Three-dimensional noise and spatial mapping system with aerial blimp robot

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Abstract: To measure environmental noises, many noise measurement and mapping systems have been studied. However, these systems are costly because many measurement points are required to construct a detailed and three-dimensional noise map. In recent years, with advances in unmanned aerial vehicle (UAV) technology, a multirotor aircraft has been frequently used as general use. Although it could be applied to acoustic measurements, it causes loud noise as it must always rotate its propellers during flying. Herein, a noise and spatial mapping system with a blimp robot is proposed. The proposed system achieved a silent, slow, and omnidirectional movement with a balloon filled with helium gas. Furthermore, the simultaneous localization and mapping (SLAM) technique is applied for the system’s positional tracking and surrounding spatial mapping with a stereo camera. To evaluate our system, three experiments were conducted. First, the propeller rotational noises of the proposed system were compared to a general recreational-use multirotor. Next, the acoustical effects of a blimp, such as reflection and diffraction, were measured to decide the microphone position. Finally, a preliminary experiment was conducted to construct a simple three-dimensional noise map in a large experimental room. The results show that the proposed system could construct a three-dimensional indoor noise map by combining the sound information and the positional information.

Keywords: Unmanned aerial vehicle (UAV), Multirotor, Balloon, Simultaneous localization and mapping (SLAM), Environmental monitoring

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1. INTRODUCTION

To reduce noise pollution, the environmental noises occurring in our daily lives must be investigated. One of the effective methods to understand environmental noise is by a noise map that visualizes the noise distribution and spatial sound propagation in the city [1,2].

In general, the measurement position is fixed and the environmental noise is measured using a sound-level meter installed temporally near the target noise source [3]. To continuously measure the noise at the specific location such as a road, the noises are observed at regular intervals by a permanently installed sound-level meter [4]. However, the number of measurement points increases as the target area becomes broader. Furthermore, because many high rise buildings are built in the urban areas, noises occurring at high altitudes must be measured using a crane and a balloon [5]. Hence, increased efforts and costs are required to obtain the noise measurements for mapping.

In addition, these measured data must be represented on the model or map, which is prepared in advance and is recently three-dimensional. The high-resolution model or map including the buildings must represent the high-resolution noise map. To construct the noise map with high efficiency and high accuracy, many noise mapping methods has been investigated [6]. The global positioning system (GPS) and geographic information system (GIS) are used generally to obtain the measurement position. The data estimation technique that is the interpolation between the measurement points is also required. Particularly in urban areas, the spatial model or map including buildings frequently changes and it is generally difficult to update...
them. Therefore, it is desirable to obtain both noise and spatial information automatically and simultaneously.

In recent years, with advances in unmanned aerial vehicle (UAV) technology, various types of UAVs have been developed [7]. UAVs are advantageous in terms of low cost and high convenience compared with manned aircraft and can help in a broad range of fields, such as aerial photography [8,9], agricultural management [10,11], network environment construction [12], luggage delivery [13], etc. A multirotor aircraft is frequently used in UAVs because of its convenience and high mobility. However, it must always rotate its propellers during flying, which typically causes loud noise. The loud noise renders it difficult to record and measure the sound using the multirotor-type UAV. In previous investigations, noise reduction has been conducted using a microphone array installed in a multirotor-type UAV [14,15]. The propeller noise of the multirotor frequently changes because the propeller rotation speed changes frequently to hold the UAV posture. Thus, the noise reduction for the propeller noises becomes difficult. Furthermore, it is also difficult to remove the effect of the propeller noises on the surrounding environment because it can cause additional noise problems. In previous investigations, various types of UAVs using a balloon have been developed. For instance, an entertainment type of UAV called Skye [16], and a natural disaster monitoring system from the air [17].

