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Structured Abstract:
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Design/methodology/approach - We propose a mobile robot that can give the audience the optical illusion of the unique movements of a sphere by mounting a spherical LED display on a high-agility wheeled robot.
Findings - We found that movements that are difficult to implement with existing mechanisms can nonetheless be visualized through the use of light.
Originality/value - We propose the concept of using pseudo-physical movements in performances with robots. We built a robot that visually reproduces the movements of a rolling sphere and is capable of faster movements and easier position estimations in comparison with previous spherical robots.

Keywords:
Mobile robot, Spherical robot, Optical illusion, Performance, LED.

Article Classification:
Research paper

For internal production use only

Running Heads:

Mimebot: Sphere-shaped Mobile Robot Imitating Rotational Movement

ABSTRACT

Purpose - When designing a performance involving people and mobile robots, we must consider the required functions and shape of the robot. However, it can be difficult to account for all of the requirements. In this paper, we discuss a mobile robot in the shape of a ball that is used in theatrical performances.

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1 INTRODUCTION

As robotics technology progresses, there are more opportunities for performers to act together with mobile robot, such as robots that act as “doubles” of actors off-stage (Jessop, Torpey, & Bllomberg, 2011), dancing humanoid robot (Kaneko, et. al., 2011), and those that imitate characters from the world of fantasy (DreamWorks Animation LLC, 2015). Some are bigger (Rhizomatiks. 2015) (Phil Reyneri, 2013), and same are smaller (BUYMA, 2015) (Barnelt, 2011) (Tovia CO., 2011) than the performers they interact with but their moves must match those of the performers. Manabe et al. (Manabe, 2011) developed a system that helps a performer recognize the object intuitively by using quadcopters controlled by the relationship between the body of the performer and the data the of movement in real space. When designing a performance involving people and mobile robots, we must consider the required functions and shape of the robot. However, it can be difficult to account for all of these requirements. For example, a performance involving objects flying in the air, which uses, set, quadcopters, could be expensive and difficult to control, whereas one using wires to lift quadcopters into the air would be more economical and possibly have the same effect on the audience. In this study, we chose a sphere-shaped mobile robot and constructed a mechanism for it to ‘act’ like a rolling ball.

There are many forms of bodily expression that use spherical objects, including works of art, such as MOVEment (Calvin Klein Collection, 2015), Moon Beams (MOMIX reMIX in Crete., 2011), Metamorphose(s) (Compagnie de Danse l'Eventail, 2010), Ballons de baudruche (Julia Tiec., 2015), La danse des ballons (Amandine Cotton., 2011), sports, such as gymnastics and freestyle football, and mime, magic, and juggling. Presenting rotating spheres on stage usually means a ball has to be used. Here, a self-propelled ‘rolling’ robot of some kind would be needed because a normal sphere cannot freely travel on a stage. Examples of spherical mobile robots include Sphero2.0 (Orbotix, 2011) which actually rolls on surfaces. In our previous research (REMOVED FOR REVIEW), we developed a system for creating performances using mobile robots and used it in actual performances. However, the dynamic performance of our rotating mobile robots is inferior to that of a robot with wheels. The mechanism of moving the center of gravity of a rolling robot makes it hard to change its acceleration. Moreover, a spherical shape under centrifugal force cannot do sudden turns. This means the robot's agility cannot match that of human performer. Furthermore, rotational mobile robots have difficulty self-positioning. The reason is that the sensors and moving parts must be inside the spherical shell, and this makes it difficult for the robot to sense the outside world by using markers, etc. Even though a robot covered with a non-transparent spherical shell can measure its position by using a camera, etc., it is difficult to measure its posture. A large error in the measured posture would interfere with the performance because the robot would not move in the directions specified in the staging. Additionally, it is difficult for a rotational mobile robot to represent a glowing rolling ball. The robot itself inside the spherical shell does not roll. Here, the shell could have LEDs attached to it. However, it is difficult to attach LEDs, microcomputer, or batteries on the spherical shell because its inner surface must also be spherical. Thus, spherical mobile robots have many constraints on their performances that pose problems on stage.

In this study, we built a mobile robot that can give the audience the optical illusion of the unique movements of spheres by mounting a spherical LED display on a high-agility mobile wheeled robot. The robot does not roll. Instead, moves quickly and accurately by using omnidirectional wheels. Additionally, the robot's capabilities can be easily expanded by attaching various devices to parts of it that are not covered by the spherical shell. The optical illusion of rotational movement is created by using lighting patterns on the surface of the sphere created using the LED system.

The contribution of this paper is threefold.

- We propose the concept of using pseudo-physical movements in performances with robots.
- We built a robot that visually reproduces the movements of a rolling sphere and is capable of faster movements and easier position estimations in comparison with previous spherical robots.
- We created a performance that included the robot interacting with a professional performer. Comments from the audience and the performer helped us to identify the challenges in regard to the reproducibility of the rotational movement of a sphere, and means of support for and implementation of the same.

In this study, we focused on productions using spherical mobile robots and did prototyping. Balls and other spherical objects are often used in performances and in ball sports. However, there are challenges to expanding this ball motif into one with interactive motion capabilities. We found that movements that are difficult to implement with existing mechanisms can nonetheless be visualized through the use of light. The main goal in this study is to show that rotational movement can be depicted in this way; it is not to create an artistic performance.

The remainder of this paper is organized as follows. Section 2 introduces related works. Section 3 introduces performances using sphere-shaped mobile robots to gain awareness of the issues involved. Section 4 explains the system proposed and presents results obtained from preliminary investigation and consideration. Section 5 explains improvement of the system and presents results obtained from experiments and consideration and evaluation of the system. Section 6 updates our system and introduces the performance using the system. Section 7 presents our conclusions.

2 RELATED WORK

Various driving mechanisms are used by sphercal mobile robots. Bhattacharya (Bhattacharya & Agrawal, 2000) summarized the mechanisms that move the center of gravity by incorporating an actuator inside the sphere. Many spherical mobile robots, such as security monitor robots (Rotundus, 2011) and cleaning robots (CCP Co., 2013), embody these mechanisms. Crosseley (Crossley, 2006) has summarized the driving mechanisms that do not involve moving the center of gravity, such as deforming the sphere, and wind power. Bruce et al. (Bruce, et. al., 2014) developed a radically different rolling robot based on a tensegrity structure. A strong, robust robot can be created at low cost by using this sort of structure. Urakubo (Urakubo, et. al., 2012) developed a spherical rolling robot that has a driving mechanism equipped with a gyro. The robot travels using the torque generated by high-speed rotation of a momentum wheel. Aoki (Aoki, Ito, & Sei, 2015) developed a robot that can transform into a sphere. The robot rolls by creating torque against the ground by making two of its legs produced from the internal sphere. The above driving methods make it harder for the robot to change its acceleration compared with a wheeled robot directly in contact with the ground. In addition, the driving methods described above cannot execute sudden turns because of centrifugal force. Another driving method is to use two independent hemispheres as wheels see Polaris (KDDI & Flower Robotics, 2009) to accelerate. However, this method does not provide enough agility to overcome centrifugal force or produce a rolling motion characteristic of a sphere. "MorpHex" developed by ZENTA ROBOTIC CREATIONS (ZENTA ROBOTIC CREATION) has a mechanism in which the outer shell opens like a flower. The robot performs rotational movement using these driving parts. Briod (Briod, et al., 2014) proposes a flying robot covered with a spherical framework. The robot is resistant to shock from the outside, can colide with an obstacle, and can also rotate. However, due to the performance of the flying robot, it is necessary to make it a skeleton in order to limit weight and pass air. It can not be seen as a simple sphere and is difficult to add a device for expanding function.

