ZeRONE: Safety Drone with Blade-Free Propulsion

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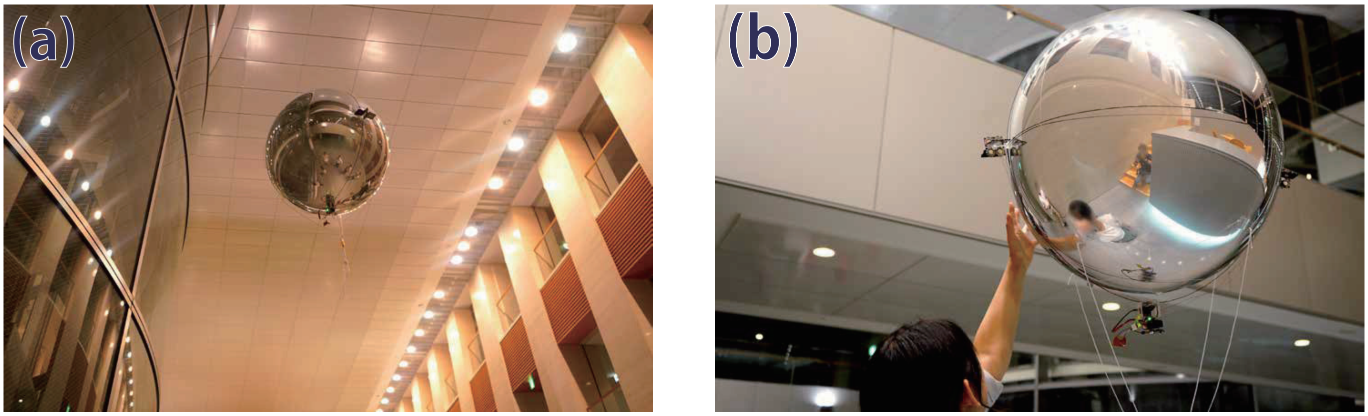

Figure 1: Our prototype: (a) ZeRONE is flying indoors. (b) The user can touch our blade-less drone without fear or injury.

ABSTRACT

We present ZeRONE, a new indoor drone that does not use rotating blades for propulsion. The proposed device is a helium blimp type drone that uses the wind generated by the ultrasonic vibration of piezo elements for propulsion. Compared to normal drones with rotating propellers, the drone is much safer because its only moving parts are the piezo elements whose surfaces vibrate at the order of micrometers. The drone can float for a few weeks and the ultrasonic propulsion system is quiet. We implement a prototype of the drone and evaluate its performance and unique characteristics in experiments. Moreover, application scenarios in which ZeRONE coexists with people are also discussed.

CCS CONCEPTS

• **Human-centered computing** → *Ubiquitous computing*; • **Computer systems organization** → *Robotics*;

KEYWORDS

Drone, Microblower, Blade-Free

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1 INTRODUCTION

Technological improvements such as better batteries, greater processing power and advanced sensors have dramatically cut the prices of drones and made them a popular consumer product. Their ability to fly freely in three-dimensional (3D) space and the wideness of their applications including transportation [1], structural inspection [26], construction [9], rescue [11] and entertainment [18] have further accelerated the development and adoption of drones in the past ten years.

Given their popularity, the research field of 'human-drone interaction (HDI)' [4], which focuses on people-drone communication has become active. Various studies have tackled subjects such as gesture input [2], creating legible drone motion [24], and ensuring proper drone-user separation distances [3, 10]. Experience to date, however, has revealed serious barriers to the closer integration of drones into public spaces. Key problems are the severe injuries possible with propeller strikes and drones falling from high altitudes. Although many drones use propeller guards to prevent propeller strikes, complete protection remains elusive as propeller guards that can adequately block fingers and hair are too heavy and degrade flight performance. Even if the drone is reliable, the loud roar generated by the rotating propellers and the strong winds tend to scare people nearby. Besides, generally speaking, flight time of a small drone is less than about 20 minutes. Therefore, the drone's flight environment is strongly restricted and it is virtually impossible to provide constant flight programs in enclosed public spaces.

In this paper, we propose "ZeRONE", see Figure 1 (a) and (b), a new drone that can fly without mechanically driven parts such as a propellers or a flapper mechanism. The proposed device is a helium blimp type drone for indoor spaces. To realize propulsion, microblowers, which generate weak winds by the ultrasonic vibration of ceramic surfaces, are attached to the drone. These devices provide propulsion force in the vertical, yaw and forward directions, so this drone can move freely in 3D space. The proposed device has several advantages over conventional drones (e.g. multicopter, plane and ornithopter). The microblowers vibrate with very small amplitude so there is no possibility of personal injury. In addition, their vibration in use is visually imperceptible. Furthermore, because the vibration frequency is in the ultrasonic range, they generate only a slight wind noise. While the micro blowers are not activate, the drone simply floats in the air without generating noise or consuming power unlike normal drones.