To create the noise map, the position of the system in the spatial map must be tracked. In the outdoors, the GPS is an effective method to track the position when the spatial resolution of the noise map is rough. However, the general GPS is not valid for the indoor condition. Its positional information is not sufficiently accurate to construct a higher spatial resolution noise map. Outdoor spatial maps are also available, e.g., Google Earth. Because the prepared spatial map is not frequently updated in general, the map is different from the actual map. Meanwhile, the simultaneous localization and mapping (SLAM) technique has been investigated in augmented reality and mixed reality. SLAM achieves both positional tracking and spatial map measuring using a monocular, stereo, or depth camera [18–23].

We herein propose a three-dimensional noise and spatial mapping system with an aerial blimp robot, consisting of a balloon that can be sufficiently silent to measure the environmental noise. We built a prototype system and performed a basic examination in a large room. The proposed system has a stereo camera to track the self-position and measure the surrounding spatial map by SLAM. Thus, the system constructs a three-dimensional noise map by combining the noise-level information, measurement positions, and spatial map. We conducted three experiments: the comparison of propeller rotation noises between the proposed system and a general recreation-use multirotor, the measurement of effect by sound reflection and diffraction using a balloon filled with helium gas, and the creation of a three-dimensional noise map in the indoor environment.

2. SYSTEM

2.1. Overview

Figure 1 shows the appearance of our proposed system. Figures 2 and 3 show the pattern diagrams of our proposed system and the directions of the propeller rotations and its driving force, respectively. The proposed UAV is required to move silently for sound recording and measurement. Its omnidirectional movement is also desirable for the measurement of a three-dimensional noise map. However, it is not necessary to move fast in most cases for the noise map measurement. Thus, our developed system is designed to achieve slow, silent, and omnidirectional movements. Because our developed system uses a balloon to obtain buoyancy, which renders its continuous hovering flight easy, the system can even fly with slow propeller rotations. A slow propeller rotation also implies that the rotation noise is reduced.

As shown in Fig. 2, both the width and height of the balloon are 1.4 m. A microphone, which is an electret microphone that is omnidirectional and its frequency band are between 30 Hz to 18 kHz with a USB interface, is installed at the bottom of the balloon assuming that the sound source to be measured is positioned under the system in most cases at high altitudes. A system control board is also installed at the bottom of the balloon such that the position of the gravity center is lower. In addition, the reduction in propeller rotation noise on the microphone is achieved by distancing the microphone from the propellers. A system control device, which can control the sensors such as a microphone, motor drivers, and a stereo camera, is also installed at the bottom. As shown in Fig. 3, six
Propellers are installed in the system to enable omnidirectional movements, i.e., two propellers at the equator for vertical movement and the other four propellers at the upper part of the balloon for horizontal movement.

Table 1 shows the information of each unit of the system. The balloon has a spherical shape with a diameter of 1.4 m, and is made of vinyl chloride material with a thickness of 0.08 mm. In an emergency situation, such as depleted battery and blocked communication with the external network, the system could return to the ground because the buoyancy of the balloon is set to approximately 5 g lighter than the weight of the system. The system used two batteries. The first battery can power the system control board for approximately an hour. The second one can power the motor drivers for approximately 10 min with the all propellers’ rotation speed at the maximum. When the propeller rotation speed is sufficiently low to hover, the battery can power the drivers for approximately 50 min.

2.2. Control Device

The control device consists of an embedded computer comprising a CPU and a GPU. The role of the control device

![Fig. 2](image1.png)  
**Fig. 2** Pattern diagrams of the proposed blimp robot and arrangement of the six propellers, stereo camera, control board, Wi-Fi antenna, and a microphone. Four propellers are installed on the same horizontal plane. The other two propellers are installed on the equator of the balloon.

