also simplify the design of the airship. The fins are fabricated using polypropylene corrugated sheets, which have increased strength. The sheets have a density of 750 g/m^2. The fins are attached to the envelope using Velcro strips and supported by connecting strings. The design of the fins follows the suggested design ratios [9] given in Table 2. The fin design parameters are shown in Table 3.

Table 2. Fin design formulae.

Design ratio	Formula	Value
Tail Area Ratio	S_f/S	0.021
Fin Aspect Ratio	b^2/S_f	0.3
Fin Taper Ratio	c_t/c_r	0.5
Span to Root Chord Ratio	b/c_r	0.55

Table 3. Fin design parameters.

Design Parameter	Symbol	Value
Fin root chord	c_r	0.51 m
Fin tip chord	c_t	0.25 m
Fin height	b	0.28 m
Fin area	S_f	0.21 m^2

2.4. Gondola design

The gondola is one of the most important components of an airship. It houses all the flight equipment as well as the payload. A gondola can be opened and closed. It is possible to customise the gondola's weight, size, storage space, and structure to achieve more flexibility. The gondola will include space for the propulsion system, flight controller, and payload. We select a simple closed design of the gondola, which is lightweight, allows easy access to the components inside, and is readily available at a reasonable cost. The size of the gondola should be large enough to accommodate all the components with reasonable separation to avoid overheating of the electronic components. The gondola is made of a 330×230×205 mm plastic storage box with a buckle-locking lid.

2.5. Stability Analysis

For determination of the centres of buoyancy and gravity of the airship, a reference coordinate system is defined such that its origin is located at the envelope nose, the *x*-axis is pointing rearward along the centreline of the envelope, the *y*-axis is pointing vertically downward, and the *z*-axis is pointing horizontally rightward. The centre of buoyancy of the envelope plays a crucial role in the stability of an airship. It was calculated to be 1.61 m from the envelope nose along its centreline. Another crucial point for stability analysis is the centre of gravity. The airship is divided into several components. For each element, the mass and location of the centre of gravity concerning some coordinate systems are determined. Then, the *x*-coordinate of the centre of gravity of the airship is calculated from

$$x_{cg} = (\Sigma m_i x_i) \;/\; (\Sigma m_i) \tag{13}$$

where x_i is the *x*-coordinate of the centre of mass of component *i* having mass m_i. The other coordinates of the centre of gravity are calculated similarly. Table 4 gives detailed calculations of the centre of gravity of the airship. The coordinates of the centre of gravity were found to be x_{cg} = 1.676 m, y_{cg} = 0.243 m, z_{cg} = 0.

Table 4. Calculation of the centre of gravity of the airship.

Component	mass [kg]	x [m]	y [m]	z [m]	m*x [kg.m]	m*y [kg.m]	m*z [kg.m]
Vertical fin - top	0.040	3.507	-0.475	0.000	0.140	-0.019	0.000
Vertical fin - bottom	0.040	3.507	0.475	0.000	0.140	0.019	0.000
Horizontal fin - right	0.040	3.507	0.000	0.480	0.140	0.000	0.019
Horizontal fin - left	0.040	3.507	0.000	-0.480	0.140	0.000	-0.019
Envelope	2.800	1.742	0.000	0.000	4.878	0.000	0.000
Empty gondola	0.330	1.156	0.977	0.000	0.381	0.322	0.000
Electric motor 1	0.070	1.156	0.975	0.290	0.081	0.068	0.020
Electric motor 2	0.070	1.156	0.975	-0.290	0.081	0.068	-0.020
Servo 1	0.055	1.156	0.977	0.100	0.064	0.054	0.006
Servo 2	0.055	1.156	0.977	-0.100	0.064	0.054	-0.006
Battery	0.188	1.284	1.067	0.000	0.241	0.201	0.000
Flight controller	0.016	1.133	1.065	0.000	0.018	0.017	0.000
Router	0.080	1.043	1.059	0.000	0.083	0.085	0.000
Radio control transmitter	0.015	1.210	1.070	0.030	0.018	0.016	0.000
Power management board	0.007	1.210	1.075	-0.040	0.008	0.008	0.000
Shaft 1	0.030	1.156	0.967	0.200	0.035	0.029	0.006
Shaft 2	0.030	1.156	0.967	-0.200	0.035	0.029	-0.006
Summation, Σ	3.906				6.547	0.950	0.000
ΣM/Σm [m]					1.676	0.243	0.000

