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Development of Intelligent Automatic Door System

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***Abstract*— Conventional automatic doors cannot distinguish between people wishing to pass through the door and people passing by the door, so they often open unnecessarily. This paper describes an intelligent door system that observes people near a door so that the door opens at the proper time and only for people who have the intention of passing through it. To achieve this, we developed a novel laser range scanner that scans the surrounding environment three dimensionally, and formulated lightweight algorithms for the sensor. The experimental results show that the sensor can control a door according to the speed of people within the required specifications and that it correctly identifies people passing by the door.**

I. Introduction

Automatic doors are used throughout every city in the world. A conventional automatic door has a proximity sensor installed on the top of the door that detects surrounding objects. No special operation by a user is required to enter an automatic door because it opens automatically when a person enters the sensing area.

The downside to this system is that even if a person just passes by a door and has no intention of entering it, the door will open unnecessarily. This occurrence wastes energy not only in terms of the energy directly used for opening/closing the door but also from other sources, such as the air-conditioning facilities. To remedy this problem, when an automatic door is installed at a place where lots of people pass by it, the following solutions are typically applied:

- decrease the sensitivity of the proximity sensor,
- narrow the sensing area of the proximity sensor, and
- install a touch sensor instead of a proximity sensor.

However, these solutions have major shortcomings: they hinder the flow of people, causing people to slow down or stop in front of the door, and touch sensors are not easy to use for handicapped persons or those carrying bags.

This paper describes an intelligent door sensor that observes people near a door so that the door opens at the proper time and only for people who have the intention of passing through it. In this study, we develop both hardware and software for an intelligent automatic door. With regard to hardware, we developed a novel laser range scanner that observes the surrounding environment three dimensionally from the top of the door. With regard to software, we developed lightweight algorithms for the sensor that are executable by microcomputers in the door sensor systems. The basis of this work is as follows:

- the door is opened only for people who intend to use it,
- the speed, width, and timing of door opening is determined based on observations of the positions, speed, and number of people who are walking.

The rest of this paper is organized as follows. Section II discusses applicable sensors and algorithms for the intelligent automatic door, reviewing related work. Sections III and IV give detailed descriptions of the proposed sensor and algorithms, respectively. Section V shows the experimental results of the proposed system and evaluates its advantages. Section VI concludes this paper and describes the direction of future studies.

Fig. 1. Target Environment

II. Intelligent Automatic Door System

A. Target Environment

Automatic doors are installed not only inside but also as entrances and exits to buildings, meaning the lighting conditions will vary throughout the day. In addition, doors to the outside are exposed to changes in temperature along with the change in seasons and are affected by the weather, such as wind, rain, and snow. In addition, many doors are located where crowds of people walk past them (Fig. 1).

B. Required Sensor Specifications

The sensor and the algorithms for the intelligent automatic door proposed in this study should function correctly in the environment described above, as well as meeting the requirements given in Section I. Generally speaking, the

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speed of human walking is 600-1600 mm/s. According to a security guideline provided by the Japan Automatic Door Association (JADA), with regard to automatic double doors, it is recommended that the speed of opening should be 1,000 mm/s or less and that the width of opening should be 800 mm or more. Taking these conditions into account, a door needs to begin opening before a person reaches a point 1,300 mm from the door, and therefore the sensor needs to cover at least a 1,800-mm radius from the door under the assumption that the detection of walking speed takes 0.3 s. In addition, a sensor for an intelligent automatic door needs to work robustly under diverse environmental conditions. As the illuminance of daylight is 32,000–100,000 lx, the sensor needs to work under an illuminance of 0–100,000 lx for 24-hour operation. Even if the sensor gets wet in rainy or snowy weather, or even if specular light shines directly into the sensor, the sensor should be able to function with little change in performance.

C. Related Work

Conventional automatic doors mainly use infrared or ultrasonic sensors, which can detect the existence of both static and moving objects. Some high-end commercial door sensors that have multiple infrared sensors control their scanning areas flexibly and reduce unexpected opening for passing-by people by dividing their scanning areas into multiple areas. However, because the resolution is not very high (the size of each divided area is 200 mm on a side at a minimum), the sensors cannot detect the velocity of objects, but detect only their presence. Therefore, to realize our intelligent automatic door, we need to either adopt a sensor that has not hitherto been used for automatic doors, or develop a novel sensor appropriate for our purpose.

Most existing methods for detecting the position of objects, that have not been utilized for automatic doors to date, use cameras and depth sensors as sensing devices.

Several types of cameras are used for detecting objects, such as simple RGB cameras [1], infrared cameras that can be used at night [2][3][4], stereo cameras that can measure distance [5][6][7] and RGB-D camera can obtain depth data and color image data [8][9]. However, in general, cameras are not robust against changes in the illumination level, and thus they are not suitable for use as outdoor sensors which are expected to work in any weather condition.

