iSphere: Self-Luminous Spherical Drone Display

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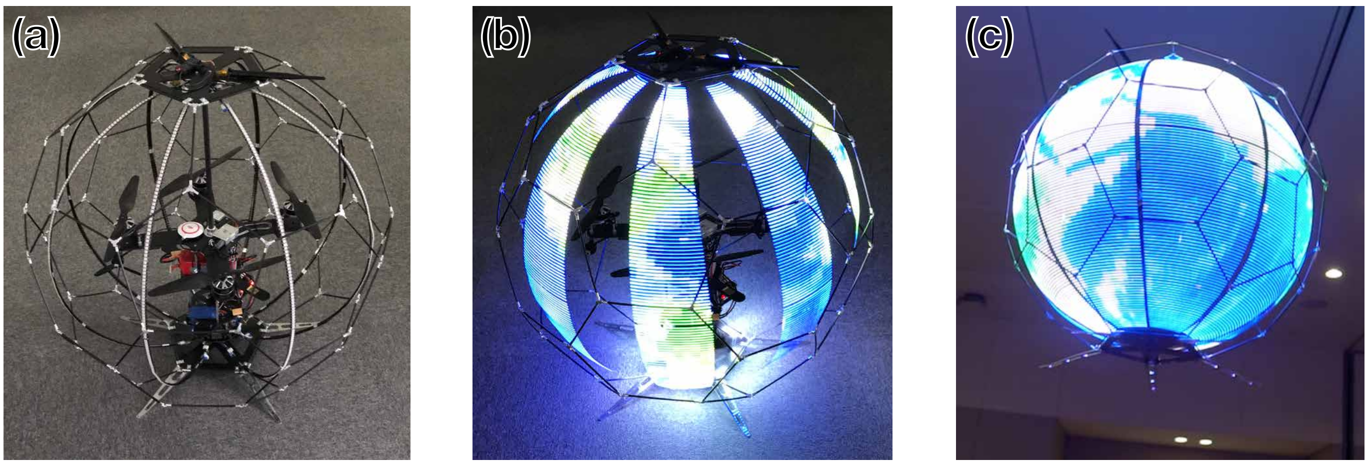

Figure 1. Our prototype: (a) iSphere in idle mode. (b) iSphere in a boot stage of display. (c) Flying iSphere with display on.

ABSTRACT
We present iSphere, a flying spherical display that can display high resolution and bright images in all directions from anywhere in 3D space. Our goal is to build a new platform which can physically and directly emerge arbitrary bodies in the real world. iSphere flies by itself using a built-in drone and creates a spherical display by rotating arcuate multi light-emitting diode (LED) tapes around the drone. As a result of the persistence of human vision, we see it as a spherical display flying in the sky. The proposed method yields large display surfaces, high resolution, drone mobility, high visibility and 360° field of view. Previous approaches fail to match these characteristics, because of problems with aerodynamics and payload. We construct a prototype and validate the proposed method. The unique characteristics and benefits of flying spherical display surfaces are discussed and we describe application scenarios based on iSphere such as guidance, signage and telepresence.

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INTRODUCTION
Technologies to dynamically control the location of displays in three-dimensional (3D) space have attracted great attention for a long time. There are two kinds of approaches in the area. One approach is to interact with virtual objects in 3D space like "Ultimate display" proposed by Sutherland [35]. The other approach is to interact with physical objects in the real world. The concept "Programmable Matter" by Toffoli and Margoulus [37] is well known in this area. They assumed extremely small particles that had controllable physical properties such as shape, density, texture and position, and the concept is to form objects in the real world by controlling the particles. Radical Atoms [13] and Claytronics [5] are also well

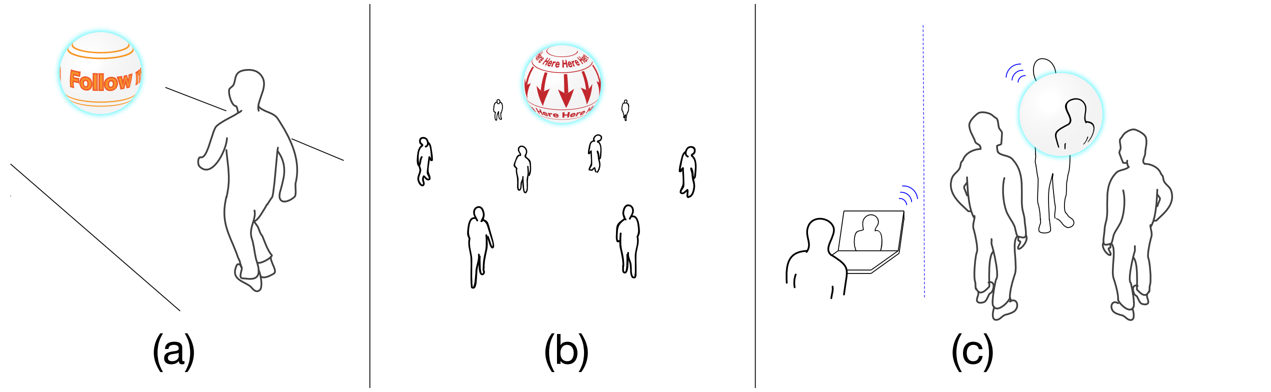

Figure 2. Possible applications. (a) Guidance application. (b) Application that presents information to the surrounding people. (c) Telepresence system capable of freely moving in 3D space.