Certain lighting effects can be helpful when a robot interacts with a user. Kobayashi (Kobayashi, et. al., 2011) used a blinking light and beeping sounds to create "artificial subtle expression" (ASE) so that a robot can communicate fluently. Rea (Rea, Young & Irani, 2012) researched how a robot can alter how people use or perceive the environment. In this case, the robot's display expresses the current mood of the room. Baraka (Baraka, Paiva, & Veloso, 2015) studied how to best express a robot's state in relation to its tasks and the environment. Sakai (Sumioka, et. al., 2013) developed a small, interactive humanoid. They evaluated the arrangement and blinking patterns of LEDs that would reproduce the effect of someone nodding. The blinking LEDs could not duplicate the motion of the robot itself. The illusion of motion, however, would improve the quality of communication. Miguel (Miguel, et. al., 2016) investigates whether a simple spherical robot, which cannot communicate with each other, will convey intentions to people with behavior based on LED lighting and pet movement. Szafir (Szafir, et. al., 2015) examined the design of explicit communication that can convey the flight intent of the flying robot at a glance. Here, our goal is to make blinking LEDs reproduce the effect of actual moving objects.

Some researchers (Lacquaniti, et. al., 2013) (Souto & Kerzel, 2013) have used computer graphics to study human motion perception of objects moving under the force of gravity. However, no one has yet attempted to use a moving object that emits light to reproduce the motion of an actual sphere. In this study, a blinking light source attached to a mobile robot causes the illusion of physical motion.

There have been previous attempts by stage directors and artists to expand the range of physical expressions afforded by moving objects. CHUNKEY MOVE (CHUNKEY MOVE, 2013) created a performance called "CONNECTED", in which objects move in accordance with a performer's motions and look like they are emotely being manipulated by the artist. Wurtzel (Wurtzel, 2015) created a performance called "AMALUNA", which combines a dancer and cloth soaring freely in the air. It uses a fan mounted in the floor of the stage. Adding illusion effects with light to a performance involving moving objects and performers can be a new dimension of entertainment.

3 AWARENESS OF ISSUES

In our previous, we gave a number of performances using spherical mobile robots. The spherical robots of these performances actually rolled in the direction of travel. In particular we did a performance combining these robots and performers at INTERACTION 2015, held at the National Museum of Emerging Science and Innovation in Japan on March 6th-8th, 2015. We were able to reliably repeat the one-minute performance over the two-hour demonstration. We performed the same demonstration at ACE 2015 (shown in Fig. 1), which was held at the White Box and Black Box arts complex in the Medini Mall, Medini, Malaysia, on November 6th-8th, 2015. However, our robots often deviated from their target positions. The error rate rose significantly as the performance time became longer. The reason was that the measurement error of the posture of the robots increased over time. It is difficult to measure the posture of robots covered with a non-transparent spherical shell from the outside. Therefore, it is difficult to correct posture through external means. Moreover, the limitations on the movements of the mobile robots, such as poor acceleration and inability to make sharp turns, limited the range of expression.

Further, we collaborated with performers in various genres to create a performance involving them and our mobile robot. These performances often required the performer to grab the robot. However,

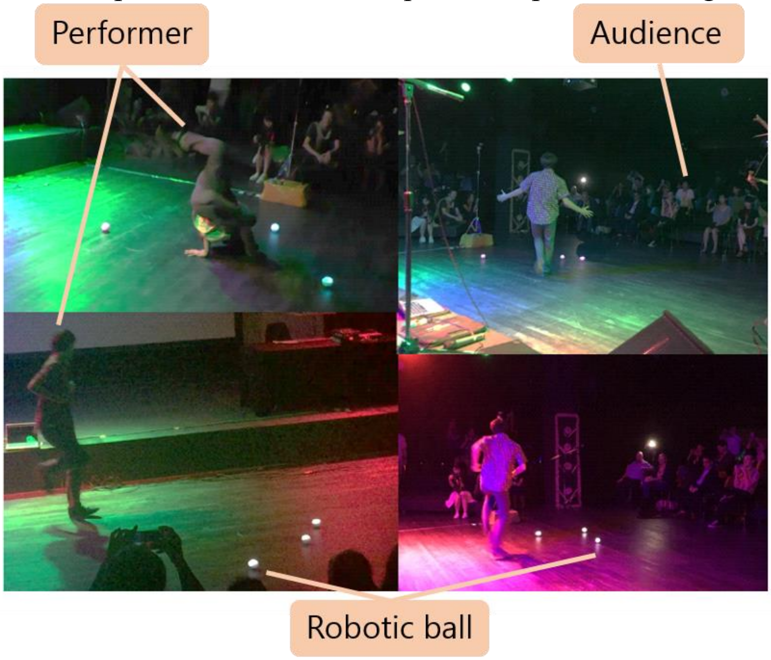

Figure 1: A performance in a real environment.

the driving parts mounted on the inside of the spherical shell made it hard for performers to grasp the robot. Moreover, we found that any violent movements of the shell could damage the robot inside.

Attaching a marker for motion capture to the outer surface in this study and using a spherical LED display can resolve these problems. In fact, we believe that these mechanisms can have the same effect on an audience that physical motion has amd can make robots and quadcopters more reliable stage elements. Here, we focus on stage effects generated with spherical mobile robots and investigated the visual effect of using alternative mechanisms to depict rotational movement.

4 PRELIMINARY INVESTIGATION ON ROTATIONAL MOVEMENT EXPRESSION OF A SPHERICAL LED DISPLAY

We studied how a changing pattern can make a ball appear to rotate. To do so, we built a mobile robot equipped with a spherical LED display and evaluated its visual effect. A motion illusion using light requires continuous movement of light. To accomplish this, we devised the method of mounting LEDs on the inside of a spherical surface with very fine gaps separating the elements. Moreover, controlling the LEDs while showing a simulation of the light patterns improves the generation efficiency of visual effects. We built a spherical LED display that met these requirements and mounted it on top of a TDSTO48-350 robot (TOSADENSHI) from Tosadenshi Co. Fig. 2 illustrates the construction of the display and the robot.

4.1 Proposed System

The appearance of the spherical LED display we created is shown in Fig. 3. We attached Dotstar LEDs (Adafruit) from Adafruit Co. to the inner surface of a transparent, spherical shell, that had a diameter of 120 mm. The completed included 530 full-color LEDs controlled by twelve Arduino nano units (Arduino). The entire sphere was sprayed with white liquid rubber so that the LEDs would be invisible and the light from them would be diffuse.

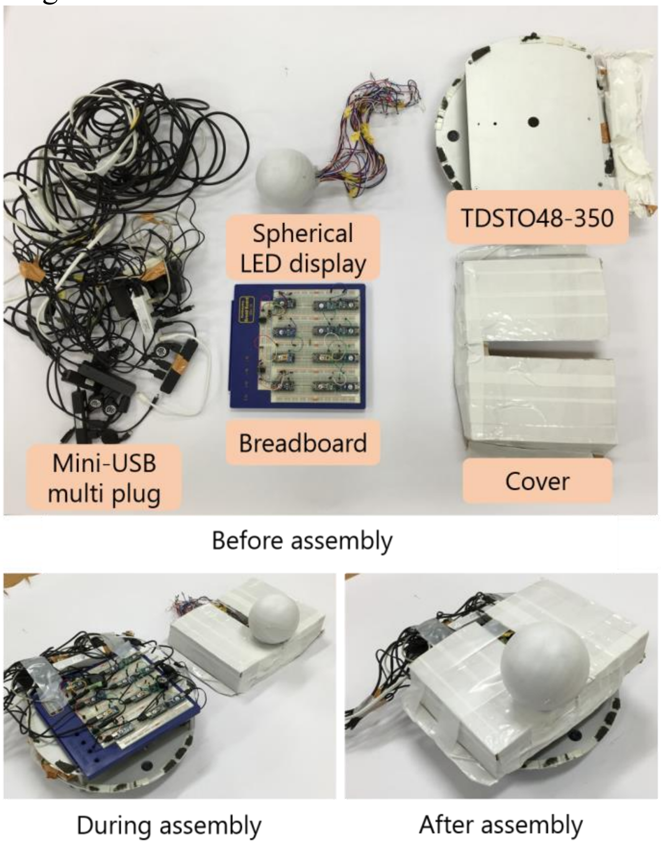

Figure 2: Combination of spherical LED display and mobile robot (TDSTO48-350).