Recently, methods that use depth sensors for measuring the position and shape of objects have been studied. Among the several types of depth sensor available, laser sensors have a higher tolerance to illumination changes, making them suitable for outdoor use. In particular, three-dimensional laser sensors are suitable for use in intelligent automatic door systems because they are able to detect the positions of objects when installed on top of doors. Thus, we use a three-dimensional laser sensor in this study. Requirements for a three-dimensional laser scanner used in our system are as follows: it should be used in outdoor environments, it should be small enough to be mounted on top of a door, and it should not be too expensive to be included in a commercial system. Unfortunately, no conventional three-dimensional sensor satisfies all of them. Consequently, in this study, we developed a novel three-dimensional laser range scanner specifically for use as a door sensor.

Fig. 2. Overview of the developed door sensor

With regard to algorithms for detecting the position and velocity of objects with laser range scanners, several have been proposed [10][11][12] and [13]. Shibasaki *et al.* tracked more than one person by using multiple laser scanners [10][11], and Carballo *et al.* detect people using multi-layered laser scanners [12]. Kurazume *et al.* tracked persons by particle filtering under the condition of occlusion [13]. However, because most existing studies assume that people will be observed in the horizontal plane using two-dimensional laser scanners, they cannot be applied directly to our situation in which a three-dimensional sensor installed on the top of a door scans people from above. In addition, because they are expected to track people as accurately as possible, the computation is too heavy to be implemented in the microcomputers inside our automatic door sensors. Therefore, we needed to develop an algorithm specifically for use with our novel sensor to achieve the functions of our intelligent automatic door.

III. Developed sensor hardware

The proposed intelligent door sensor is a three-dimensional laser range sensor that measures the distance to points on the surface of objects by two-dimensional laser scanning. An overview of the developed sensor and the specifications are shown in Fig. 2 and Table I

The sensor is installed on the top of a door frame and scans objects obliquely downward. The detecting plane assumes the shape as shown in Fig. 4, with the sensor fitted at a tilt angle of 20 deg. If the sensor is attached at a height of 3.5 m, the effective sensing area is 5,000 mm wide and 3,000 mm deep. The sensor obtains vertical and horizontal angular signals from two resonant mirrors and the distance to points on the surface of scanned objects, and then calculates a three-dimensional point cloud of the scanned objects.

Measurement is based on a time-of-flight (TOF) method, in which the distance is calculated from the difference in time between emitting a laser beam and receiving the reflected beam. Typical ways of measuring the time difference

TABLE I

SPECIFICATION OF THE SENSOR

Specification	
Optical source	laser diode
Measuring	TOF (Pulse Modulated Signals)
Scanning device	Resonant Mirror
Horizontal Range	72 deg
Vertical Range	42 deg
Frame Rate	10 Hz
Observation Points	5440 points/frame
Temperature Resistance	-20 ∼ 50 ℃
Size	127(H)×230(L)×83(W)

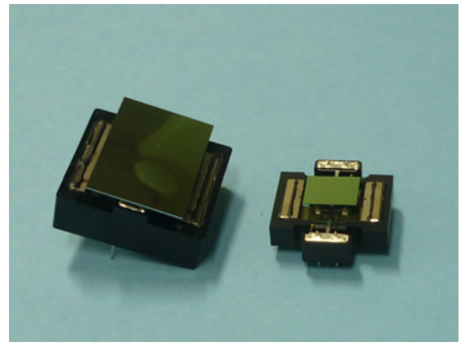

Fig. 3. Resonant mirrors

TABLE II

SPECIFICATION OF RESONANT MIRRORS

	low-speed mirror	high-speed mirror
Resonant frequencies	12.7Hz	387Hz
Hinge material	silicon rubber	SUS t=0.25
Mirror	22 × 20 Au mirror	12 × 10 Au mirror

are methods based on the phase difference of amplitude-modulated signals, and methods based on the difference of the rise time of pulse-modulated signals. Measurement by the first method is accurate, but the maximum measurement distance is short, so this method is unsuitable for outdoor use. Thus, we adopt the second method, in which we can extend the maximum distance by increasing the intensity of the laser beam. In order to remove noise, we adopt a method for calculating distance by analyzing waveforms using a highly sensitive analog-to-digital (AD) converter, to distinguish multiple echo signals.

The main characteristic of our sensor is the implementation of two-dimensional scanning by the use of two resonant mirrors. The corresponding picture and the specifications are shown in Fig. 3 and Table II. The reflective surface of both mirrors is made of silicon. The mirror in the θ-direction has a metal hinge for fast oscillation at 400 Hz and has a field of view of 42 deg. The mirror in the ϕ-direction has a hinge made of silicon rubber containing carbon nanotubes for slow oscillation at 10 Hz, and has a field of view of 72 deg.