known as concepts that describe the embodiment of various 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 was to create arbitrary bodies anywhere in the real world by overcoming gravity. Our research goal is to control the physical position of untethered displays in 3D space. There are two main approaches to controlling the 3D position of objects that appear to hover. One uses invisible tethers to levitate physical objects. Examples include the use of acoustic-potential fields [25] and magnetic fields [20].

The other assumes the use of self-levitating objects. Past devices include a robotic helium balloon [16] and a blimp [36], but systems using drones of the type called multi-copters have been attracting intense interest over the last decade. This is because the drones have higher mobility, robustness against winds and greater payloads and these characteristics allow various rich interaction interfaces to be designed. Moreover, drone cost has been greatly lowered by technological improvements such as better motors, batteries, electric speed controllers (ESCs), and flight controllers.

Intel demonstrated that "Shooting Star" [12] could display large figures in 3D space by hundreds of small drones each equipped with RGB LEDs. MicroAd presented "SKY MAGIC" [21], a system for stage performances by larger drones decorated with multi LED strips. Gomes et al. proposed "BitDrones" [6], a prototype of interactive programmable matter that used a swarm of small drones equipped with small flexible high-resolution thin-film touch screens or RGB LEDs; however, it could not simultaneously display images in all directions.

There are two ways to create large high-resolution omnidirectional displays: 1) integrate an extremely large number of extremely small drones, and 2) create giant drones that have high resolution omnidirectional displays. The former remains very difficult due to the limitations of weight of electric components, stability, and cost. The latter is also difficult, because large and high resolution displays are susceptible to air flow and their weight and size degrade the flying characteristics.

This paper proposes "iSphere", a lightweight drone that uses a spherical persistence of vision display (POV) to output large omnidirectional images with high resolution and brightness as shown in Figure 1. Since our proposal is based on the POV display, it maximizes the resolution and size of the display surface while minimizing the problems of aerodynamics and payload. iSphere can jump over obstacles in the environment and present various images with high resolution in any direction from anywhere in 3D space shared by humans. In other words, iSphere is a new omnidirectional display having computer-controlled physical position in 3D space. We regard iSphere as the first prototype toward a new platform that can physically and directly create arbitrary objects in the real world. iSphere is also the first flying display proven able to combine high mobility and visibility, with 360° field of view.

We consider that iSphere will make various new interfaces possible in 3D space. For example, an iSphere can lead a user to his/her destination by presenting guidance images while flying as shown in Figure 2 (a). We believe that spatial and direct evacuation guidance can be realized by using iSphere in rescue situations. iSphere can provide information simultaneously to surrounding people as shown in Figure 2 (b), because of its 360° display surface. Of particular interest, a high altitude iSphere can directly present information to many people spread over a wide area. iSphere can display images over the entire surface of a sphere unlike conventional methods [6, 12, 8] which suffer aerodynamic problems when displays are placed on both the top and bottom sides. We regard these characteristics as important in applying iSphere in a rescue or signage applications. Moreover, iSphere supports remote controlled applications such as telepresence. Figure 2 (c) illustrates a telepresence system using iSphere. The iSphere displays the upper body of the remote user while the environment around the iSphere is captured by a camera mounted on it. This telepresence system makes it possible to fly over obstacles in the environment and communicate with remote people. Thus, iSphere has potential to become spatial platform that can made new applications such as signage, rescue and remote communication.

Our work makes the following three contributions: First, we outline and discuss the unique benefits and possible applications of the spherical flying interface iSphere. Second, we reveal the method used to implement an interface with drone mobility, high resolution, and large bright spherical display. Third, we confirm that the proposed method is feasible by implementing a prototype.

The remaining sections of this paper discuss the following: First, we introduce previous research on 3D space interaction and other studies related to the underlying mechanism of iSphere. Second, we describe the principles and design parameters of iSphere. Third, we introduce the iSphere prototype and confirm its characteristics. Finally, we discuss possible applications, limitations, and the future of our proposal.

RELATED WORK

In this section, we survey the literature in four categories: 1) augmented reality, 2) external systems to levitate physical objects, 3) self-levitating physical objects such as drones and balloons, 4) spherical surface displays.