Traditional drones for applications such as carrying cargo and taking professional photos are so dangerous and noisy that only human-free spaces can be used. Although there are drones designed to implement aggressive interaction [4, 18] with a human, it is still difficult to fly it in spaces occupied by people because the user must monitor the dangerous drone while flying and it generates a lot of noise. ZeRONE with its superior safety, quietness, and long flight time makes it possible to build new spatial platforms for human living spaces.

Our work provides three contributions: First, we outline and discuss the unique benefits and possible applications of ZeRONE. Second, we reveal the method used to implement ZeRONE. Third, we implement a prototype and evaluate its performance. The remaining sections of this paper discuss the following: First, we introduce previous research on 3D space interaction including HDI. Second, we describe the principles and design parameters of ZeRONE. Third, we introduce the ZeRONE prototype and confirm its characteristics and performance. Finally, we discuss possible applications, limitations, and the key attributes of our proposal.

2 RELATED WORK

Devices that can move freely in real 3D space have been attracting significant attention for a long time. Realizing such devices would make it possible to create input/output interfaces at arbitrary places in real space, and the possibility of interaction-oriented applications would greatly increase. Programmable Matter, a concept by Toffoli and Margoulus [28], is well known in this field. They assumed material that had controllable physical properties such as shape, density, texture and position. Their concept is to form objects in the real world by controlling it. Radical Atoms [8], Tangible Autonomous Interfaces [20] and Claytronics [5] are also well known as concepts that embody various tangible objects by using computer controllable materials or robots in the real world.

Numerous studies have attempted to realize the concept of controlling the physical properties of things. Their aim is to create a new spatial platform that can gather or output information at arbitrary places in the real world. There are two main approaches to controlling the 3D position of physical objects that appear to hover. One uses external systems that generate invisible tethers to levitate physical objects. Examples include acoustic-potential fields [21] and magnetic fields [15]. The other assumes the use of self-levitating objects. This latter approach is gathering a lot of attention because the invisible tethers impose too many limitations. The most popular drone in this area is the multi-copter; basically a rotorcraft with more than two rotors. Multi-copters have higher mobility, robustness against winds and significant payloads and these characteristics allow various rich interaction interfaces to be designed. For example, Szafir et al. [25] proposed a multi-copter with LED strip to present direction. iSphere [29] combines a drone with a persistence of vision display. Flyables [13] allow users to interact with tangible objects in mid-air. BitDrones [6], is a prototype of interactive programmable matter that uses a swarm of small drones equipped with small flexible high-resolution thin-film touch screens or RGB LEDs.

Although multi-copters are a promising technology for realizing rapid movement to any spatial location, they also have many limitations. For example, people are at risk of serious injuries, because they may be hit propellers of the falling or miss-operated drones. The very strong noise caused by drones in flight is also a problem. Grace et al. revealed that the maximum noise of DJI Phantom II quadcopter is about 80 dBA, on par with a freight train passing 15 m away [7]. Moreover, the big noise and danger of drones can disturb and create fear in people. Duncan et al. investigated a comfortable drone-participant separation threshold and reported that at least 0.6 m is necessary [3]. Cauchard et al. also reported that users accustomed to a drone can bring it within their intimate space (1.5 ft) [2]. Unfortunately, the small drones used in the field of HDI have short flight times, just a few tens of minutes, and it is difficult to maintain operation as a spatial platform for long periods.

Thus, studies that use balloons that are lighter than air and can generate buoyancy without creating noise or consuming electric power have been published. Kuznetsov et al. proposed a fixed balloon that can sense air quality and visualize the results by altering the color of its surface [14]. PRoP is a blimp-based drone that uses propellers to move in the air and the user can browse remote spaces by controlling it via the Internet [23]. Airjelly and Ollie are blimp-based, autonomous and ambient robots that fly around by flapping their wings [12, 22]. Diri is an autonomous helium balloon with a propeller mechanism designed to document activity in spaces [19]. Tobita et al. proposed a telepresence system using blimps onto which the remote user's face is projected [27].

3 PROPOSED METHOD

We propose a safe drone, ZeRONE, which develops thrust by the imperceptible vibration of surfaces. It eliminates the need for propellers and flapping mechanisms. As the thrusters available produce very weak forces, we mount them on a blimp type drone that has virtually zero weight. This section uses the example of the most simple configuration to explain the principle and architecture of ZeRONE.

