Outdoor Environment Simulators for Evaluating Safety Sensors of Personal Care Robots
— Artificial Sunlight Lampheads and Simulated-Snow Chamber —

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Abstract—This paper presents two types of outdoor environment simulators: the artificial sunlight lampheads and the simulated-snow chamber. The artificial sunlight lampheads are a set of light source apparatuses for reproducing near-natural direct sunlight. The simulated-snow chamber is a testing apparatus for simulating the visibility reduction due to snowfall. The specifications of the simulators are described in detail and related testing procedures are discussed. Some preliminary experimental results are provided to demonstrate their necessity.

I. INTRODUCTION

A personal care robot has to recognize its surroundings for sharing workspace safely with humans. Thus, adequate safety sensors are required to detect possible hazardous objects and events. And the personal care robot has to be operated anywhere the humans want to go, including outdoor, unlike an industrial robot. Thus, the sensors have to work properly under the worst-case conditions assumed in outdoor environments. The direct sunlight and the bad weather (snowfall) can be the biggest factors for degrading the sensor performance.

Because of these, we have developed testing apparatuses for evaluating whether the personal care robots and their safety sensors can provide enough performance under various environmental conditions. Among them, this paper presents two types of outdoor environment simulators: the artificial sunlight lampheads and the simulated-snow chamber. The artificial sunlight lampheads are a set of light source apparatuses for reproducing near-natural direct sunlight. The simulated-snow chamber is a testing apparatus for simulating the visibility reduction due to snowfall.

In this paper, we focus on the evaluation of vision-based safety sensors, which have some advantage for the personal care robots. By collecting fundamental data with these simulators, we aim to contribute to related safety standards for the sensors.

The rest of this paper is structured as follows. In Section II, we discuss the vision-based safety sensors for the personal care robots and their environmental requirements, as the background of this research. Then, we provide the specification of the artificial sunlight lampheads and discuss the procedures of light interference testing. Next, we describe the specification of the simulated-snow chamber and demonstrate its necessity from preliminary experimental results. Finally, conclusion is given in Section V.

II. BACKGROUND

A. Vision-Based Safety Sensor for Personal Care Robot

Because a personal care robot is operated with humans together, it has to detect the approaching human bodies or parts by safety sensors, unless the robot is inherently safe owing to small size, light weight or low power.

Although there are various types of the safety sensors, in this paper we focus on vision-based sensors. Here we define the vision-based sensor as a sensing device with one or more imaging elements with optical systems. It observes the world as an array of pixel values under projective geometry [1]. The typical products include a monocular camera device, a stereo camera system with two or more camera devices, and a 3D measurement camera device, which projects some active light. In this paper, we do not consider the types of the sensors, that is, we do not go into the details of the sensing techniques and algorithms.

The vision-based sensors are very widely used in various systems, but they are not so common for safety-related use. The vision-base sensors have some good features: a wide field of view, the three-dimensional detection zone configurable by users, and small size and low cost that can be potentially more reduced. These are suitable for small-scale systems, like personal care robots. Therefore, they will be widely used also for the safety use, especially for the personal care robots, as they become increasingly popular in the near future.

B. Outdoor Environmental Requirements for Sensors

The International Electrotechnical Commission (IEC) develops and distributes the IEC 61496 series that are technical standards for the Electro-Sensitive Protective Equipment (ESPE), which is safety equipment for detecting a human body or part with non-contact sensing techniques [2-4]. These standards specify not only functional and design requirements, such as the fault tolerance and detection capabilities of the ESPEs, but also environmental requirements, such as ambient air temperature, humidity, electrical stimulation, mechanical impacts, light interference, pollution of optical components.
It is required that the ESPEs complying with the standards carry on with normal operation under the specified environmental conditions or at least they do not fail to danger. And the new technical specifications, IEC/TS 61496-4 series, are currently being developed for monocular cameras and stereo camera systems [5][6].

The standards, however, are intended to keep workers physically safe in indoor factory working environments. As far as we know, there have not been safety standards to be referred for the outdoor environmental requirements for the vision-based safety sensors. Especially, the direct sunlight and the bad weather, like rainfall, snowfall and fog, can adversely affect the sensor performance when operating robots in outdoor.

III. ARTIFICIAL SUNLIGHT LAMPHEADS

A. Environmental Requirements on Direct Sunlight

The international standard of laser scanners, IEC 61496-3, requires that a laser scanner product based on the standard carries on with normal operation under an illumination of 1,500 lx produced by incandescent light bulbs, and it does not fail to danger at 3,000 lx. For comparison, an illumination of 1,500 lx is recommended for very precise work in precision machine factories [7].