Augmented Reality

A number of studies have addressed interaction with virtual objects in 3D space. This field is called augmented reality (AR), a term coined by Thomas et al. [27]. AR allows the user to see the real world, with virtual objects superimposed upon or composited with the real world [1]. 'Video-see though" combines real-world view with computer-generated imagery (CGI) by digitally mixing video from a camera with CGI. Sutherland demonstrated a method to present merged images to users through head-mounted displays [35]. NaviCam [15] introduced a mobile AR system based on the user's handheld device. Parrot released the commercial game product "ARdrone", which is combined mobile AR system and drones [28].

"Optical see-through" uses a semi-transparent display to directly overlap CGI with the user's field of view (FOV). TouchLight [4] presents the user with a virtual image by projection on a semi-transparent screen. Hololens [22] is a head-mounted display having a depth sensing camera and semi-transparent screen for mapping the around environment and overlapping virtual objects on a user's field of view. Moreover, it makes possible to directly manipulate virtual objects with gestural input.

Creating AR by drawing CGI on physical objects in the real world with no dedicated screen has also been explored. "Shader Lamps" [31] introduced a method for rendering CGI onto physical objects by using projectors. Researchers have also explored how to interact with physical objects onto which CGI was projected [10, 29].

Non-self Levitating Interface

Research on controlling physical objects by computers has been also explored for a long period. The idea is the basis for various notable concepts such as "Programmable Matter"[37], "Radical Atoms"[13], "Claytronics"[5] and so on.

Thus, various methods to realize the idea have been tried. Lee et al. demonstrated "ZeroN" [20] which is a method to control the 3D positions of a magnetic material with a strong magnetic field. "Pixie Dust" [25] can form sparse images in 3D space by controlling the positions of small, lightweight particles with an acoustic-potential field. A method to control lightweight objects using air-jets has been proposed [14]. Other well known methods include the use of fog [30] and water drops [2]. Systems as those of [20, 25, 30, 2] are likely to combined CGI projection technology, because physical objects can not generate images by themselves.

One proposal directly writes voxel in self-luminous plasma in the air with strong lasers, Kimura et al. [18]. Ochiai et al. [26] use femto-lasers to create touch interaction plasmas, which are safer those generated by a nanoseconds laser.

Self-Levitating Interface

This section details the approaches known to be based on self-levitating objects. Karagozler proposed the use of robotic helium balloons [16]. A blimp equipped with a projector was used to realize a telepresence system in Tobita [36].

Of more particular interest are the methods using multiple drones of multi-copters type. Floating displays can be created by flying a swarm of tiny drones holding RGB LEDs [6, 12, 19]. BitDrones uses small drones equipped tiny flexible thin-film touchscreens or RGB LEDs [6]. Sky Magic uses a swarm of larger drones equipped multiple LEDs [21].

Jürgen et al. created "Displaydrone" to project images on adjacent walls [34]. They also described a variant that had a screen and a projector on a single drone [33]. Nozaki et al. described how to project an image onto the screen on another drone [8].

How a flying drone can realize display as well as an interaction interface has also been investigated. Pfeil et al. explored interaction metaphors for interacting with a drone in 3D space [17]. Cauchard et al. investigated the concept by conducting a Wizard of Oz experiment [3]. Nitta et al. proposed Hoverball, a flying interactive ball with built-in drone, to enhance traditional ball sports [24].

Spherical Display

Flat rectangular surface displays are the most widely adopted form factor in modern devices such as personal computers, smart phones and public displays. Holman et al. have proposed "Organic User Interfaces" as a user interface with a non-flat display [9]. Although various forms of displays have been proposed in the last decade, spherical displays have unique characteristics in that they offer an unobstructed 360° field of view to all users. Hashimoto et al. developed "Panorama Ball Vision", which is a spherical display based on a POV display [7]. We adopt their idea of realizing a spherical display by spinning an array of arcuate LED tapes around a common axis. Geo-Cosmos is a huge and high resolution spherical display consisting of ten thousands of organic LED displays pasted onto a spherical surface [23].

Moreover, research aimed at interacting with spherical images has also been conducted. Kettner et al. generated a spherical screen using multiple external projectors [32]. Their display can be physically rotated in place as a large trackball. Benko et al. made multi-touch possible on a spherical display [11].