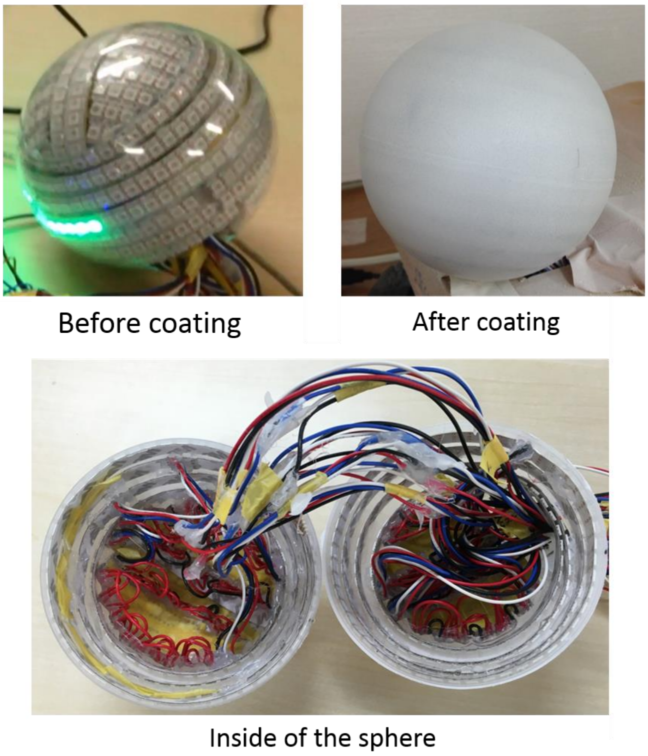

Figure 3: Appearance of spherical LED display.

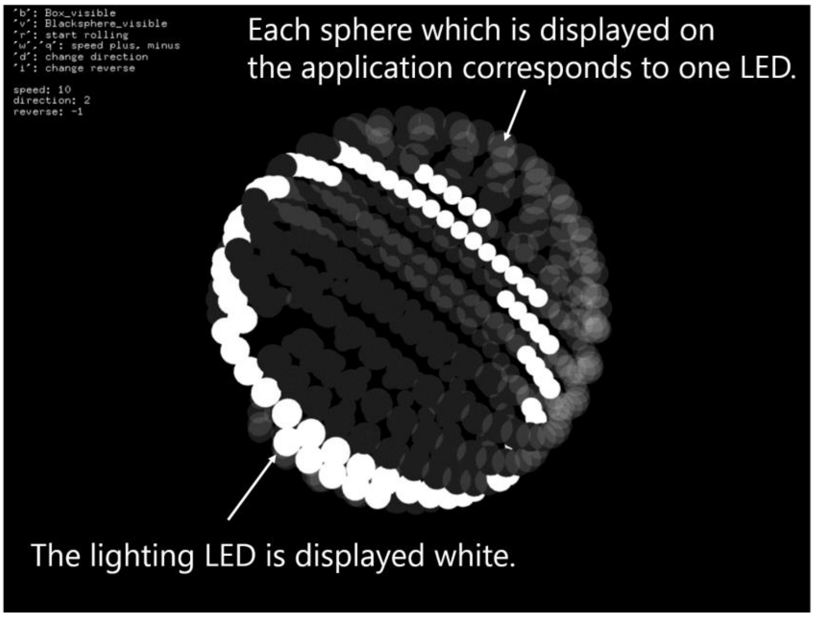

Figure 4: UI of application for controlling the light of LEDs.

A UI of the application for controlling LEDs is shown in Fig. 4. We developed the application for controlling LEDs by using openFrameworks and the development environment was Xcode. Each sphere which is displayed on the application corresponds to one LED. The application sends lighting patterns to Arduino nano that is connected to the spherical LED display every 25 msec. Users can change the light patterns by typing multiple keys on the keyboard and the light patterns for each LED are allocated to these. Users can change the lighting range of the lighting pattern, rotational speed of light and direction of rotation by typing on the keyboard in the same way. The PC sends out all spherical LED display information, including those sections which are illuminated and those that not illuminated on the application. Therefore, operation results are reflected on the spherical LED display in real time.

4.2 Experiment Procedure

We investigated the influence of visual effects using light. The two items we surveyed were as follows.

1. Relationship between lighting patterns and optical illusions.
2. Relationship between the distance between the sphere and audience and the level of optical illusion.

We recruited nine male and two female participants with an average age of 23.8 and asked them to look at six performances including the moving robot with the spherical LED display. The observation points (see Fig. 5) were as follows.

- Observation point A
  P1: Rolling motion depicted with one light ring.
  P2: Rolling motion depicted with two rings.
  P3: Rolling motion depicted with six rings.

- Observation point B
  P4: Rolling motion depicted with one light ring.
  P5: Rolling motion depicted with two rings.
  P6: Rolling motion depicted with six rings.

The lighting patterns are shown in Fig. 6. At observation point A, the participants watched the sphere through a mirror from a distance of 10 m. At observation point B, the participants watched the sphere from a distance of 5.5 m. The performer danced for about 30 seconds. The song that was used was 110 bpm. The participants watched the performances from a height of approximately 110 cm above the floor, so that they could not see the mobile robot mounting the sphere on stage. The lights of the room were turned off to highlight the light from the LEDs. Only the performer was highlighted by a spotlight. If the lighting pattern rotated in the advancing direction, the rotational speed of the mobile robot was 0.3 m/s. The participants were asked after they had watched all the performances.

Q1: Did the sphere appear to be rolling?

We asked these questions in order to determine the reason for any breaking of the optical illusion, to suggest possible improvements to the optical illusion, and to identify aspects that the participants noticed, such as the size, shape, and change in movement velocity.

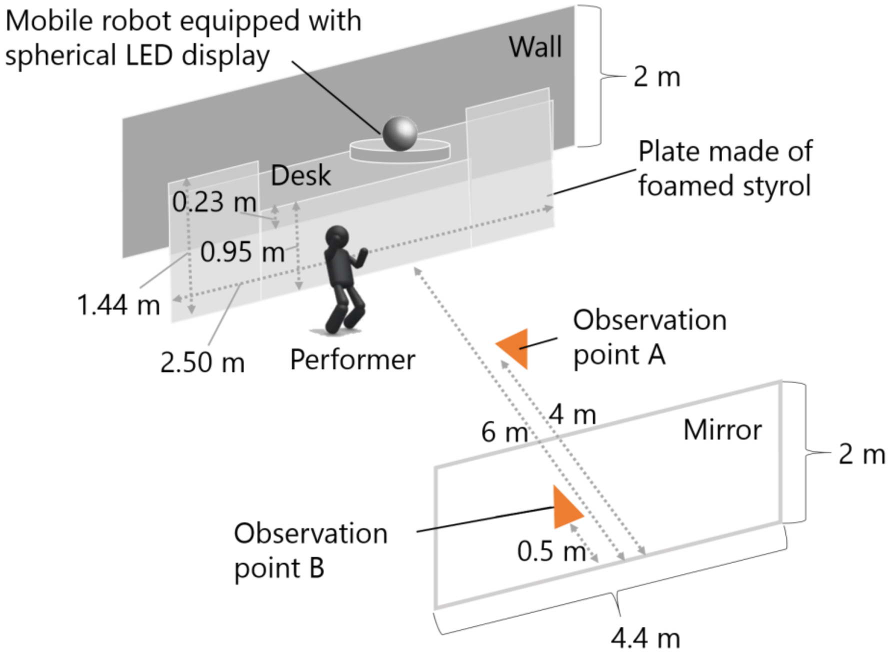

Figure 5: Floor plan of preliminary experiment.