3. AIRSHIP DEVELOPMENT AND TESTING

3.1. Propulsion system

The propulsion system consists of two 5.0" ×4.5" tri-blade propellers driven by RS2205-2300 brushless motors to produce thrust. Each propeller motor has a maximum thrust of 1024 g weight. Each of the two brushless motors is connected to a shaft which can be rotated using a servo motor to tilt the propeller, hence providing the required thrust vectoring. The brushless motor speeds are controlled using LittleBee 20 A electronic speed controller (ESC). The tilting of each propeller is controlled by an MG995 servo motor with an operating speed of 0.2 s / 60° at no load when powered by 4.8 V.

3.2. Flight control system

The flight controller used to control the airship is a Pixhawk 4 Mini autopilot. The Pixhawk 4 Mini uses the Pixhawk 4 FMU processor and memory while removing interfaces that are not often utilised. The onboard sensors include ICM-20689 accel/gyro, IST8310 magnetometer, BMI055 accel/gyro, and MS5611 barometer. In addition to the onboard sensors, a Holybro M8N GPS module is used to obtain positioning data of the airship when operated outdoors.

The flight controller, the electric motors and other electronic components of the airship are powered by a 2200 mAh three-cell ZOP Power rechargeable battery. A PM06 power management board provides each component with the required power at a suitable voltage. All the components are connected to the power management board, which is then connected to the rechargeable battery. Figure 5 shows the power distribution board connections.

A six-channel Flysky FS-i6 radio transmitter and Flysky FS-iA6B receiver are used for the remote control of the airship. PX4 autopilot was used as the flight control software, and QGroundControl was used as the ground control software.

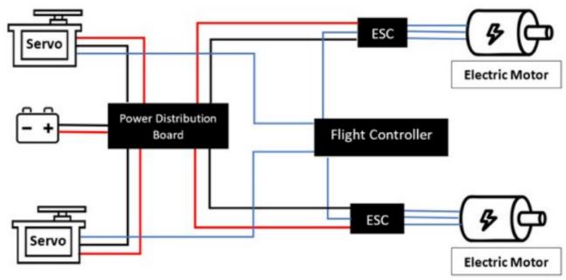


Figure 5. Schematic of a power board connector.

3.3. Fin attachment

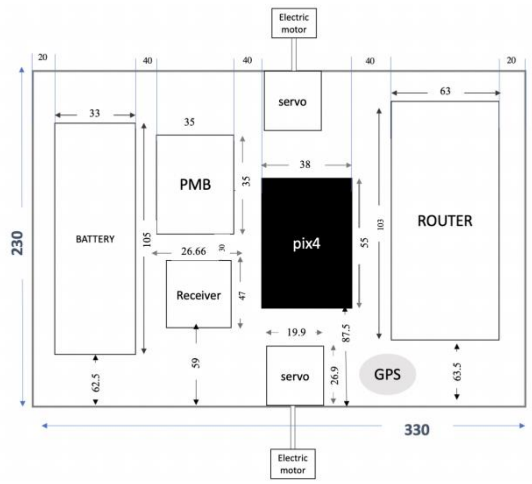
The fins are made from 4mm thick lightweight polypropylene. The attachment will be secured to the envelope using a lightweight cable, and Velcro will cover the bottom side of the fin.

3.4. Payload

For our project, we will choose femtocell as the type to demonstrate the efficiency of the idea, and it will be more suitable for the micro airship prototype. Furthermore, we choose 4G/LTE Mobile Router DWR-930M to provide wireless coverage. It has a maximum range for a medium-sized house or a summer camp. The router is rechargeable, meaning it does not require power from the primary source.

3.5. Gondola arrangement

All the components inside the gondola are attached to the floor using Velcro (see Figure 6). This keeps the components fixed when manoeuvring the airship and allows the removal of any element easily for inspection or replacement.