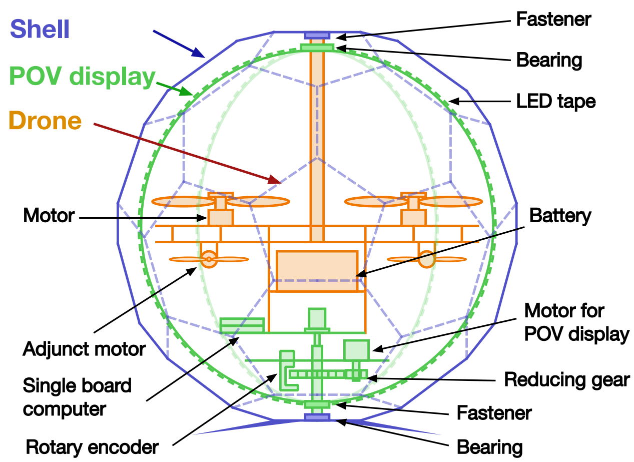

Figure 3. Simplified architecture of our proposal.

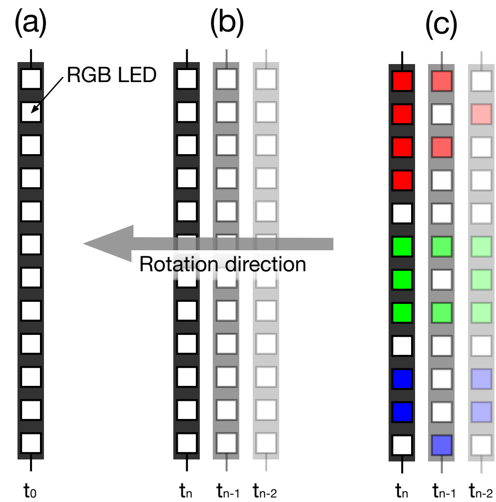

Figure 4. Mechanism of POV display. (a) Serial RGB full color LEDs on a tape. (b) LED tape moves at high speed. (c) Controlling LEDs on each tape according to its position. This forms "POV" characters in the user's vision via POV.

PROPOSED METHOD

In this section, we show the principle and architecture of iSphere.

General Architecture

iSphere is a spherical display that can fly to any location and present large and high resolution images to all directions. iSphere consists of three main components as below.

1. The drone to produces thrust for flying.
2. The POV display to create a spherical image.
3. The shell prevents the propellers and the LED tapes from hitting things.

These components are arranged as shown in Figure 3 shows. The drone is set at the center of iSphere. The POV display consists of multiple arcuate LED tapes The shell forms the body of iSphere. As shown in Figure 3, the drone, the POV display and shell have the same rotation axis, but the POV display rotates independently of the drone and the shell.

The mechanism of the POV display is explained below. When a person sees an object, its image remains captured by the retina of the eye for a short interval of time. The phenomenon is called persistence of vision and iSphere utilizes this phenomenon. When an arcuate LED array (Figure 4 (a)) moves at high speed, it is perceived as a series of arrays as shown in Figure 4 (b). When the LEDs are activated in synchronization with position, an image can be formed as shown in Figure 4 (c). iSphere creates the spherical display by combining multiple arcuate LED tapes, a motor to rotate them, and a rotary encoder for image and rotation synchronization.

Aerodynamics

iSphere is lifted and directed by the high speed airstream generated by the drone. Since this airstream must not be obstructed it is difficult to apply previous proposals such as pasting displays [23] and screens [11] around the drone. By contrast, the POV display uses multiple LED tapes with very small vertical area that obstruct the airstream only slightly.

Weight

The key concern is to minimize the weight of the display that the drone must carry. Our proposal offers superior weight savings as the POV display simply rotates lightweight LED tapes to create the spherical display surface. Moreover, iSphere offers superior scalability. Increasing its radius to create larger display increases the surface significantly more that the length (and thus weight) of the LED tapes. In other words, as the system becomes bigger, less of the total weight is occupied by the POV display.

Shape of Display

We consider that the spherical display is the best match for an interface that moves freely in 3D space, because the relative physical relationship between users and the interface dynamically change when the interface or user moves.

Take the case of a route guidance drone leading users to their destination by presenting guidance images to them as shown in Figure 2 (a). In this example, the relative angle and distance of the drone and the users dynamically change during their movement. A drone equipped with a flat display would have to be physically reoriented at every turn or corner. In contrast, iSphere simply alters the displayed information as required. In addition, the spherical display makes it possible to simultaneously present different information to people on different sides of iSphere.

Our proposal allows the use of other display surface shapes, provided they are shapes of solid revolution such as cylinders and circular truncated cones, see Figure 5. Thus, the proposed method offers some degree of freedom in terms of display shape.