3.1 Microblower

It is well known that a piezo element vibrates mechanically when an AC voltage is applied. The microblower [16] is a new pump invented by Murata Manufacturing Co. that uses piezo elements as actuators, see Figure 2. Although the microblower is superior in terms of safety and silence, it generates very slight thrust. We measured the reaction force of a microblower driven by an AC signal (22.2 $V_{p\text{-}p}$, 26 kHz, square wave) using a precision balance. While the microblower weighs about 1.4 g, it produces a reaction

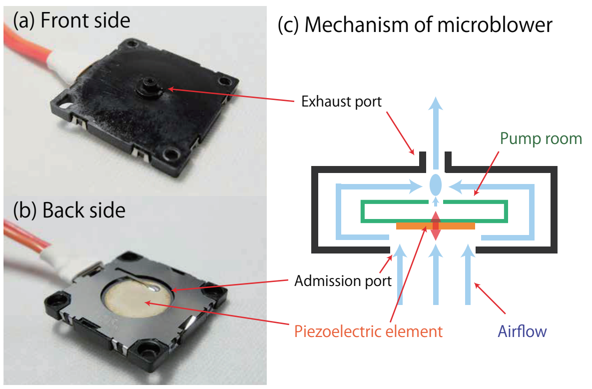

Figure 2: (a) The front side of microblower. (b) The back side. (c) The mechanism of microblower. The piezo element set in the pump room vibrates at ultrasonic frequencies.

Table 1: Driven blower(s) according to each direction.

Direction	Driven blower
Forward	2, 2'
Upward	1, 3'
Downward	1',3
Yaw turn (Right)	2'
Yaw turn (Left)	2

force of about 0.04 g. ZeRONE uses the microblowers as thrust generators. Our approach assumes a vehicle with neutral buoyancy and the simultaneous use of multiple microblowers, which increases thrust and generates thrust vectoring.

3.2 Parts arrangement

The basic ZeRONE mainly consists of four components as below.

(1) A helium gas balloon to create neural buoyancy
(2) Microblowers to produce thrust
(3) Control and energy-supply circuit.
(4) Structural parts: frame, weights, etc.

There are several component arrangements. The simple example shown in Figure 3 is prototyped and tested; others forms are described later. Microblowers are installed on the left and right sides of the drone. One blower module consists of four microblowers and six modules are used (total of 24 microblowers). Each module is labeled in Figure 3. The balloon is set at the center of ZeRONE and provides the buoyancy needed. The soft body of the balloon eliminates the fear of collision injuries.

The control circuit, battery and weights are attached to the bottom of the balloon. This weight is adjusted so that the entire drone is neutrally buoyant in the air. Because of the center of gravity is set some distance under the center of lift, ZeRONE is rotationally stable (in roll and pitch not yaw).

While the prototype cannot smoothly replicate arbitrary flight patterns, it has enough degree of freedoms (DoFs) to move to any place in 3D space. Since the microblowers used provide no reverse thrust, the prototype cannot move backwards. Table 1 shows

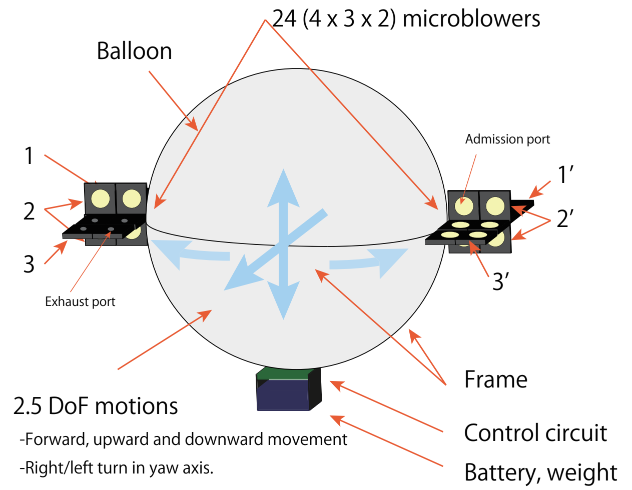

Figure 3: One example architecture of ZeRONE.

how ZeRONE moves when driving different pairs of microblower modules. Pairs of modules are activated simultaneously, eight microblowers, to move upward, downward, and forward. Roll movement is theoretically possible by driving pairs of microblower modules (1 and 1', or 3 and 3'); but the prototype is too stable to permit this. These module pairs develop thrust in opposite directions to cancel pitch movement direction when going up or down.

3.3 Possible structures

We can easily increase the DoFs of movement of ZeRONE by installing more microblowers. In this section, we discuss the possible structures and their DoFs in flight.