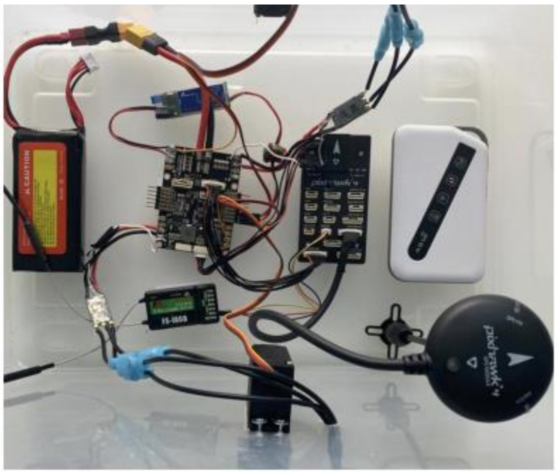


Figure 6. Gondola design with the positioning of the components.

3.6. Flight testing

Before testing the airship, the envelope was inflated with helium and air. A compact wireless router was used for payload demonstration, which reduced the airship's gross weight. The envelope was filled with 99.999% pure helium and regular atmospheric air to compensate for the airship's gross weight reduction. Following that, all subsystems are assembled. Following the assembly, we verified that each subsystem was stable and in the appropriate position. The flight control and propulsion system were tested while the airship was tethered. When testing was satisfactory, the airship was released and tested for takeoff and climb; hovering; cruise; and descent and landing phases inside one of the high-rise buildings at UAE University. The testing confirmed that the airship can fly at the desired altitude. Figure 7 shows the airship during indoor flight testing. The wireless router payload was tested for providing a wireless 4G network over a wide area for multiple users using different platforms, as shown in Figure 8.

Figure 7. Indoor testing of the airship flight control system.

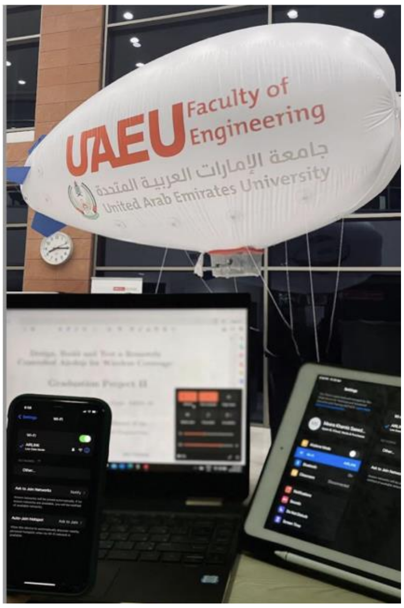


Figure 8. Indoor testing of the wireless coverage of the airship.

4. CONCLUSION

This paper demonstrated the design, development and flight testing of a remotely controlled micro airship for wireless coverage. The design of the micro airship followed a systematic LTA design procedure modified to suit a micro-size airship. The airship envelope was sized to have the lifting capacity required by the wireless communication payload and the necessary flight equipment. The gondola was large enough to accommodate all the flight equipment and the payload without exposing the electronic components to excessive heating. The gondola box allows firm attachment to the envelope yet easy access to the components inside. The propulsion system was all-electric, using two tilting propellers driven by brushless electric motors. The tilting of the propellers allows for varying thrust vectoring required by the different phases of flight. The propellers can be tilted independently, allowing for the airship's manoeuvring without adding a fin rotor or a rudder. The fins were sized appropriately for a micro airship designed for low-speed flight. No rudder or rotor was added to the fins. Velcro and lightweight cables were used to attach the various subsystems. The flight testing of the airship with the payload was satisfactory.

However, the yawing response of the airship was prolonged, which was expected since the moment arms of the propulsive rotors are much smaller than that of a typical fin rotor. A rotor can be added to one of the vertical fins for faster yawing response. A rudder will not be very effective unless the airship is flown at a higher flight speed. A further possible development of the airship is to make it flight autonomous. Autonomous flight of the airship will alleviate the burden of having to control its flight when it is needed for wireless coverage.

CONFLICTS OF INTEREST

The author affirms that this publication is not affected by any conflicts of interest.

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