Visibility

A single drone must offer larger display areas and higher resolutions to present richer information to a user. iSphere has

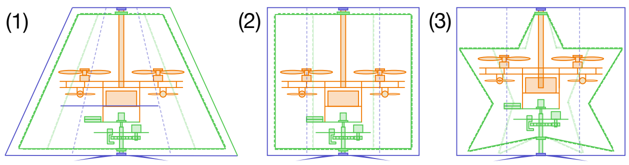

Figure 5. Examples of possible shapes. (1) Circular truncated cone form. (2) Cylinder form. (3) Star form. The shell and display can have different forms.

not only high resolution but also large compound display areas. iSphere can present different information to users on opposing sides as the displays are visually isolated. In addition, iSphere obscures the drone from the user's vision, because the bright images formed attract and hold the user's attention.

The brightness of the display is also important, because the viewing environment is likely to varying widely. Adequate brightness is needed to ensure that the user can see the image even when iSphere is in a bright environment or when it is far from the user. We meet this requirement by using high output LEDs.

Rotational Dynamics

The POV display and drone share the same rotation axis and are connected via the slip ring. When the POV display motor rotates the LED tapes, a reaction torque is generated as shown in Figure 6. Unless countered, this reaction torque would make the shell and drone spin creating significant rotational forces that would it difficult to control drone movement and thus iSphere. While it might be possible to retain control while the drone spins, we choose the other approach of preventing drone rotation. Our solution has two parts. First, iSphere takes off after making the rotational speed of the POV display constant to prevent the reaction torque from changing significantly while flying. Secondly, iSphere produces additional torque to cancel the reaction torque generated by POV display, see Figure 6. While the copter can employ differential propeller driving to create the torque needed, this degrades lift efficiency so the iSphere prototype uses small additional propellers like a helicopter tail rotor as shown in Figure 6. The rotation speeds of the additional propellers are controlled to suit LED tape rotation. As a result, to the user, drone and shell do not appear to rotate.

IMPLEMENTATION

Overview

This chapter explains how we implemented our iSphere prototype. Figure 7 shows an overview of the prototype. The outside diameter of the prototype is about 88 cm and weight is about 4.5kg without battery. The battery is 6 cells having and common in the whole system. The prototype consists of drone, POV display and shell as described in the prior chapter. The shell is rigidly fixed to the frame of the drone by a 12mm plain weave carbon fiber tube.

Drone

The drone is set at the center of iSphere, see Figure 7. The drone is a quadcopter and so has four main propellers (13 x 3.5

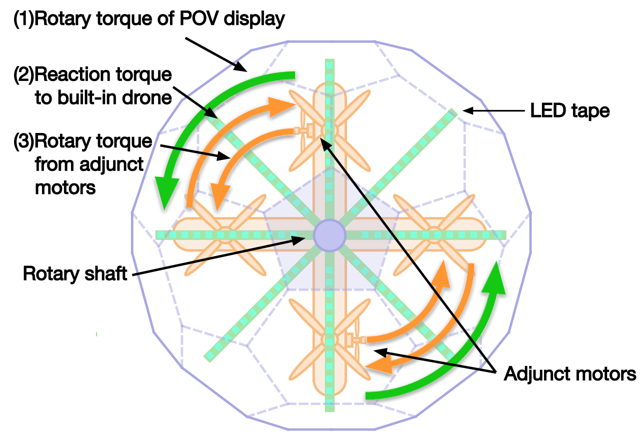

Figure 6. Overhead view of the rotation dynamics of iSphere. Reaction torque from POV display is countered by two adjunct motors.

inch, 2 blade), motors (DYS Quanum MT Series 4012 480KV) and an ECSs (HOBBYWING XRotor Pro-50A) as Figure 8 shows. The flight controller (DJI A2) is connected only the quadcopter's components such as the four main motors, the ESCs and the receiver (FUTABA, R7008SB) and independent from the two adjunct motors (DYS MR2205 2300KV) having propellers (5 x 4.5 inch, 3 blade) and POV display. Each motor is placed 55 cm diagonally apart, and the maximum total thrust of the motors is over 9 kg. The drone frame was fabricated by NC cutting 5 mm thickness carbon fiber plate and aluminum material, instead of customizing a commercial product. Although it is better to make all parts with lightweight and high rigidity carbon, complex components such as joints and ball bearing holders are made of aluminum because it is difficult to make them in carbon.

Persistent of Vision Display

The POV display consists of eight arcuate LED tapes as Figure 7 shows. Each LED tape is 1 m long and holds 144 full-color programmable LEDs (Shenzhen Shiji Lighting APA102). Each LED is driven by 32 bit data across the Serial Peripheral Interface (SPI).

The LEDs are connected to a single board computer (SBC) Raspberry PI 3 via the slip ring (Senring M022A-18) as Figure 9 shows. The SBC also drives a brushless motor (DJI E305 800KV) and ESC (HobbyKing 70A ESC) to rotate the LED tapes via a gear having 1 / 12 reducing ratio. A photo interrupter and reducing gear with eight holes used to sense display rotation speed.