![Fig. 3](image2.png)  
**Fig. 3** Rotational directions of six propellers and the directions of its driving forces. The driving forces of four propellers at the upper position are directed to the horizontal direction. The other two force directions are directed to the vertical direction. Green and blue rounded arrows show that the rotational direction of propellers are clockwise and counterclockwise, respectively, when viewed from the front and above.
device is to receive messages from the external host PC and subsequently operate based on the message. Figure 4 shows the commands and signal flows in the control device. The software on the embedded Linux OS analyzes the control commands that are sent from the external host PC using TCP/IP protocol over the IEEE802.11n wireless network. When the commands for the movement of the system are received, an I2C signal is generated to control the motor drivers. The motor drivers generate pulse width modulation (PWM) signals to drive the DC motors. Because the movement commands include the information of movement speed and direction, the system controls the appropriate DC motors with voltages based on the speed information. When the command to start recording is received, the microphone signal starts to be recorded into the memory via a USB. The sampling frequency is 44.1 kHz and the quantization bit is 16 bit. Simultaneously, the video movie of the stereo camera is also recorded via the USB.

### 2.3. Propeller Configuration

The number, arrangement, and driving force directions of the propellers decide most of the restraint conditions of the UAV dynamical systems. Various arrangements of propellers in balloon-type UAVs have been proposed [16,17].

Our proposed system has six sets that comprise a DC motor and a propeller each, which are the simplest and most fundamental configuration for an omnidirectional movement. The six propellers are divided into three groups depending on the driving force directions. The driving force direction in each group of propellers is mutually orthogonal. Figure 3 shows the front and top views of the arrangement of propellers. Two propellers installed at the equator contribute to the movement along a perpendicular line. Although the propellers must be installed at the equator to facilitate the accurate direction of the driving forces along the perpendicular line, the other four propellers responsible for the horizontal movement need not be placed at the equator. Considering the effect of the propeller rotation noises on the microphone at the bottom, it is desirable that the propellers are installed at the upper part of the balloon. Therefore, the other four propellers responsible for the horizontal movement are installed at the level of the first-quarter part from the top.

The two propellers in each pair are symmetrically installed along the perpendicular axis that passes through the center of the balloon. When the driving forces of the two propellers are directed in the same direction, each propeller rotates in the opposite direction to cancel the anti-torques of the propeller rotations as much as possible. The driving force direction can be reversed by changing the direction of the electric current flowing into the DC motor. Thus, the system combines the three orthogonal driving force directions and its opposite directions to move omnidirectionally.

### 2.4. Simultaneous Localization and Mapping

To produce a three-dimensional noise map, both the positional and spatial information of the system must be
obtained. Recently, the various techniques for obtaining the positional information such as simultaneous localization and mapping by image processing, which is termed SLAM [18–23], have been developed for automatic driving, augmented reality, etc.

In the proposed system, a stereo camera (ZED Stereo Camera, STEREOLABS, Inc.) was installed on the balloon as shown in Fig. 2(a). In this research, the stereo camera records the movie and calculates the depth from the distance of two cameras, and SLAM processes the spatial mapping and positional tracking from this information. The moving paths were estimated by offline signal processing using the recorded movies and the map could be created after the measurement.

2.5. Noise Mapping

In our proposed system, the host PC can combine the surrounding spatial information obtained by SLAM and the sound pressure information obtained by the microphone, which are stored in the memory on the blimp robot. The host PC downloads all the data from the memory. To build a three-dimensional noise and spatial map, we used Unity software¹, which is a game development platform to build high-quality three-dimensional models in the computer.

Figure 5 shows the process flow of creating a noise map from the recorded signal and stereo movie.

![Fig. 5 Process flow of creating noise map in host PC from recorded signal and stereo movie.](image)

3. EXPERIMENTS

We conducted three experiments: the comparison of propeller rotation noises between our proposed system and a general multirotor for amateur use, the measurement of effect by sound reflection and diffraction with a balloon, and the creation of a three-dimensional noise and spatial map in the indoor environment.

3.1. Evaluation of Propeller Rotation Noise

To compare the propeller rotation noises of our proposed system and that of a general multirotor for amateur use, we measured the propeller rotation noises in the hovering condition while rotating all four propellers of a general multirotor and only two propellers at the equator of the balloon. The experiments were conducted in an experimental room at the Honjo Campus, Waseda University. In the experimental room, the SPL and A-weighted SPL of the background noises were 34.9 dB and 17.1 dB, respectively.