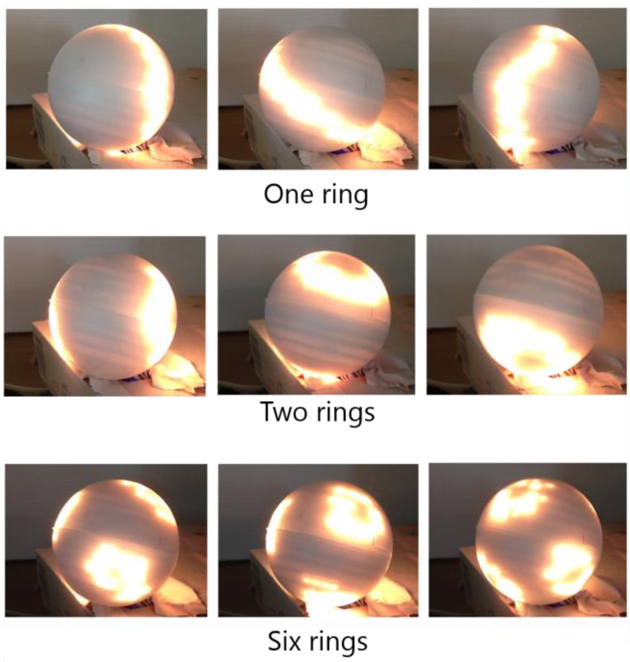

Figure 6: Lighting patterns.

4.3 Results and Considerations

The results for Q1 are shown in Fig. 7. The vertical axis indicates the average value for the performances given by the eleven participants calculated on a five-point scale. The vertical bar indicates the standard deviation, and the horizontal axis indicates each individual performance.

Two of the participants responded that “If I was away from the light, it looked beautiful,” and “it would be likely to be fully utilized on a big stage.” It is possible that the appearance of the light changed with distance.

When more rings were shown in the lighting pattern, the participants gave a higher evaluation. Two of the participants responded that “the lighting needs to have a surface area that can be recognized as a sphere,” and “the more patterns there are, the more it seems as if it is rotating.”

Nine out of the eleven participants noticed that the velocity of the sphere and the rotational speed of the lights were not the same and commented on it. This indicated that we needed to find a way to assure that the velocity and rotational speeds are the same.

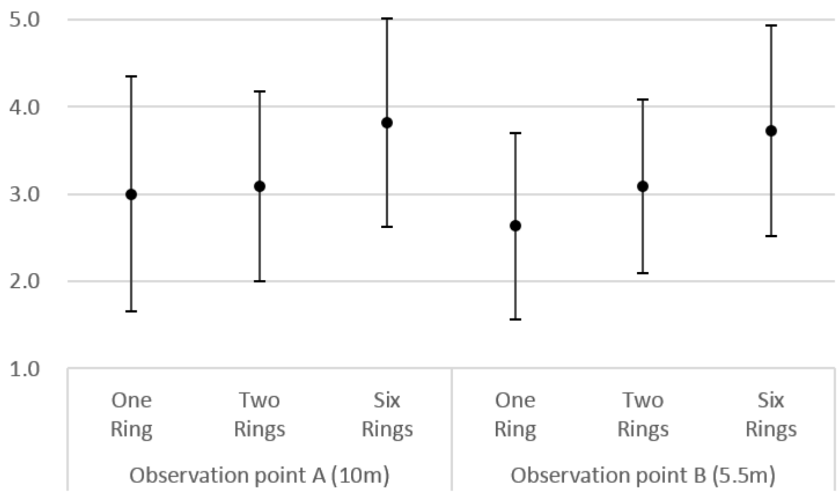

Figure 7: Result of Q1 of the questionnaire.

5 DEVELOPMENT AND EXPERIMENTS SPHERE-SHAPED MOBILE ROBOT

5.1 Improvement of the system

The findings of the preliminary study showed that it is necessary to synchronize the rotation of the lights of the spherical LED display with the distance moved by the robot. In an actual stage performance, to facilitate the optical illusion of a rolling sphere, the driving part, i.e., the mobile robot should be as low and as small as possible.

Fig. 8 compares the system configurations before and after we made improvements to the system, while Fig. 9 shows the robot we created and Table 1 compares the TDSTO48-350 and the mobile robot we created. The driving part is hidden by covering the entire mobile robot with a plastic cover. When the sphere is on stage, it is difficult to see that there is a robot directly under it, and this probably makes it easier to create an optical illusion of a rolling sphere. In addition the diameter of the mobile robot is only 0.67 times that of the TDSTO48-350. In order to accommodate all of the mechanisms within the plastic cover, The controlling microcomputer was swapped with an mbed unit (ARM Co.) and 12 Arduino nano units.

The mobile robot sends out the velocity information and the angle information to he mbed in real time. The mbed uses this real-time information to control the LED lighting patterns and texture of the display. In this way, the distance traveled by the mobile robot can be synchronized with the rotating pattern of the LED lights. Moreover, to generate a lighting pattern in the mbed, the application doesn’t have to generate the lighting pattern for controlling the light used in the investigation of visual effects. In this way, the amount of information to be transmitted to the mobile robot was able to be reduced.

We compared the traveling performance of Sphero2.0 and that of the mobile robot we created (Fig. 10})）. To examine the acceleration capability, the arrival times for a distance of 1.0 m were compared. Here, Sphero2.0 took 1.39 second, and our robot took 1.00 second. Thus, our mobile robot accelerated faster than the other.

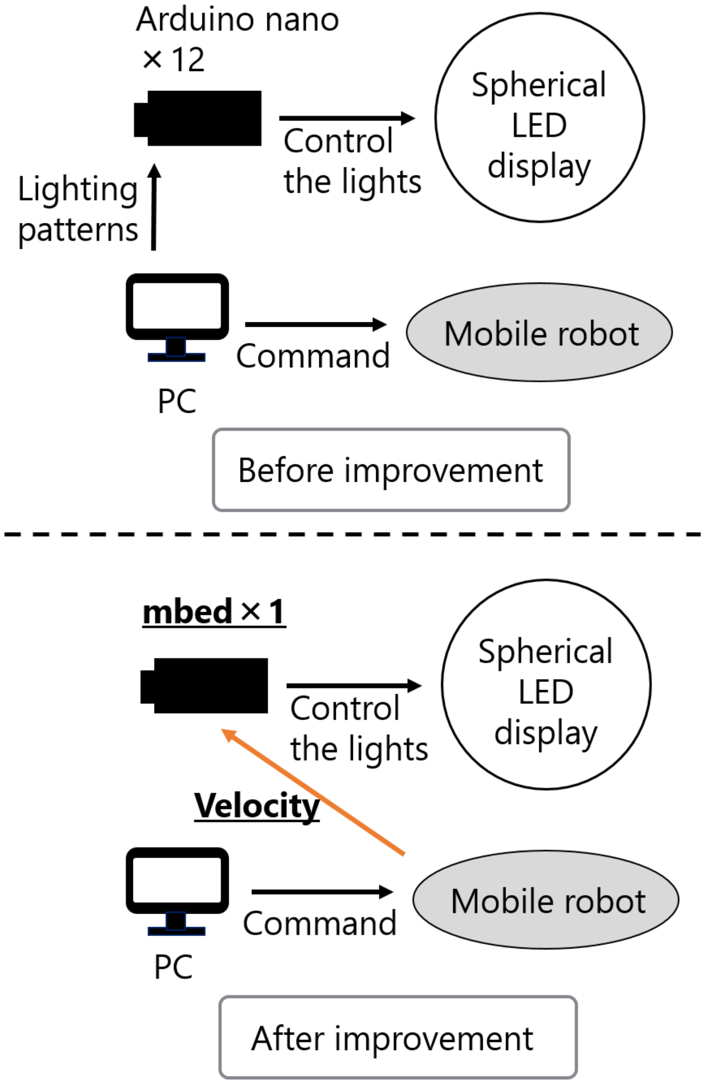

Figure 8: Comparison of system configurations.

Table 1: Comparison of TDSTO48-350 and created mobile robot.