In addition, the adjunct motors are also driven by the SBC to cancel rotation counter torque from the POV display. The rotation speed of adjunct motors ω_m is controlled according to the rotation speed of POV display ω_p as follows. The parameters α and b were manually calibrated as to counter the torque of POV display rotation.

$$\omega_m = \alpha \omega_p + b \tag{1}$$

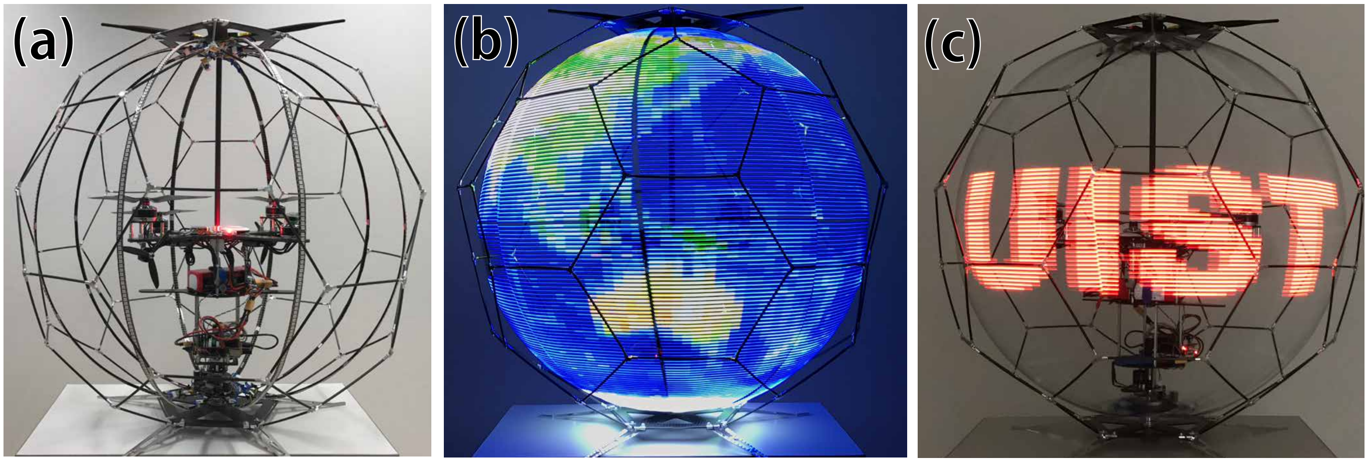

Figure 7. Overview of our prototype. These pictures were taken using 1 / 24 second exposure times. (a) Overall view of iSphere with display off. (b) iSphere presenting an image over entire surface. The image hides the built-in drone. (c) iSphere creating a partial image. Idle image areas appear semi-transparent.

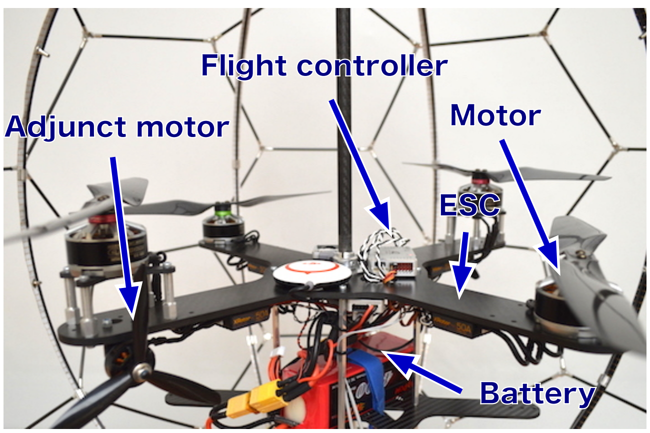

Figure 8. Setup of drone in iSphere.

The SBC holds the rotation speed of the LED tapes at 3 rps (revolutions per second) using feedback control. The frame rate f can be simply calculated using rotation speed r rps and the number of LED tapes N as follows. Thus, our prototype has a display rate of 24 fps (frames per second).

$$f = N \times r \tag{2}$$

The use of the SPI provided by the Raspberry PI 3 demanded a novel solution to drive the virtual display of 144 (height) x 136 (width) pixels at 24 fps. The communication speed needed, about 14Mbps (144 x 136 x 24 x 32 bits), is higher than the SPI capacity in GPIO of Raspberry PI 3. Thus, we drive the LEDs via a Universal Serial Bus (USB) 2.0 to an FT4232 that has two SPI ports. The FT4232 drives the LED tapes using the two SPI in parallel. In this way, the prototype can display 144 x 136 images at 24 fps. Figure 7 (c) shows the POV display of our prototype presenting "UIST". Intriguingly, parts other than the UIST logo appear to be semi-transparent, because the thin LED tapes are rotating so quickly.