Figure 6 shows the comparison of the rotation noises between the general multirotor and the proposed system on an elevation angle. The sound-level meter with a wind shield, RION Co., Ltd. NL-32, was placed 2.0 m from the center of each product and rotated by 45° in the elevation direction from 0° to 180°. The 0° and 180° mean the direction toward the bottom and the top of each product, respectively.

The SPL of the propeller rotation noises of the proposed system was reduced by 9.5 dB on average in all directions compared with the general multirotor. The A-weighted SPL was also reduced to beyond 20 dB in all directions. Particularly, the propeller rotation noise at 0° shows a significant difference between the general multirotor and the proposed system. The general multirotor typically rotates the propellers to hover, and causes wind noise. Thus, propeller rotation noises of the proposed system is reduced compared with the general multirotor, thus causing less noise to the surrounding environment.

3.2. Acoustical Effect of Balloon in Sound Field

To evaluate the acoustical effects of the balloon on the average. Subsequently, the signal was converted to the sound-pressure level (SPL). Meanwhile, the three-dimensional and actual-scale model of the surrounding object was obtained by SLAM, which includes the shape and color information. Additionally, the averaged SPL with a time constant of 125 ms is represented by the colors of the spherical object, of which the position represents the measurement position. Thus, in our proposed system, the sound and positional information can be simultaneously observed as three-dimensional models with actual-scale objects such walls and the floor of a room.

¹Unity Technologies, https://unity3d.com
recording by a microphone, we measured the impulse responses near the surface of the balloon with a loudspeaker. Two types of experimental conditions were investigated: with balloon (condition 1), and without balloon (condition 2).

Figure 7 shows the arrangement of the measurement to investigate the effect of the balloon on microphone recording. This shows the top view. The sound-level meter was displaced by 5°.

Fig. 7 Arrangement of impulse responses measurement to investigate the effect of the balloon on microphone recording. This shows the top view. The sound-level meter was displaced by 5°.

around the center of the balloon. The sampling frequency was 96 kHz.

Figures 8 and 9 show the impulse responses without and with the balloon, respectively. The X axis and Y axis represent the time and angle, respectively, which is the microphone position in Fig. 7. The color bar on the right represents the relative SPL, and the 0 dB of each graph is based on the maximum value of the observed SPL. Figures 10 and 11 show comparisons of the impulse responses with and without the balloon at 0° and 90°, respectively. The amplitudes in the figures were normalized by the maximum of amplitude at 0° without the balloon.

As shown in Figs. 8 and 10, a direct sound from the loudspeaker arrived at 7–14 ms without the balloon. Subsequently, the reflected sounds from the floor arrived at 17–20 ms. As shown in Figs. 9 and 11, a direct sound from the loudspeaker is also observed at 0°–45° and a diffracted sound around the balloon is shown at 45°–140°. In addition, the transmitted sounds through the balloon were observed at 60°–180°. The balloon is filled with helium gas and the sound speed in helium gas is...
approximately three times faster than that in air. Thus, the transmitted sounds through the balloon arrived at the microphone faster than the direct and the diffracted sound.

Figures 12 and 13 show the spectrum of the impulse responses without and with the balloon, respectively. In addition, Figs. 14 and 15 show comparisons of the spectrum of the impulse responses with and without the balloon at 0° and 90°, respectively. All impulse responses were normalized by maximum of amplitude at 0° without balloon in time domain. As shown in Fig. 12, only slight changes caused by the directivity of the sound source were observed without the balloon. With the balloon, similar SPLs were observed under 3.5 kHz at 0°–90°. However, because of the interferences of direct sound and reflected sound by the balloon surface, stripe patterns resembling comb filters were observed. Beyond 90°, stripe patterns were not observed, but, the SPLs significantly decreased because most of the sounds were reflected by the balloon.
because of the system flight. The microphone was installed at the bottom of the blimp. To avoid the stripe patterns of the spectrum caused by the reflection, it is desirable to use the directional microphone that is directed to the outside of the balloon.