By contrast, outdoor illumination condition is much harsher. For example, the direct sunlight exceeds 100,000 lx at mid-summer with a clear sky. As stated above, however, the outdoor illumination is not obviously specified in the existing standards.

In addition, natural sunlight is not suitable for developing test procedures, because it is not always under optimal conditions for the tests. For the test procedures, a testing apparatus that is constantly-available within an indoor space is preferable.

B. Spec. of the Artificial Sunlight Lampheads

The artificial sunlight lampheads are light sources which can reproduce direct sunlight for light interference testing for evaluating the vision-based safety sensors of the robots. They can deliver high-intensity light to a broad range of areas including the entire body of the robot and its surroundings. Therefore, during the light interference testing, we can examine sensor devices that remain installed in the robot while it is operating normally.

We developed two types of lampheads: a wide-area lamphead and two limited-area lampheads. The wide-area lamphead is intended for illuminating the workspace of a robot to be tested, and the limited-area ones are for the part of the robot. Figure 1 shows the photographs of the lampheads.

For the light source of the lampheads, we adopted metal-halide lamps, which are widely used in entertainment fields, such as movies and dramas. The power outputs are 18 kW for the wide-area lamphead and 4 kW for the limited-area ones. The lighting has wavelength characteristics close to the actual sunlight [8].

The lampheads can be continuously tilted in ±90 degrees in the elevation and depression angles, so the culmination altitude of the sun can be simulated in various regions in the temperate zone. The irradiation angle of the lampheads continuously varies from narrow to wide (the wide-area: 11 to 75 degrees, the limited-area: 7 to 65 degrees), so the irradiation area and the illumination intensity can be adjusted according to the test conditions.

The color temperature of the light source is approximately 6,000 K corresponding to the sunlight at noon. It can vary by putting color-temperature conversion filters in front of the lamphead. Therefore it can reproduce the late afternoon sunlight which can raise significant problems more frequently for the robotic sensors. Table I summarizes these specs of the lampheads.

| TABLE I. SPEC. OF THE ARTIFICIAL SUNLIGHT LAMPHEADS |
|---------------------------------|---------------------------------|
| **Wide-area lamphead**          | **Limited-area lamphead**       |
| Lamp                            | Lamp                           |
| Metal-halide (18,000 W)         | Metal-halide (4,000 W)          |
| Lens diameter                   |                                 |
| 630 mm                          | 300 mm                         |
| Irradiation angle               |                                 |
| 11 degrees (narrow)             | 7 degrees (narrow)              |
| to 75 degrees (wide)            | to 65 degrees (wide)            |
| Illumination intensity          |                                 |
| More than 60,000 lx             | More than 18,000 lx             |
| (irradiation distance: 10m)     | (irradiation distance: 10m)     |
| Tilt range                      |                                 |
| ±90 degrees in the elevation and depression angles |
| Color temperature               | Approximately 6,000 K           |
| Others                          | Color-temperature conversion filters |

Figure 1. Artificial sunlight lampheads. A larger lamphead is for illuminating a wide area and two small ones are for limited areas.
D. Discussion: Light Interference Testing

Here we discuss light interference testing for the artificial sunlight lampheads. Firstly, we propose test configurations and procedures based on the IEC 61496 series. Figure 3 illustrates two types of the configurations.

The lamphead, a sensor, and a background board are fixed as shown in the figure. The sensor is to be tested either mounted on a robot that is functioning normally but in still condition or under similar conditions. Then the lamphead is turned on, and the sensor is tested whether it can detect a specified test piece within a detection zone.

The detection zone is defined as a zone within which the robot detects the test piece(s). The shape and dimensions of the detection zone is decided depending on the applications of the robot.

The test piece can be a simple solid model, like a sphere and a cylinder. It simulates a human body or part that can be possibly harmed by the robot. During the test, the test piece is moved into and out of the detection zone, for example, by using a linear actuator. The speed of the test piece can be estimated relatively from both the motion of the robot and the maximum approach speed of the human body or part [9].

For setting up the test configurations, the worst-case conditions for the sensor should be taken into account. The important conditions are as follows: the size, dimensions and surface reflectance of the test piece and the surface pattern of the background. They should be determined either from the possible operating environments of the robot, or based on the IEC 61496 series.

Next, we propose testing procedures:

- As illustrated in Figure 3(a), the artificial sunlight is irradiated directly to the robot, and then the sensor is tested whether it does not fail to danger (a fail-to-danger test). The irradiation direction should be determined by taking into account the worst-case lighting conditions for the optical sensing systems of the robot. In addition, a shadow is repeatedly casted on the robot by putting in and out a shade board.