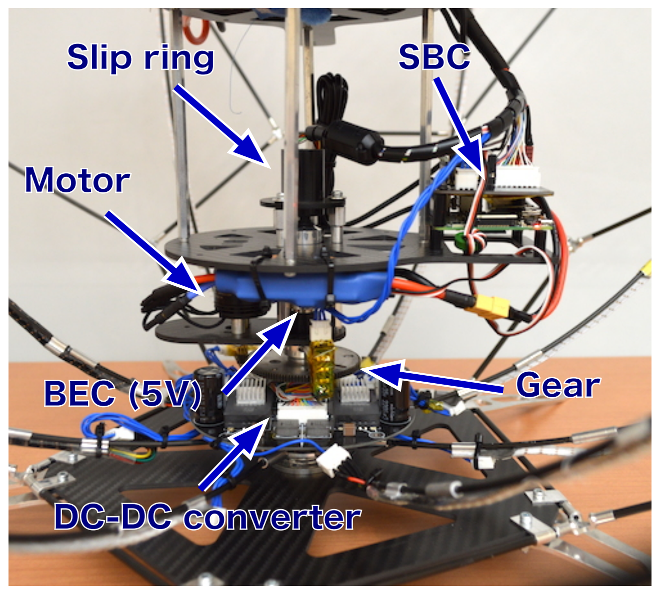

Figure 9. Setup of POV display.

Incidentally, the use of many LEDs raises problems with current draw as well as communication speed. Each LED is driven at 5 V and has maximum electric current draw of 70 mA. Total electric current of the eight LED tapes having 144 pixels exceeds 80 A or so which is enough to destroy the slip ring. For this reason, a 22.2 V power supply is placed inside to reduce electric current passed through the slip ring. After passing the slip ring, iSphere drops the 22.2 V to 5 V so the current requirements are satisfied.

Shell

The shell is a cage to prevent the propellers and LED from hitting other things. It weighs about 0.3 kg. For the prototype, we built it as a truncated icosahedron having 60 vertices and 90 edges. The edges are carbon tubes (4 x 3 x 18 mm) and the vertices are aluminum alloy joints. The bottom plate has five aluminum legs for landing.

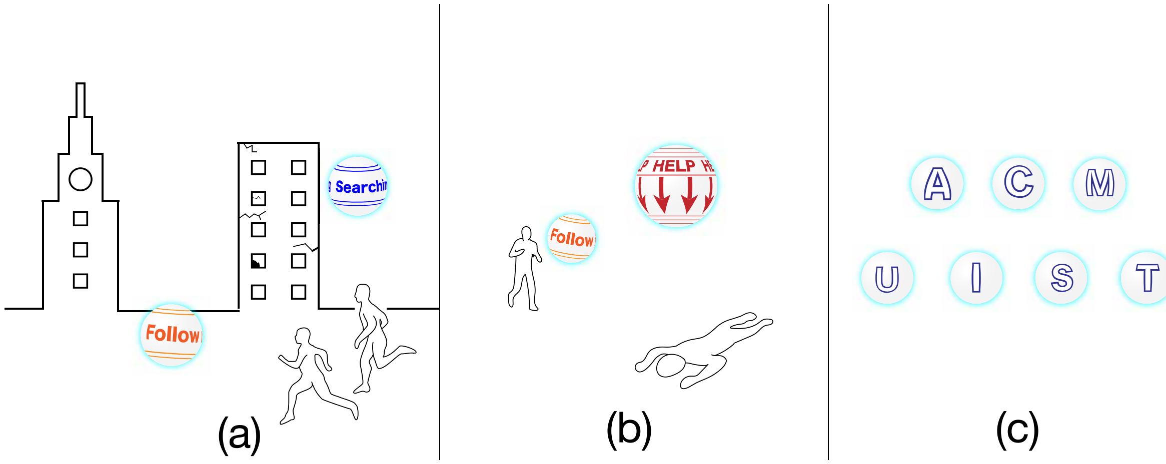

Figure 10. Application scenarios of iSphere. (a) Rescue application that search the people and guides them to shelters. (b) Asking help from the surrounding people. (c) Presenting large images by a swarm of iSpheres. Characters "ACM UIST" are displayed.

Figure 11. Experiment on visibility. iSphere is 100 meters from the camera.

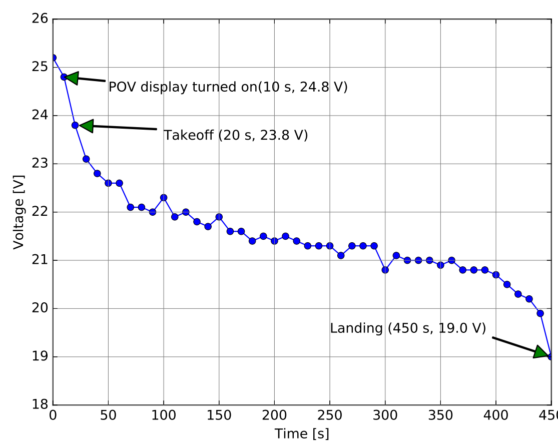

Figure 12. Experimental result of power consumption while flying.