	TDSTO48-350	Mobile robot created in this study
Diameter	350 mm	200 mm
Weight	3500 g	600 g
CPU	H8/36064	STM32F405
Continuous driving time	60 minutes	30 minutes

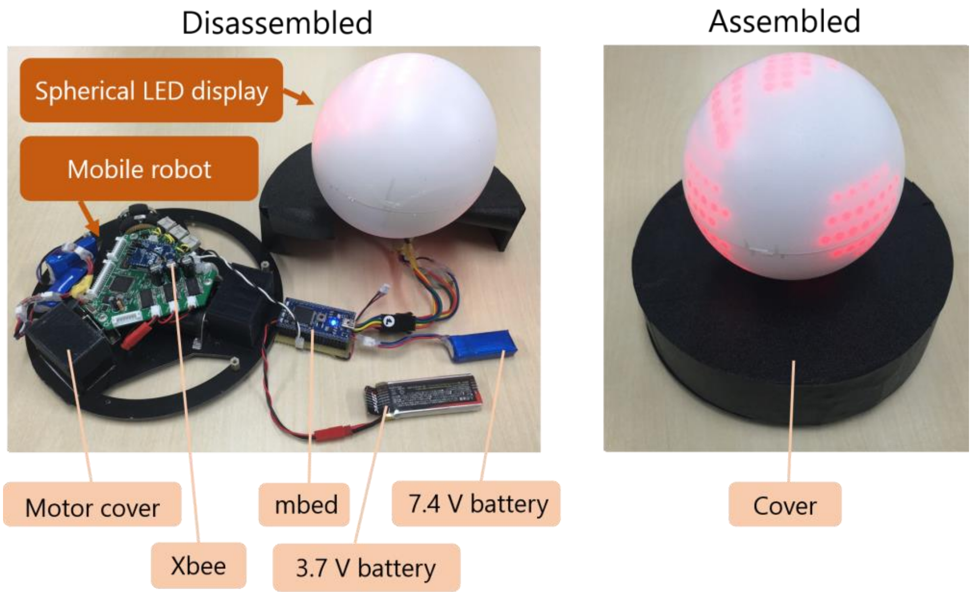

Figure 9: Appearance of the system.

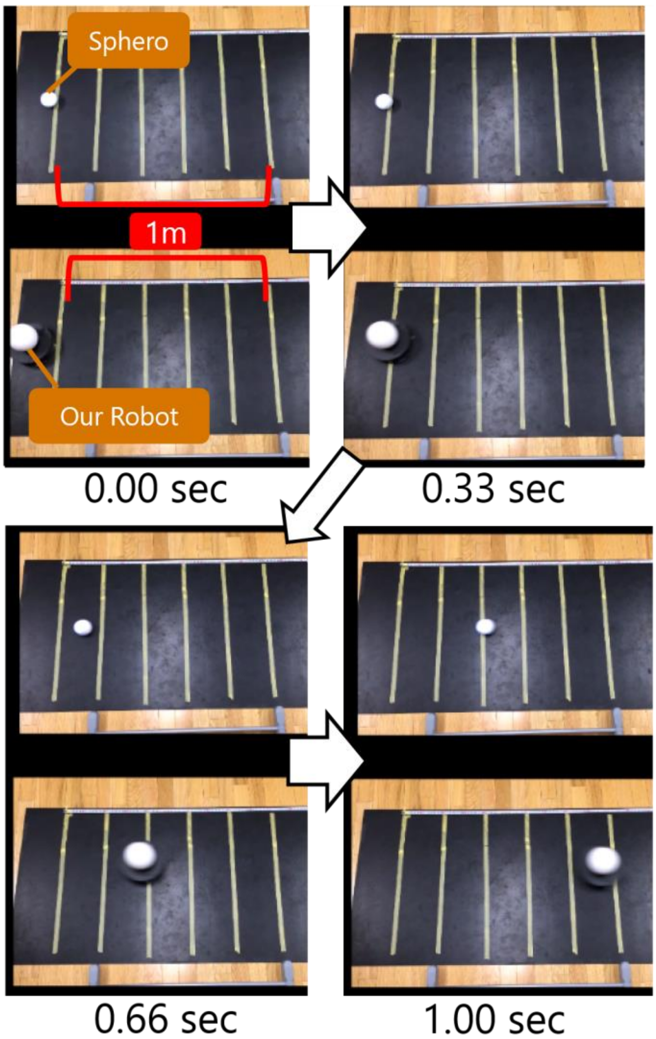

Figure 10: Acceleration comparison test of spherical mobile robots.

5.2 Experiment Procedure

We investigated the rotational speed of the lights and the moving speed of the mobile robot. The three items we surveyed were as follows.

1. The question of whether participants who could not see the movements of the spherical mobile robot experience the optical illusion of a rolling spheres.
2. The relationship between the velocity of the robot and the perception of the optical illusion.
3. Influence of the deviation between the amount of "rotation" and the moving distance on the illusion.

Regarding item (1), we assumed a situation in which the robot would be used in a real performance. We asked participants watching the spherical LED display for the first time if they thought that the sphere itself was physically rolling, rather than LED lights turning on and off. If the participants believed the optical illusion that the sphere was rolling, robots such as this one can probably be used in real performances. Regarding items (2) and (3), the allowable ranges of each item can be determined by investigating the influences of each item on the optical illusion. Regarding (3) in particular, the sphere sometimes slipped depending on the texture of the floor, for example, as in bowling. If it is possible to give the optical illusion of a special rotation, for example when a mime pretends the floor is made of ice, this could potentially widen the range of expressions and stage effects.

Twelve males with an average age of 22.7 participated in the experiment. The procedure was as follows.

Step 1 A participant enters the room. He/She watches a performance involving the mobile robot equipped with a spherical LED display and has no knowledge about how it operates. He/She answers verbally the question of whether or not the sphere appears to be rolling.

Step 2 The participant receives an explanation of the function of the spherical LED display and gets to know how it works.

Step 3 The participant watches an actual rolling LED ball.

Step 4 The participant watches the visual effects of the spherical LED display and evaluates it by comparing it with the actual rolling LED ball that he/she watched it in Step 3.

The floor plan is the same as that of Fig. 5. The lights of the room were turned off to highlight the light from the LEDs. The performer was highlighted by the spotlight. The performance used the same as choreography as the one described in Section 4. In Step 1, a spherical LED display presents the rotation, and the participant observes it from observation point B of Fig. 5. Each participant watches a performance only one time in Step 1. After the presentation, an experimenter orally asks the participant two questions: "Did the sphere appear to be rolling?" and "What mechanism do you think makes the sphere moves?" In Step 2, the experimenter explains the mechanism of the mobile robot and orally confirms whether or not the participant recognized the mechanism. In Step 3, the position that the participant observes from is the same as in Step 1. The LED ball is actually rolling, and the presented lighting pattern is as shown Fig. 11. The participant watches the actual rolling LED ball only one time in Step 3. The performer does not give a performance. In Step 4, the observation point is the same as in Step 3. The performer does not perform. The LED display shows showed the following visual effect patterns, i.e., combinations velocity and rotation.

- Velocity
  0.3 m/s, 0.6 m/s, 0.9 m/s, 1.2 m/s.
- Amount of rotation of lights with respect to the moving distance
  0.5 times, 1.5 times, 2.0 times (moving speed of 0.6 m/s).

The performance involved a person with a mobile robot. We suppose the performer's moving speed is within 1.3 m/s, which is the average walking speed, and we set the speed of the robot in its range. We asked the participants immediately after they had watched each of the visual effect patterns.

Q1 Did the sphere appear to be rolling?

The participant evaluated Q1 where in the reference evaluation of the rolling of an actual sphere was as 5, i.e., the largest value. In addition, we let participants to freely comment on what they saw.