During the fail-to-danger test, the following items are verified: When the test piece(s) exists in the detection zone,

- if the output of the sensor still remains in the ON-state, the test is a fail. The ON-state means there is nothing within the detection zone. This is a failure to danger.
- if the sensor output goes to the OFF-state, the test is a pass. The OFF-state means there is something detected in the detection zone. The sensor works normally under the sunlight.
- if the sensor may go to the lock-out condition, which is a condition preventing normal operation by a fault. If the sensor goes to the lock-out condition, the test is also a pass. In the fail-to-danger tests, the lock-out condition is permitted, because the sensor output certainly to go to the OFF-state in the lock-out condition. This is a failure but not to danger.

We consider that these are a minimum set of the test conditions for the personal care robots that are operated in outdoor environments. Additional tests shall be conducted depending on the applications.
IV. SIMULATED SNOW CHAMBER

A. Environmental Requirements on Bad Weather

We can evaluate sensor performance under bad weather conditions by field tests or by using test facilities reproducing near-natural whether phenomena, such as rainfall, snowfall, and fog. Such tests under the natural or near-natural conditions are very valuable for many purposes, for example, in the field of disaster prevention [10].

However, there are some difficulties for testing the sensors. In the field tests, it is difficult to predict the location and time of the natural bad weather. In addition, it may not fulfill the required test conditions in most cases. In using the test facilities, they require large-scale equipment, which may be usually operated under wet conditions.

A testing apparatus constantly-available within the indoor limited space is preferable, just as with the artificial sunlight lampheads. Additionally, we consider that it is important to be easy to use in a dry condition.

B. Spec. of the Simulated-Snow Chamber

The simulated-snow chamber is a testing apparatus which can simulate the visibility reduction due to snowfall. Figure 4 and 5 show the photographs and the schematic view of the simulated-snow chamber. It has an enclosed testing space consisting of transparent plastic sheets and aluminum frames. The testing space has a width of 1,500 mm, a height of 1,000 mm and a depth of 4,000 mm.

The particles of the simulated snow are made of white expanded polystyrene beads. They are circulated in the chamber by air pressure to reduce the visibility of the testing space. The visibility reduction is variable as the snowfall amount is varied by controlling airflow. As shown in Figure 4, the sensor performance is evaluated by observing the test piece placed in the testing space through the observation window.

C. Results of Preliminary Experiments

Here we provide the results of preliminary experiments carried out by using an experimental system which consists of the simulated-snow chamber. For the experiments, we built an experimental VBPD. The VBPD (Vision-Based Protective Device) is a vision-based safety related product, which is a kind of ESPE (Electro Sensitive Protective Equipment). The ESPE is specified in the IEC 61496 series. The IEC 61496-1 states that the ESPE has at least three components: a sensing device, a controlling/monitoring device and an output signal switching device (OSSD).

Therefore, the experimental VBPD simulates the three ESPE components with consumer products: a Microsoft Kinect sensor for the sensing device, a laptop PC for the controlling/monitoring device and a signal light for the OSSD. We developed the software with the OpenNI library on the Ubuntu Linux OS.

Figure 4. Simulated-snow chamber. The view of the testing space (left) and the front wall of the chamber (right).

Figure 5. Schematic view of the simulated-snow chamber.

Figure 6 shows a photograph of the experimental system in operation. In the setup of the experiment, when an object(s) exists within 3,000 mm distance from the sensor in its field of view, the output goes to the OFF-state, which means there is something in the detection zone. At this time the signal light turns red. See also supplemental video.

The other setups of the experiments were as follows: The test piece was a white polystyrene sphere 200 mm in diameter. It was exactly placed at 3,000 mm distance from the sensor on its optical axis. We placed a white polystyrene board as a background at 4,000 mm distance from the sensor. The particle diameter of the simulated snow was approximately 1 mm. The ambient light intensity by fluorescent lights was approximately 600 lx at the test piece position.

Figure 6. Photograph of the preliminary experimental system in operation. A Microsoft Kinect is placed at the observation window of the chamber. When the sensor detects the test piece placed in the chamber, the signal light turns red. See also supplemental video.
Figure 7. Example of the preliminary experiment results without the simulated snowfall. The upper left shows an intensity image acquired by the sensor of the experimental VBPD. The upper right is a depth map, in which darker gray indicates farther away from the sensor, and yellow means no depth data. The red broken rectangles indicate the masked region of the binary mask operation. The lower is an object detection result, in which the detected object is displayed in light blue.

Figure 7 shows example images acquired by the sensor of the experimental VBPD, when the testing space was clear without the simulated snowfall. The upper left and right are an intensity image and a depth map respectively. In the depth map, the darker gray pixels correspond to points farther away from the sensor. The yellow corresponds to regions where the sensor did not produce depth information.