DISCUSSION

Possible Application

We introduced the application examples of guidance and stage performance in the previous section. This section discusses the potential of our proposal.

First, we conducted experiments to confirm the practicality of iSphere. We confirmed that iSphere under manual control matched the mobility of a regular quad-copter as expected. At the same time, we confirmed that the displayed images could be seen from any direction. Second, we conducted an experiment on visibility to determine the distance limits of iSphere. We displayed a randomly selected letter as shown Figure 11. The observer had 20/15 vision and could reliably read the letter on the display up to 100 meters away in weak sunlight when the background was a building.

An evaluation of visibility showed that iSphere can present information over long distances. For that reason, we consider applications that combine signage and guidance for rescue operations in the event of a disaster as shown in Figure 10 (a). iSphere wander in the disaster site to find people needing assistance. Besides, iSphere verify their condition, and guide them to the nearest safe shelter. If someone can not move due to an injury or is unconscious, iSphere would rise up or fly around, and call together people for assistance like Figure 10 (b). Thus, the proposed method can concurrently and directly present information to people over a wide area, whether they have information technology devices like smart phones or not. The above discussion and tests reveal that iSphere can present information over long distances and so is able to more directly present visual and spatial information to people.

The another possible application involves creating a much larger display by slaving a swarm of iSphere as Figure 10 (c) shows. As shown, it is possible for each iSphere to display a single character and thus form high resolution sentences in the air. Although, here is a problem of gaps between drones, it is possible to use swarm of drones as a single giant canvas.

Limitation

Although our drone has unique advantages such as 360° field of view, visibility and mobility, it also has some obvious disadvantages. First, it has short flight time. The Figure 12 shows a time-series voltage drop, when the drone equipped with two batteries (KyPOM KT4500 6S 35C) having 6 cells (25.2 V) and 4500 mAh and flies at a 1 m height in a windless outdoor. We observed the voltage while flying via a telemetry function. As shown in the figure it has only about 7 minutes flight time. It is possible to achieve longer flight times by optimizing the motors and weight; however, it is impossible to make it fly for many days like balloons. Moreover, the prototype drone is heavy and noisy as its multi-copter components were designed for load carrying and mobility.

Regardless of its current limitations, we consider that our system has higher potential in creating a lot more useful interactive applications than balloons, because it has many advantages such as higher payload, speed, and robustness against wind. The greater payload widens the design space and allows the mounting of advanced sensors (e.g. omnidirectional camera, laser range finder, and a mesh touch sensor pasted on the shell). These sensors allow various rich interaction interfaces to be implemented. The fast speeds offered by the drone make it possible to quickly approach users and interact with not only stationary people but also walking or running people. Furthermore, its high visibility, robustness against wind, and tether-free flight allow it to be used not only indoors but also outdoors. Although there are also problems such as poor visibility under direct sunlight and lower resolution than ordinary monitors, they can be solved by using smaller and powerful LEDs and field-programmable gate arrays (FPGA) to control them.

Future Work

We aim to evolve our proposal in several different directions. First of all, we will develop autonomous control of a single iSphere using its own sensors or environmental sensors, because the prototype requires manual control. Next, we will make it possible to simultaneously control many iSpheres by using group control technology. The goal of these technologies is to build an information delivery platform that can display images anywhere at any time. This platform will contribute to improving communication in various areas such as signage, rescue, and entertainment as Figure 2 and 10 show.

We are also considering the installation of bidirectional data communication links for telepresence operation as shown in Figure 2 (c). Operator support is another exciting research thread. The iSphere is given overall direction by the operator but can automatically avoid obstacles while plotting and performing local movements by itself. Of course, emergency routines will be needed to handle cases where the operator loses connection with the iSphere.

While our proposal as described herein generates curved 2D images on rotating bodies such as spheres and cylinders, we target to make it will be possible to display true 3D images. The goal is to display any 3D object anywhere in 3D space.

CONCLUSION

We presented iSphere, a flying spherical display that can show high resolution and bright images. iSphere is, in effect, a 3D spaceball that allows images to be generated in all directions. We explained the principle and construction of the proposed method. A prototype was built and tested to confirm the practicality of implementation. We also discussed the unique characteristics and benefits of iSphere and describe possible applications in various situations such as guiding, rescue, and entertainment. The results gained confirm that iSphere has the potential to become a new category of display. Its current limitation and future research directions were elucidated.

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