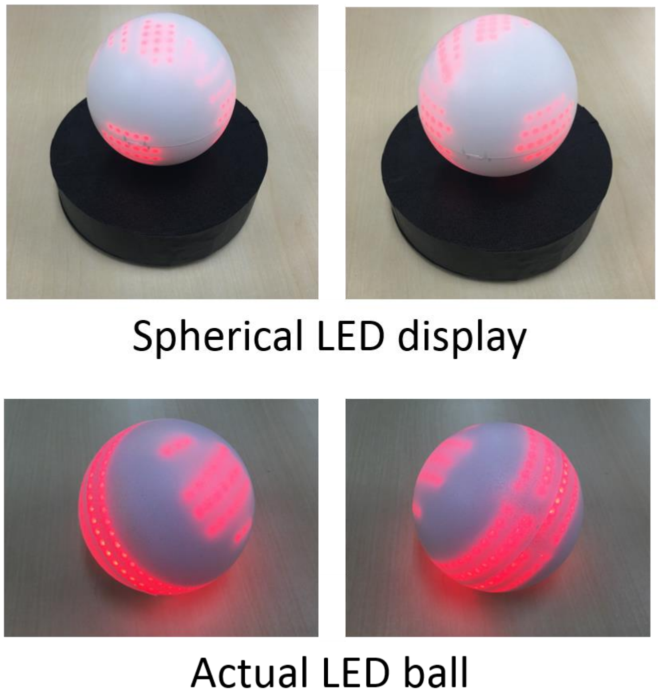

Figure 11: Lighting patterns presented.

5.3 Results and Discussion

Eleven out of the twelve participants believed the illusion that the sphere was rolling during at the performance. When participants received an explanation on the function of the spherical LED display and got to know the rotational movement of the lights in Step 2, the participants answered “I thought that the sphere was just rolling”, “I thought that the LED ball was rolling by running on electric rails.” and “I thought there was a driving part inside the LED ball and that the LED ball was rolling because its center of gravity was moving.” These answers confirmed that the participants perceived the sphere to be physically rolling. However, one participant recognized that the rotation was due to the lights. The participant commented that the lights he saw were not discrete but continuous. Accordingly, we considered that the participant possibly recognized some aspect of the lights, or that the sensitivity of the participants eyes was affected by the experimental conditions.

The results of the questionnaire in relation to item (2) of the previous section are shown in Fig. 12. The vertical axis indicates the average value of the answers to Q1 that the twelve participants gave. The vertical bars indicate standard deviation. The horizontal axis represents the velocity of the robot when the visual effects were presented. We assessed the difference between the velocities by using ANOVA. There was no significant difference; however, as the figure indicates, the slowest speed of 0.3 m/s and the fastest 1.2 m/s received low evaluations. When the rotational speed of the light pattern was slow, the participants commented that they “found that the lights of the spherical LED display did change not smoothly”, “felt discomfort when watching it closely (i.e., carefully)”, and “found that the LEDs looked pebbly”. These problems can be avoided by covering the sphere with smaller LEDs. On the other hand, when the rotational speed of the lights was fast, we got comments such as “the flicker of the light patterns impaired the appearance of the sphere” and “the sphere appeared to be moving while the lights randomly flickered.” We supposed these problems could be overcome by raising the frame rate of the display above its current 30 fps.

The results of the questionnaire on the amount of rotation of the light pattern with respect to the moving distance were used to investigate item (3) of the previous section. They are shown in Fig. 13. The vertical axis indicates the average value of answers to Q2 from the twelve participants. The vertical bars indicate standard deviation. The horizontal axis represents the amount of rotation of the light pattern with respect to the moving distance. We assessed the difference between the amount of rotation of the light pattern with respect to the moving distance by using ANOVA. There was a significant difference ($F_{(2,22)} = 5.01$, $p < .05$). Moreover, we assessed the difference by using a Bonferroni test. Here, as well, there was a significant difference between the rolling-to-movement ratios of 1.5 and 2.0 ($p < 0.05$) the optical illusion diminishes when the rotation increases too much relative to the distance moved. The optical illusion tends to be maintained when the rotation is reduced rather than increased. We received comments such as, “the robot seemed to be rotating much more when the rotation was larger than the distance moved.” and “I felt the optical illusion happening when the rotation was synchronized with the movement.” Regarding the rotation, the effect on the optical illusion seemed to be small even when there was noise due to slipping and sensor errors. Moreover, the evaluation was poor when the rotation was reduced. We received comments such as, “the rotation was as if a bowling ball was slipping on the lane" and ``the lighting method was interesting”.

In summary, eleven out of twelve participants believed the illusion that the sphere was rolling when they watched the performance, which is surprising. Our system visually reproduced the movements of a rolling sphere. There is strong possibility that it can be used to give the optical illusion of a rolling sphere in real performances. Moreover, the improved hardware and software made the illusion possible even when the LED ball moved too slowly or too quickly. Furthermore, we found that attention needs to be paid to the relationship between rotation and moving distance when setting up a performance.

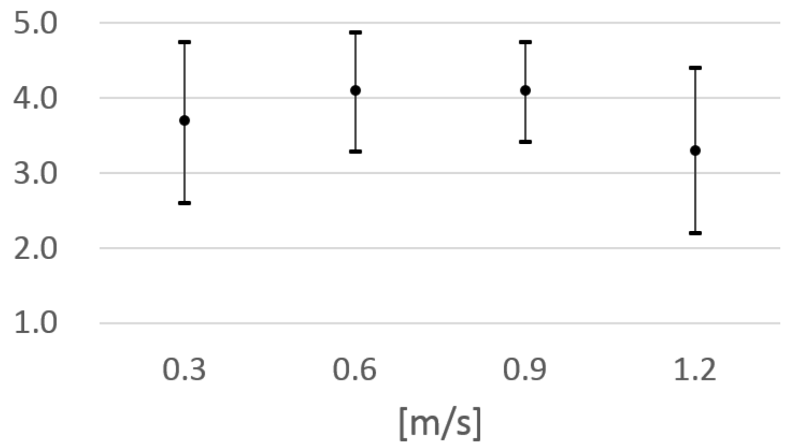

Figure 12: Questionnaire results regarding speed of the robot.

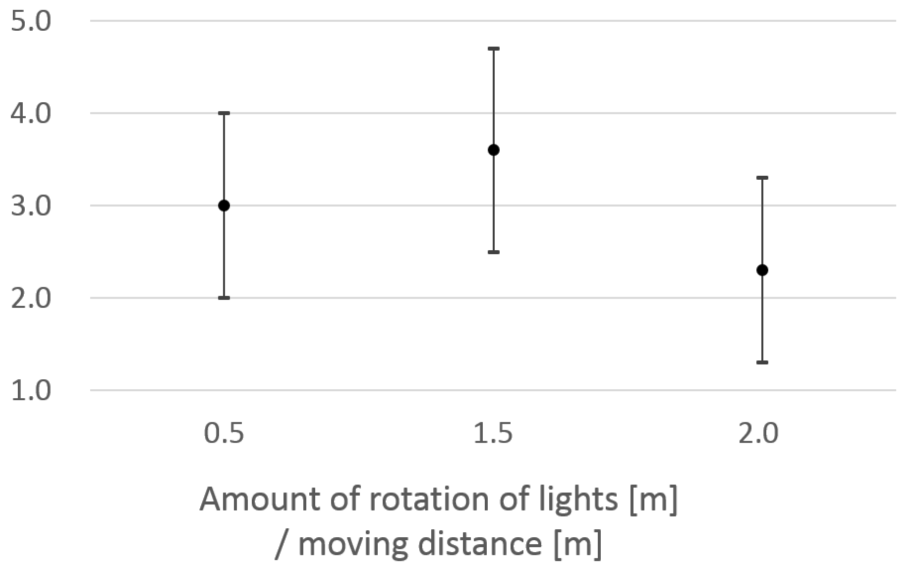

Figure 13: Questionnaire results on amount of rotation of light pattern with respect to the moving distance of the robot.

6 TESTING THE ABILITIES OF THE SPHERE-SHAPED MOBILE ROBOT

6.1 Improvement of the system

We improved the system to create a more convincing optical illusion, by incorporating all the experimental results described in the previous section. Some improvements were aimed at transporting the performance to a live stage. The resulting LED display is shown in Fig. 14.