Figure 4 (a) shows a type of drone with microblowers on more axes. It has 32 micro blowers in total; four are directed in each of eight different directions. This drone would be heavier than the one in Figure 3, but could move in any direction without changing its orientation by driving various combinations of microblowers. Although it can rotate around the yaw axis, rotation around the pitch and roll axes would require careful alignment of the gravity center.

The second structure sets all microblowers in one direction on a great circle as shown in Figure 4 (b). This structure uses internally mounted servo motors to drive the pitch and roll axes inside the balloon. Since the gravity center is below the servo motors, when the servo motors rotate, the center of gravity changes and the balloon and microblowers rotate. Take rising for example. Changing the center of gravity viewed from the microblower can drive the great circle horizontal with the microblowers facing downwards as shown in Figure 4 (b'). The drone can also be rotated in the yaw axis direction by driving only the microblowers on one side. Unlike the structures in Figure 4 (a), (c), the configuration includes movable parts; however, all mechanical parts are contained within the balloon so there is no possibility of them hitting people. Note that since all microblowers are facing the direction of movement, it has higher thrust and speed than the other types in Figure 4 (a), (c).

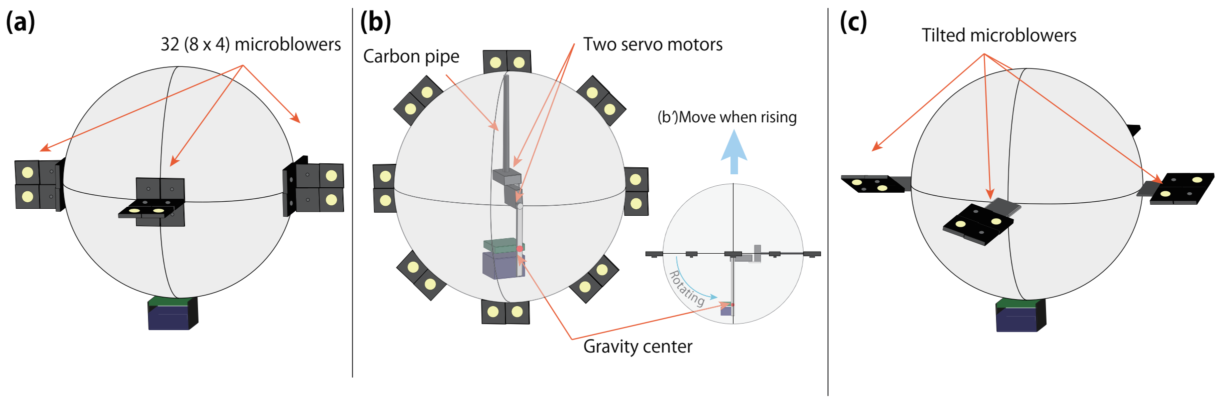

Figure 4: Examples of possible architectures. (a) Omnidirectional type. (b) Servo motor type. (c) Tilted microblower type.

Moreover, by combining Figure 4 (a) with Figure 4 (b), it is possible to make a drone capable of moving and rotating in all directions.

Figure 4 (c) shows a microblower drone structured like a multicopter. The current microblowers can't produce reverse thrust or a torque reaction force unlike motor-driven propellers. This omission can be offset by installing contra-tilted microblowers on both sides of each arm as shown in Figure 4 (c). Although this structure can achieve movement in all directions, their off-axis orientation reduces thrust efficiency. For that reason, more microblowers or higher power ones are required for realization.

4 IMPLEMENTATION

This chapter explains how we implemented our prototype. Figure 5 shows an overview of the prototype and Table 2 shows all parts and their weights.

The balloon is a 24 inch aluminum-metallized film balloon from S.A.G.Balloons. The maximum gas capacity of the balloon is 140 L and when filled with helium gas the balloon can lift about 100 g according to the maker's catalog. The 100 g lift capacity includes the weight of the balloon itself. Thus, the actual payload of the aircraft is 89.4 g (106.4 g - 27.0 g) i.e. weight that can be lifted by the balloon.

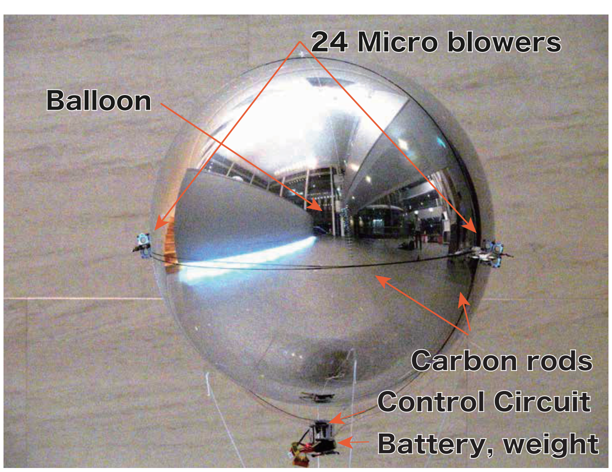

Figure 5: An overview of prototype. The diameter of the drone is about 60 cm.