To the depth maps, a binary mask operation is applied. The outside of the red broken rectangle are masked. As a result, we can exclude redundant objects: the chamber walls, ceiling and frameworks, which can be partly detected closer than the test piece. After the mask operation, the experimental VBPD tries to detect objects within the detection zone. The lower image of Fig. 7 shows an example of the detection results. The detected objects are displayed in light blue. They correspond to the pixels closer than or equal to 3,000 mm. The test piece was clearly detected in this experiment because of no snowfall.

Then, we provide results how the amount of snowfall affects the sensor performance. The experiment began with the condition without snowfall (Fig. 7), and then the snowfall was discretely increased until the sensor did not detect the test piece. In this experiment, we made the simulated snow within the range 0 to 1,300 mm approximately from the sensor.

The experimental results are shown in Fig. 8. The left and right columns indicate intensity images acquired by the sensor and images displaying object detection results respectively. All the images are cropped at the mask operation. In the result images, the detected object is indicated in light blue, and the no-depth region in yellow, as with Fig. 7. The each row in Fig. 8 indicates the different amount of snowfall. The lower pair of the images corresponds to the heavier snowfall.

It is clear from the results that the no-depth regions increase with the increasing the snowfall, and finally it becomes not to detect the test piece. This means the experimental VBPD can fail to danger when snow falls.

Figure 8. Example of preliminary experiment results on the various amounts of the simulated snowfall. The left column shows intensity images acquired by the sensor (Kinect) and the right column shows object detection results. The pair of the images at each row shows the different snowfall amount. The lower corresponds to the heavier snowfall.

Next, we provide a result on the relationship between the snowfall region and the sensor performance. In this experiment, we made the snowfall amount fixed at the same as the second row of Fig. 8.

Figure 9 shows an example of the experimental results. The left and right indicate an intensity image and an object detection result respectively, as with Fig. 8. In the detection result image, darker blue indicates the detected objects farther away from the sensor.

It is apparent from the result that the snowfall away from the sensor can be detected as the objects, in contrast to the snowfall close to the sensor shown in Fig. 8. Therefore, it is difficult to distinguish the test piece from the snowfall regions. However, this does not lead to a failure to danger, because the experimental VBPD outputs the OFF-state. This result means at least that a distance to snowfall can affect sensor behavior.

Finally, we provide a result from a different sensing device. In this experiment, we reconstructed the experimental VBPD using a Swissranger SR4000 sensor instead of the Kinect sensor. They use the different measurement techniques: the Kinect sensor uses active triangulation with structured light, and the SR4000 sensor uses the time-of-flight techniques.
and ones by the natural snowing.

Figure 9. Example of preliminary experimental results from the different region of snowfall. The left and right are an intensity image and an object detection result respectively. Darker blue indicates farther away from the sensor. The snowfall amount was the same as the second row of Fig. 8.

In this experiment, we set up the simulated snow chamber system at the same as the third row of Fig. 8; the snowfall range was within 0 to 1,300 mm approximately from the sensor and the snowfall amount was heavy enough for the sensors.

Figure 10 shows an example of the results. The left and right are an intensity image and an object recognition result, which are cropped. It is apparent that this sensor can detect the snowfall in the neighborhood as the object regions, instead of the no-depth regions. In this case, the experimental VBPD does not fail to danger, but it is difficult to identify the test piece, as with Fig. 9. The result means that the sensor behavior against snowfall can be different depending on the measurement techniques.

V. CONCLUSION

In this paper, we have introduced the two different outdoor environment simulators: the artificial sunlight lampheads and the simulated-snow chamber. We have discussed the light interference testing on the direct sunlight, and provided the preliminary experimental results on the sensor behaviors under the simulated snowfall.

Our future work is as follows: For the artificial sunlight lampheads, we will improve and expand the light interference testing by integrating the test procedures using other light sources, like incandescent lights, fluorescent lights, stroboscopic lights, and laser beams. In addition, we will discuss quality testing for various robotics products, for example, the testing of the operability of the display monitors and operation panels of the robots under the direct sunlight.

For the simulated-snow chamber, we will examine behaviors on other sensing devices. Through the experimental described in this paper, we obtained the interesting results from the Kinect sensor and the SR4000 sensor. Therefore we will try to test available sensor products using the other different measurement techniques. Additionally, comparison with natural snowing is required for the simulated-snow chamber. We will have to demonstrate the relationship between the visibility reductions by the simulated snowfall and ones by the natural snowing.

We would like to collect fundamental data by using the proposed outdoor environment simulators for contributing to related safety standards for the vision-based safety sensors and the personal care robots [11].

REFERENCES