We covered a white, spherical shell having a diameter of 170 mm with 999 Dotstar LEDs. These full-color LEDs were controlled by one mbed. The results described in the previous section indicated that the lights needed to be dimmed in order for the display to change its lighting smoothly. Therefore, we positioned the LEDs 7 mm from the sphere's shell. Since the spherical surface area illuminated by each LED became wider as a result, it was more difficult to distinguish each individual LED. Furthermore, in order for the light to be biased, all LEDs face a normal vector out of the sphere. Moreover, the intensity of the light needed to show the lighting pattern was discussed in the previous section. The lights are switched on and off in a binary pattern. In order to make rotating light patterns flow more smoothly, we used medium intensity light, which is thought to create a stronger optical illusion of a sphere rolling. In addition, to increase the visibility of the display, we attached a mechanism to it that allowed it to move up and down.

The appearance of the mobile robot is shown in Fig. 15. In order to increase the visibility of the spherical LED display, we attached a mechanism to it which allows it to move up and down(Fig. 16). Therefore, it can be visible from the stage, while still remaining low enough to be in the viewpoint of an audience. In addition, it has the potential to give a much more realistic effect by being able to hit the wall a little bit and jump up and down slightly. Additionally, its upwards and downwards motion makes it appear as if it were ascending an invisible staircase. There is a possibility for it can be be used in a much wider variety of stages and spectacles.

The appearance of the new robot is shown in Fig. 17. A spherical robot that moves by using its own center of gravity can be held by a performer. On the other hand, the robot that we described in the previous section cannot be held by a performer. Therefore, there is a possibility that it would limit rather than expand the range of expressions. To widen the range of expressions, we made it possible to detach the spherical LED display from drive section (i.e., the mobile robot). The robot and display had a wireless connection via Xbee. In order to safely attach the spherical LED display to the robot so that it would not fall off, the inside of the sphere and the mobile robot were equipped with magnets.

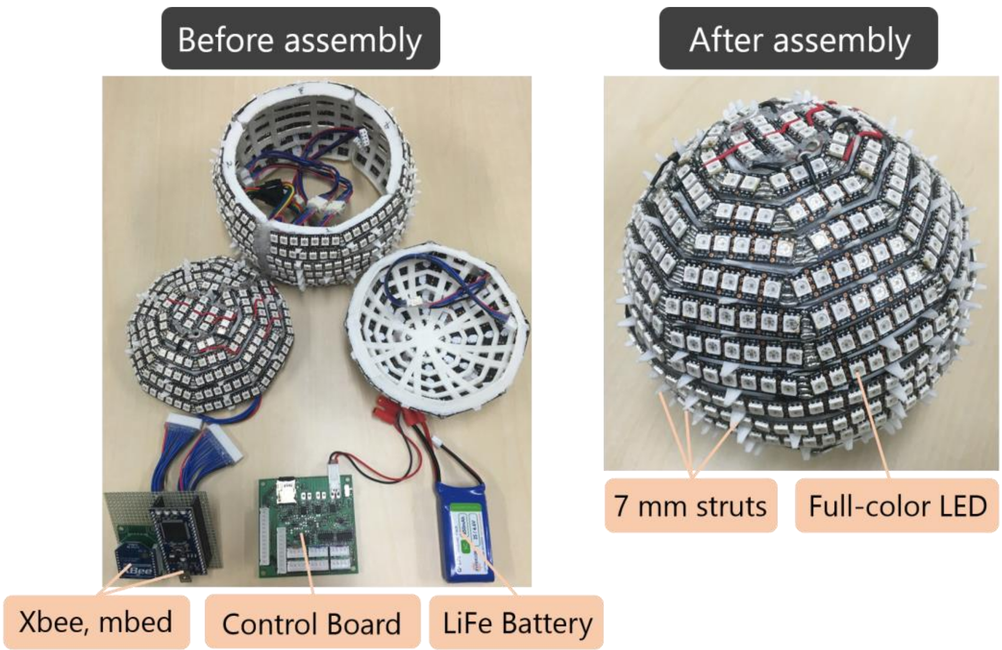

Figure 14: Appearance of Spherical LED Displays.

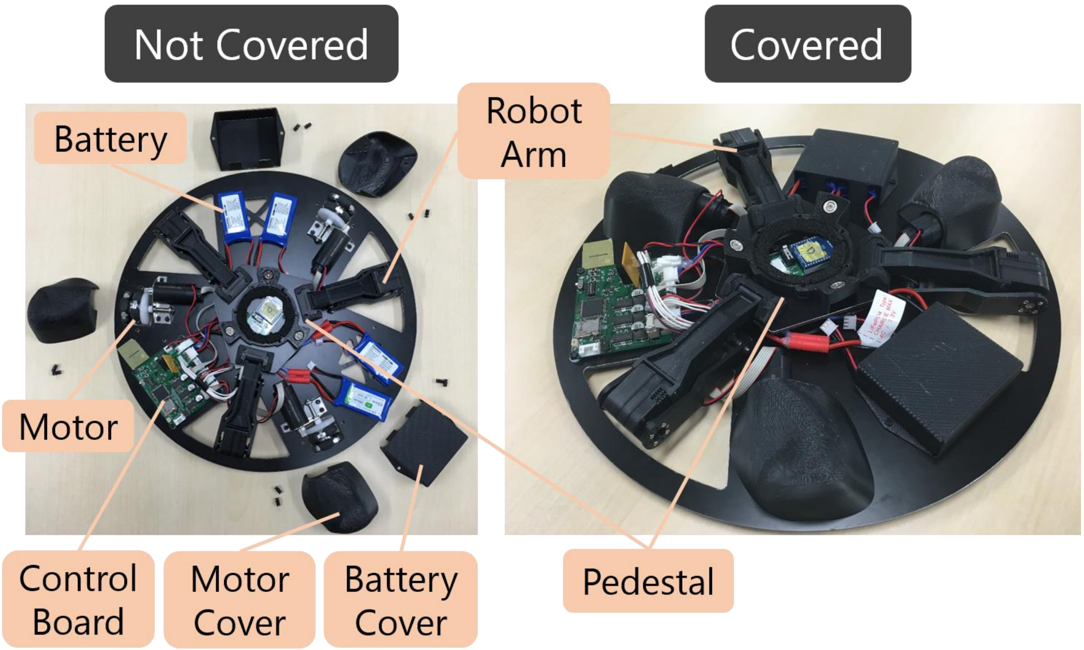

Figure 15: Appearance of Mobile robot.

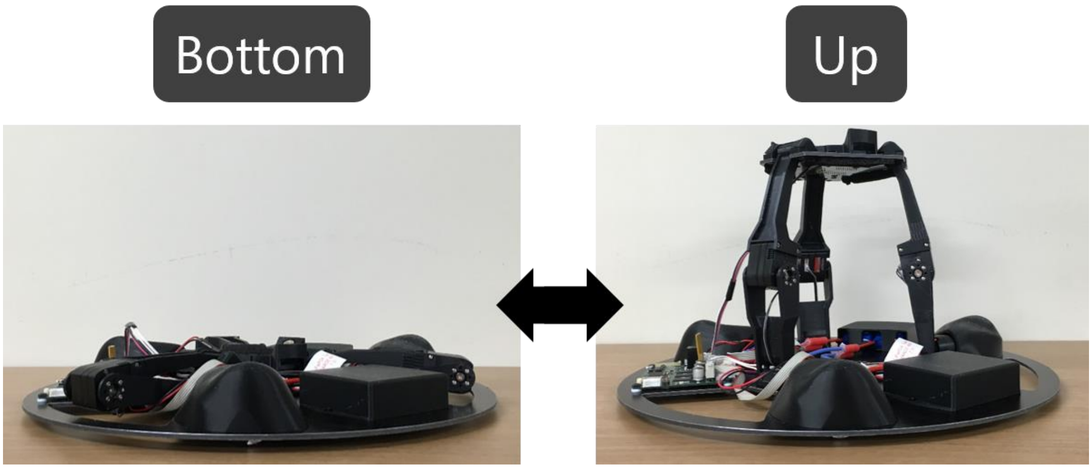

Figure 16: A mechanism of moving up and down.