The aluminum-metallized film is strong against helium gas leakage and can maintain buoyancy for a longer time than rubber balloons. Besides, it is also harder to rupture and safer than a rubber balloon. Even if a small hole opens on its surface, it slowly falls while the gas gradually leaks out.

The drive circuit, receiver, battery and weight to adjust buoyancy are installed at the bottom of the body. A 3S Lithium-polymer (Li-Po) battery (11.1 V, 180 mAh) was used since a high voltage is required to drive the piezo elements. The drive circuit has an H-bridge, microcontroller, and linear regulator generating 5 V for the microcontroller and receiver. The microcontroller alters the H-bridge according to the receiver's signal. Piloting is realized by a FHSS compatible transmitter using 2.4 GHz band radio waves. Although advanced sensors such as an inertial measurement unit (IMU) and laser range finder were available, we did not use them in this initial prototype.

The 24 microblowers, six modules, are connected to the circuit and individually activated at the activation level indicated. They are driven by a 26 kHz square wave of 22.2 $V_{p\text{-}p}$ and activation level (16 steps) is adjusted by 30 Hz PWM. Strictly speaking, each microblower has a slightly different resonance frequency and it is

Table 2: All parts without weights to adjust buoyancy included in the prototype.

Part	Overview	Num.	Total weight
Balloon	24 inch balloon.	1	27.0 g
Microblower	MZB1001T02	24	31.4 g
Carbon rods	0.8 x 1.2 x 1000 mm	4	5.3 g
Drive Circuit	6CH H-Bridge	1	8.0g
Receiver	KingKong RX800-PRO	1	1.2g
Battery	3S 180 mAh Li-Po	1	18.9 g
Others	Joint, Screw, Velcro, etc.	-	14.6g
Total	-	-	106.4 g

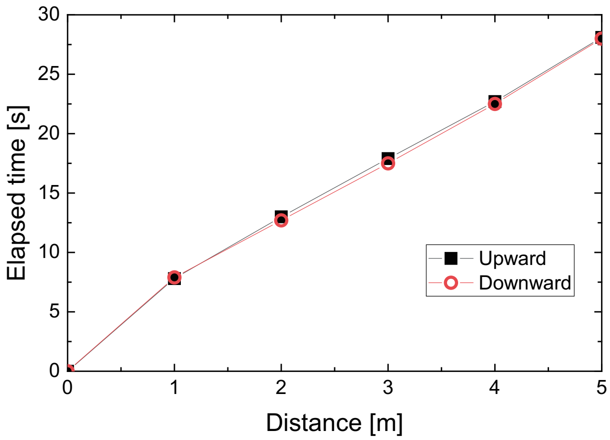

Figure 6: The speeds of ZeRONE when moved upward and downward.

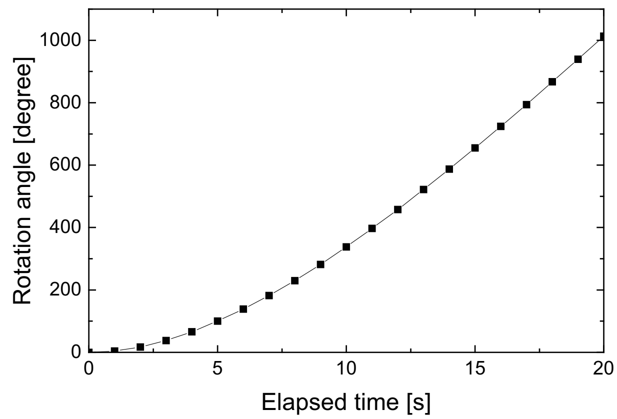

Figure 7: The rotation speed of ZeRONE.

possible to increase overall thrust by careful selection of the microblowers or tuning the frequency to each microblower. When modulation by 30 Hz PWM is used to decrease the output, some slight bass sound is generated in the audible range. However, because the microblower gradually reduces its output as the driving AC shifts from the resonance frequency of 26 kHz and no drive is created with the shift reaches several kHz, we believe that it is possible to control the force output of the microblowers such the ultrasonic range is maintained.

Mechanical parts excluding balloon, carbon rods, etc. were 3D printed. We did not use any expensive parts, the proposal can be easily implemented at a low price.