3.3. Three-dimensional SPL Distribution Measurement with Blimp Robot

A preliminary experiment of the three-dimensional noise map with our developed system was conducted with no wind condition in the area of 6 m length/6 m width/7 m height, which is part of the experimental room at the Honjo Campus, Waseda University [24]. Figure 16 shows the arrangement of the measurement. We used two loudspeakers: a flat-panel loudspeaker array that is combined with four flat-panel loudspeakers (WASEDA E.E. W3232) for generating a 1-kHz octave-band noise and an ordinary loudspeaker (YAMAHA NS-10M) that outputs 500-Hz octave-band noise. The characteristics of these loudspeakers were reported in [25]. Figure 17 shows the directivity of the flat-panel loudspeaker array. As the figure shows, the flat-panel loudspeaker array has a sharp directivity. The SPL was 90 dB at 1 m from each loudspeaker. The flat-panel loudspeaker array was tilted 60° from the floor. The ordinary loudspeaker faces toward the ceiling. The floor was covered by sound absorbers to reduce the effect of the sound reflection from the floor.

We measured the SPLs in this area both by human work and by our proposed system. The number of points measured by human work using the sound-level meter is 125 points in the measurement area of 5 m length/5 m width/5 m height. The distance of adjacent measurement points was 1 m. Figures 18 and 19 show part of the measurement points by human works and the its SPL maps by using a sound-level meter in the plane parallel with a 3 m distance from the flat-panel loudspeaker array, and in the plane perpendicular to the flat-panel loudspeaker array, respectively. The measurement at all 125 points took two and half hours by human work.

Figure 20 shows the results of spatial mapping and measured SPLs on the trajectory of the UAV. The SPL and
measurement position was obtained every 0.125 s. The SPL was calculated from the average of the power of sound pressures during the analysis length. It was assumed that the moving speed was sufficiently slow to ignore the Doppler effect. The microphone signal was calibrated using a 1-kHz sine signal. The line color indicates the SPL.

The system’s trajectory and spatial map were estimated by the SLAM technique with the stereo camera. In this experiment, SLAM was provided by the ZEDfu software version 2.1.0 (STEREOLABS, inc.). In this research, stereo video was recorded with 60 frames per second in 1,920 x 1,080 resolution. In the setting of ZEDfu, the spatial mapping resolution was 0.08 m, and the depth range was 10 m. The obtained spatial map included a three-dimensional mesh data and its texture to reconstruct a three-dimensional computer graphics of the surrounding environment. The spatial and SPL map shown in Fig. 20 can be built via the Unity software. In addition, the SPL data was spatially discrete only by the sound-level meter. However, it is possible to obtain the SPLs more continuously by our proposed system.

For comparison, Fig. 21 shows the SPLs along the moving path of the proposed system using the sound-level meter and the proposed system. The result of the sound-level meter was linearly interpolated from the nearby four SPLs and subsequently obtained along the moving path of the proposed system. The result of the sound-level meter was interrupted during the process, because the proposed system trajectory exceeded the measurement area by the sound-level meter. The proposed system result was calculated by 125 ms moving average from the energy of the original sound pressure signal. As shown in Fig. 21, the difference between the two results was approximately 2 dB at the maximum. This is attributable to the error of the estimated trajectory and the effect of the balloon reflection. However, the measured SPLs by the proposed system were sufficiently accurate to create the environmental noise map.
4. CONCLUSION

We herein proposed the aerial blimp robot for creating the three-dimensional noise and spatial map. Using the helium-filled balloon and six propellers, the system can move omnidirectionally and quietly. The system noise is reduced by more than 20 dB A-weighted SPL in the hovering condition compared with the general multirotor. In addition, by applying the SLAM technique to track the measuring points and to create a spatial map, the system can measure in a free movement path. From the comparison result with the microphone measurements, we found that the measured noise map was sufficiently accurate to understand the environmental noise. For future work, it will be more efficient to create a three-dimensional noise map by interpolating the measurement results and by an effective plan of the flight path.

REFERENCES