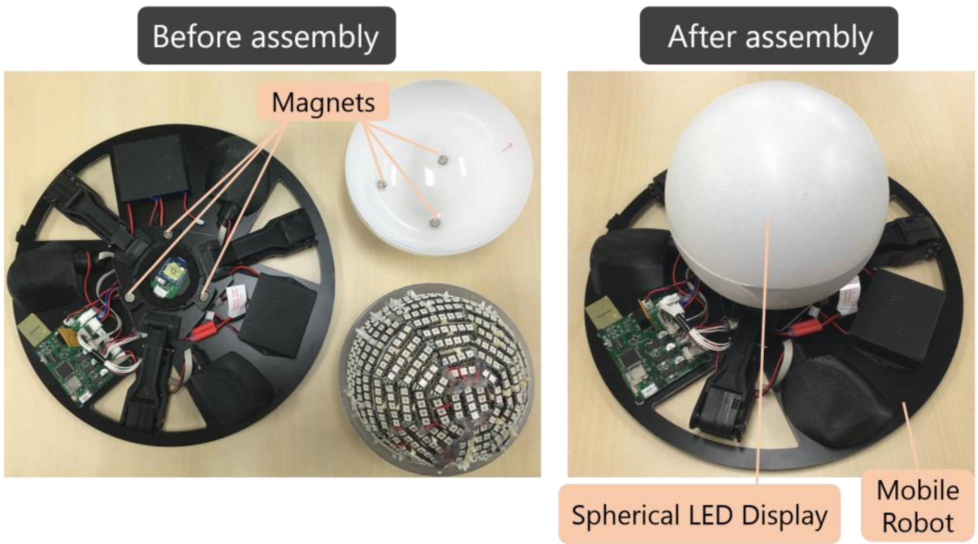

Figure 17: Combination of mobile robot and spherical LED display.

6.2 Performance using optical illusions

By using the ability of the spherical LED display to mimic a real sphere, it is possible to project optical illusions on the surrounding environment. For example, by creating a large difference between the rotational speed of the sphere and its velocity, it would be possible to make the floor appear slippery (as if it were covered in ice) in the minds of spectators. Similarly, it is possible to make the sphere appear be pushed, as if acted upon by an invisible force (such as wind), or to create the appearance of an invisible wall by making the sphere slam to a halt. As in mime, in creating the appearance of an icy floor, strong winds, or the presence of an invisible wall, the addition of environmental effects can enhance a performer's show. Moreover, adding a mechanism to control the vertical motion of the spherical LED display, it would be possible to make it appear to roll over a rough surface, or even to ascend or descend an invisible staircase. Additionally, the robot freely controls its own rotational speed and can represent its time axis. Therefore, it "collaborates" with a mime in creating optical illusions in the surrounding environment.

We recorded his performance (shown in Fig. 18) and exhibited it at Robotics x Future 2016 (there were 1460 attendees at the 18th team exhibition, which included our team). The attendees had the following reactions: "until being told how the mechanism worked, I was convinced that the sphere was physically rotating on its own", "it looked as if the sphere was spinning on its own", "it looked as if the sphere was attached to the wall, and rolling on it", "it seemed that the camera angle was changing, which was very interesting", "it looked as if the robot was surprised", "it looked as if the video's playback speed was changing", "in one scene the robot was gentlemanlike" and "if the sphere could go up and down the man's waist, the amount of situations it could be used in would increase."

Although the audience got their impressions from a recording and not a live performance, many of them believe the optical illusion that the sphere was rotating, and thought the whole thing very mysterious. From these impressions, we can assume that the optical illusion is conveyed just as effectively in this format.

Figure 18: Performance using spherical mobile robot.

6.3 Considerations

We asked Mr. Naoki Iimuro, who created the choreography for this performance, for his personal impressions, which are reported below.

"A spherical robot on a moving stand demonstrated higher power output and mobility than expected. It was able to move very naturally during scenes such as when it pushed against a wall without appearing too burdened. A trick where an item was loaded, unloaded and the robot's `reaction bar's' width expanded to show the robot's character was also well received. The idea to have the spherical robot itself glow as an LED and give the illusion that it was moving was very interesting. However, the balance between the intensity of the spherical robot's glow with the display of a person led to a visual problem. In the first place, users `want to see a person not a stand'. How that visual problem can be overcome will be an important topic in designing the next performance. There is a potential for a simple separation of the spherical robot's body and the stand, but regardless unpredictable responses can be expected. If the robot were a bit lighter and easier to use and could fit comfortably in one's hand, it would lead to an especially good collaboration between robots and pantomime. We can expect more progress in the future."

At present, the robot is much more noticeable than the performer is in the main part of the performance, so it is difficult to say that the highlight of expressions is good. This problem may be able to be resolved by always illuminating the performer on the robots side, or by shining a spotlight on the performer¥rq{}s side, having the performer wear something shiny device, and using a combination of black light and a fluorescent substance. Moreover, in the current performance, the spherical LED display did not have an interactive mechanism to react in real time to the motions of performer. The high-agility mobile wheeled robot has improved performance compared with a conventional spherical robot. However, taking the influence on the stage performance into account, it is difficult to use it in ways that have the possibility of breaking the device, such as throwing the sphere like a ball, trying to bounce it, or rolling it on the surface of some other body. In the current mechanism, the diameter of the lower mobile robot is bigger than the upper sphere. Therefore, an audience might see the lower part, which may worsen the quality of the performance. In the future, we need to make the lower part small enough to hide below the upper part.

On this occasion, we employed odometry to measure the estimated position of the robot at any given moment. Since this performance is roughly 3 minutes and 30 seconds long, we could use this system without any troubles and didn't need any expensive equipment for measuring its exact position such as a motion capture device. From this we came to the conclusion that with this sort of position-estimating camera needed for a mobile spherical robot which also changes its own center of gravity, the cost of setting such a system up is low, and this would allow us to transport this show into many different locations.

7 CONCLUSION

This study described the creation of a mobile robot with high agility and simple self-localization features that is equipped with a spherical LED display capable of producing the illusion of motion unique to its shape, i.e., rolling in any direction. The system was built and preliminary investigations were conducted on optical illusions produced by its lighting effects. As a result, the success of the optical illusion was not observed to be affected by the moving distance of the robot in relation to its directional rotation; however, there was a tendency for it to be affected by the lighting pattern of the robot. Additionally, comments from test participants indicated the importance of the relationship between the rotational speed of the lights and its velocity. The results of the preliminary experiments were incorporated into improvements to the system. The improved system allows for lighting patterns of the spherical LED display to be produced and controlled in real time based on the velocity of the robot. In this way, the moving distance of the mobile robot can be synchronized with the rotation of the lighting pattern of the spherical LED display. Further tests conducted on the optical illusions it could produce indicted that 11 out of 12 test participants saw the robot as a rolling sphere. These experiments demonstrated that the larger the difference is between the distance traveled by the robot and its rotation, the weaker the effect of the optical illusion. Because the performances in this experiment were limited, further tests of the mobile robot at higher speeds and in various performance settings are needed. We created a performance featuring the robot with a professional performer and were impressed by its effect on audience.

As for future challenges, our work has possible applications in sports. The LED lights would be visible, in a poorly-lit environment in which it would be hard to see. The resulting effect might lead to the creation of various digital sports. Moreover, children and the elderly, who cannot move their bodies as well as adults, could easily participate in games that involve rolling a heavy ball, like bowling. They could also play games like soccer that involving accurately passing a ball around.
The robot can easily incorporate information related to education and sports; for example, its movements can be improved through programming. We need to do the performance in real environment and seek collaborations with various performers to establish new representation methods.

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