5 EVALUATION

5.1 Kinetic performance

ZeRONE has a quite different kinetic performance from propeller-based drones since the actual weight of ZeRONE is virtually zero and its thrust is also very small. We moved ZeRONE in each direction in a room with no wind and confirmed that we could control ZeRONE as expected. Compared with regular drones, its movement and response are slow and inertial effects are very prominent.

Its kinetic performance was evaluated. We measured the time taken by ZeRONE to move up and down five meters in the experiment. Before the experiment, neutral buoyancy was set by adjusting the weight. The micro blowers used to move were same as Table1 shows. Thus, eight microblowers were used to move up and down and four were used to rotation in the yaw axis. In the experiment, the drone started in the stationary state and the microblowers were then driven at maximum to the end.

Figure 6 shows the results of the two experiments. As the number of micro blowers used for rising and falling are the same, the results were almost the same. In both directions, the prototype took approximately 28 seconds to move five meters. The maximum speed of about 20 cm/s was attained at the two-meter point.

The next experiment measured the rotation speed around the yaw axis. In this experiment we rotated the drone for 20 seconds, see Figure 7. The rotation speed continued to rise gradually and reached about 80° / s.

5.2 Energy consumption

Although ZeRONE doesn't consume electricity to provide lift, controlling the microblowers does. The drive circuit continuously consumes about 50 mA even if the microblowers are not activated. This is mainly due to the receiver and the microcontroller. When the drive circuit receives the control signal via the transmitter holding by a user, it activates the microblowers. When the microblowers are activated, the current dynamically changes and the average value increases. While the current required depends on the number and the activation level of microblowers, about 220 mA flows on average when eight microblowers are driven at maximum level. The capacity of the current battery is 180 mAh and we confirmed that the prototype continued to work for more than thirty minutes with eight microblowers driven at maximum. Note that ZeRONE does not crash but keeps drifting if the battery becomes empty.

5.3 Noise level

If drones are to be used in public spaces, the noise problem is a particular concern. ZeRONE generates only a light sound of wind while moving. To confirm this, the volume at the time of maximally driving the eight forward microblowers was measured. The environment in which we conducted the measurements was an office with average environmental noise of 45.7 dBA. We measured the noise from a total of 15 different places in this environment as shown in Figure 8.

As shown in Figure 8, the noise of the drone depends on the direction; the sound is lowest at the exhaust port side. The highest noise level in this experiment was 57.7 dBA, which is much lower than the 80 dBA noise (15 meter separation) yielded by a DJI Phantom II [7]. Although it was still slightly audible at eight meters distant, the noise level was almost the same as ordinary background noise. From the above, we regard ZeRONE as having excellent quietness.

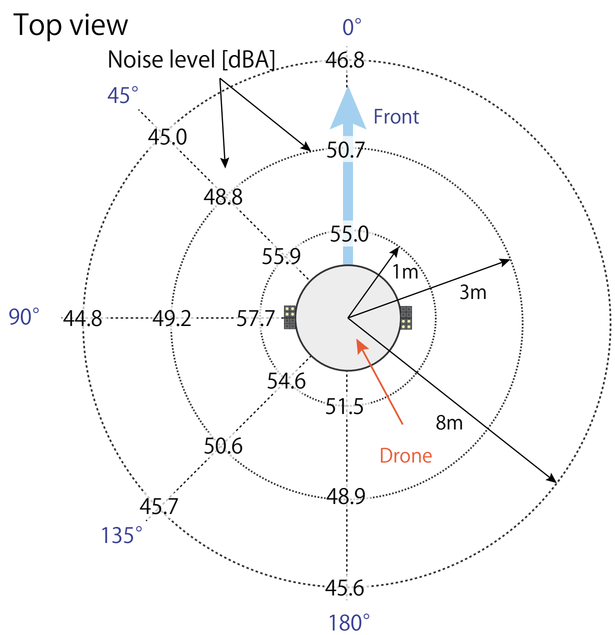

Figure 8: The noise levels in each places.

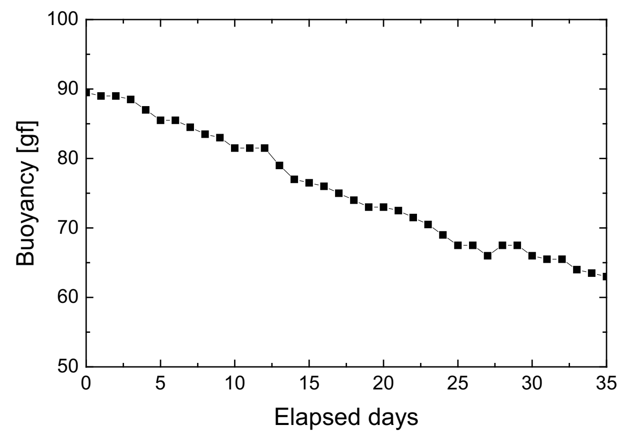

Figure 9: Change in buoyancy.

5.4 Operational time

Considering the intended daily use of ZeRONE, its flotation time is an important factor. Long operating time leads to lower maintenance costs and encourages applications such as long-term sensing. We investigated how the buoyancy of the balloon changed over a 5 week period. The temperature varied between 26 and 29 degrees and the atmospheric pressure also changed between 992 and 1007 hPa in the period. The balloon was the same type as the one used in the prototype. Figure 9 shows the change in buoyancy. The initial buoyancy was 88 g; however, helium gas gradually escaped from the balloon and it fell to 63 g in 5 weeks. The measurement environment was a normal home environment so pressure and temperature were not controlled. Therefore, the rate of decrease was not perfectly linear. The current prototype can float for about 2 weeks; however, as the buoyancy of the balloon changes, the ballast weight must also be changed to ensure constant buoyancy over long periods.

6 DISCUSSION

6.1 Possible application

First, we conducted experiments to confirm the practicality of ZeRONE. Its features of safety and quietness are not offered by regular drones. We confirmed that the prototype could fly for long periods and be manually controlled as expected This section discusses the potential of our proposal by introducing sample applications.

Figure 10 (a) is an image of it used for advertising. Though the prototype used a spherical balloon, any form of balloon is possible if its buoyancy is sufficient. For example, ZeRONE units that form logos or words can fly above the crowd at events or halls as shown in Figure 10; they offer good advertising opportunities and entertainment. It is also possible to show videos by projecting images on the surfaces of the balloons. Currently, it is necessary to use external projectors given their weight and power concerns; however, we consider that mounting a projector on a ZeRONE is possible by adopting lighter projectors or larger balloons. Guiding applications that directly lead people to their destinations are also possible if stronger microblowers are equipped. Sensing is also a potential application.

ZeRONE has the potential to become a new spatial platform for environment sensing applications. For example, it can fly a camera over a crowd to monitor their movements. The current prototype is already able to carry a camera, see Figure 11. ZeRONE, which can fly safely over people, can take pictures everywhere, unlike drones that are prohibited from flying over people due to safety concerns. The data collected by a swarm of ZeRONE units would be valuable for human flow analysis and security. Obviously, it can be used not only for video, but also for collecting various environmental data streams such as temperature, humidity and sound.

Figure 10 shows applications that use the mirrored surface of the currently-used balloon. As Figure 1, 3 shows, the aluminum-metallized film balloon filled gas has a specular surface and reflects lights. Examples of applications using this mirrored surface are shown in Figure 10 (b). It is possible to capture omnidirectional images from an arbitrary point in the air by using the convex mirror surface of the balloon and a high-performance camera on the ground. Although omnidirectional imaging tends to require a high resolution camera that is difficult to mount on the balloon, this method needs a camera on the ground. Moreover, it is possible to not only capture but also project an image anywhere by using the mirror-like surface of the balloon and a projector with sufficient brightness and resolution. For example, an object can be projected onto a desk from a hidden projector and the user can cast a spotlight on the desk without a desk light. ZeRONE has the potential to overcome the limitations posed by the occlusion of cameras and projectors.

The flying telepresence application proposed by Tobita et al.[27] is also supported by ZeRONE. This application allows a remote user to communicate using a drone on which his/her face is displayed.

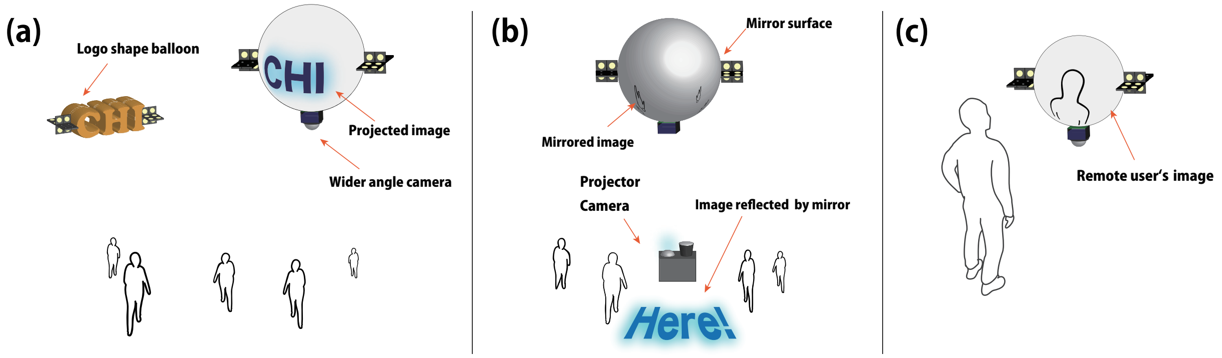

Figure 10: Possible applications. (a) Advertising and sensing, (b) Utilizing the mirrored surface, such as video capturing and projection, and (c) Tele-communication

Figure 11: View provided by ZeRONE. This picture was captured by a camera mounted on the prototype.

The flying telepresence system has the benefit of avoiding obstacles unlike traditional wheel-mounted telepresence systems. Moreover, it is possible to realize a higher presence by using balloons in the shape of the user's face like the system of Misawa et al. [17]. Users can casually touch or move it since ZeRONE is safe. Not only communication but also games and education are possible application fields.

6.2 Limitations

Although ZeRONE has many unique advantages such as safety, quietness, and long flight times, it also has some obvious disadvantages. First, the thrust is so slight that its movement is very slow and it takes a lot of time to move and to stop. However, the microblower was originally designed for device cooling and not for generating propulsive power. Therefore, we believe there is room to improve thrust by optimizing the microblower architecture. A higher thrust microblower would allow the use of larger balloons with greater payload or higher speeds. If the drone can follow a walking user by improving the thrust and/or decreasing the air resistance, for example, interactive applications that lead users directly to their destinations and a flying telepresence system capable of communicating with a walker would become available.

The key problem is its weakness against winds. Since ZeRONE has high air resistance and weak thrust, it is moved easily by air conditioner winds or by humans walking past it. This makes it difficult to use ZeRONE outdoors and indoors if strong air conditioning is present. As suggested for the previous problem, solutions include adopting more microblowers, higher power blowers, or lower air resistance balloons. In addition, the high aerodynamic inertia of ZeRONE demands high speed feedback control of the blowers to prevent course deviation.

Finally, there is the short time available for controlled flight. Although the balloon can float for several weeks, it uses a lot of electricity to move and consumes the battery in about 30 minutes at maximum thrust. This is longer than the flight time of most small drones; however, it should be extended assuming the need to provide interaction continuously in everyday life. Since general energy saving techniques, such as use of sleep mode or DC/DC converter, is not applied in this current implementation, there is still a room to decrease the energy consumption. In particular, sleep mode would be effective because the response of the prototype is not quick. Further reductions in energy consumption or extending battery life are possible, for example, developing higher efficiency micro-blowers, greater battery efficiency, or balloons with lower air resistance. The easier way is to obtain more buoyancy by using larger balloon, thus supporting the use of larger batteries. Simply increasing the diameter to 80 cm would yield about 100 g of additional buoyancy. This makes it possible to install not only larger batteries, but also more advanced sensors such as IMU, laser range sensor, or wide angle camera. Moreover, speaker units and laser projectors are being rapidly made much lighter and smaller than conventional DLP or liquid crystal projectors and so can also be installed.

7 FUTURE WORK

We aim to evolve our proposal for building new practical platforms that can sense and present information in the real world. First of all, we will enhance our drone so that it can sense and present information via advance sensors and displays. Although it may depend on external devices such as motion capture cameras and projectors because of payload limits, we aim to achieve systems intended for drone application in the future. Next, we will develop a ZeRONE that automatically moves to a gas station and recharges itself when it detects a gas shortage. Moreover, we will simultaneously control many ZeRONE units by using swarm control technology as in Figure 10 (a). Furthermore, we will combine data analysis technology with ZeRONE swarms to build a new spatial platform that can automatically collect and analyze data and present information to enhance the ubiquitous environment.

We will also investigate the human perception of ZeRONE. Issues include psychological resistance and discomfort to an object floating above them or what parameter values, such as speed and direction, are most comfortable. We intend to make it a practical platform that can always operate in the human living space.

8 CONCLUSION

We presented ZeRONE, a blimp type drone based on a blade-free propulsion mechanism. As ZeRONE is a safe, light and quiet drone that uses a blade-free mechanism, it can fly freely in the human living space. We explained the principle and construction of the proposed method. A prototype was built to confirm the implementation practicality of ZeRONE. We also investigated its fundamental characteristics such as kinetic performance and energy consumption in experiments. We also discussed the unique characteristics and benefits of ZeRONE and described possible applications including motoring, guiding and telecommunication. The results gained confirm that ZeRONE has the potential to become a new spatial platform for ubiquitous environments. Its current limitations and future research directions were elucidated.

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