The transmitter unit consists of a semiconductor laser and a transmitter lens, and the diameter of the short-pulse laser beam is as narrow as possible. The beam is sent to the scanning unit, which has two resonant mirrors, each one of which is used for two-dimensional scanning. The beam reflected by an object is returned to the receiver unit by the two mirrors. Finally, as the transmitted and received beams are coaxial (having the same optical axis), another mirror is used for optical separation.

Because the proposed sensor uses a TOF method in a coaxial optical system, it is little affected by strong direct light, such as sunlight, up to an illumination of 200,000 lx. Additionally, software filtering using multiple-echo technology can remove reflected light caused by snow, rain, and drops of water on the optical window surface and mutual interference caused by other sensors. The combination of these technologies and a scanning system that uses two resonant mirrors means we can realize a sensor that is small, stable, and robust enough for use in diverse environmental conditions.

IV. ALGORITHM FOR INTELLIGENT DOOR SENSOR

This section describes the algorithm for controlling the intelligent automatic door. It controls the speed, width, and timing of opening the door.

First, the noteworthy points which are approaching the door are extracted from an observed point cloud. And then, out algorithm estimates the position and velocity of the people and determines whether each person has an intention of entering the door or not. Finally, when a person who intends to enter the door is detected, a command to open the door is sent to the door controller. This algorithm is lightweight enough to be executed by microcomputers in the door sensor system. The algorithm consists of the following four phases: preprocessing, estimation of the approach speed based on radial segmentation, estimation of the intention based on striped segmentation, and decision of opening.

A. Preprocessing

In this phase, we extract data used for door control from output of the sensor and transform their coordinates.

1) Extracting Beams for Estimation: As described above, the sensor we developed emits 5,440 beams every scanning, and its output is the distance from the sensor to the point where each beam hits. Preliminarily, the background of a scanning area is recorded when no one is there. By background differencing, beams that hit non-background objects are extracted from the sensor output. The extracted beams are classified into two categories depending on the change of the distances: c-beams and s-beams. Beams whose distance gets shorter are categorized as c-beams, and beams whose distance does not change so much are categorized as s-beams. The remaining beams, which belong to neither categories, are not used in our algorithm. C-beams are used for detecting people approaching the door, while s-beams for detecting people who stop around the door.

2) Coordinate Transformation: The data extracted above, which are the distances for the extracted beams, are transformed into positional data of points where the beams hit

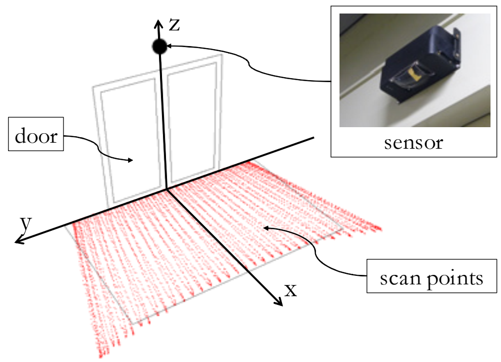

Fig. 4. Set up of the intelligent automatic door sensor (Red dots are *scan points*)

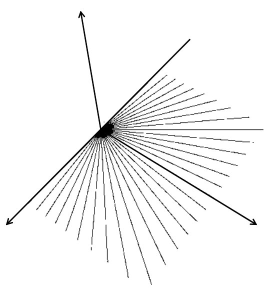

Fig. 5. Radial area by the door

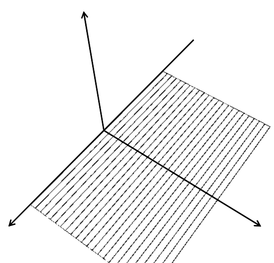

Fig. 6. Stripe area by the door

people. The coordinate system is constructed as follows: the origin is located at the projected point of the sensor onto the ground, and the x, y, and z-axes are taken to be the direction perpendicular to the door, the direction parallel to the door, and vertical, respectively(see Fig. 4). In the following, we call the point where a beam hits an object the *scan point* of the beam. The x and y-coordinate values are used in the proposed algorithm. Although it is not mentioned in this paper, applications that consider the height of objects would be possible if the z-coordinate values were used.

B. Estimation of the approach speed Based on Radial Segmentation

For estimating the position and velocity of people moving to the door, we segmented the scanning area into radial cells as shown in Fig. 5. For each cell, scan points of c-beams are summarized and the position and velocity of a moving person is calculated. In our implementation, the measurement area is segmented into 30 radial cells by 6 degrees.

1) Grouping: The person closest to the door in a cell alone is considered in our algorithm even if more people exist there. The reason why this strategy works is as follows: if a person intends to pass another person from behind, he or she needs to move to a neighboring cell because a cell is too narrow for a person to pass another person inside the cell.

In order to pick up the closest person, a histogram is created as shown in Fig. 7. The horizontal axis is the value of x-coordinate of scan points (every 100 mm), and the vertical axis is the count of the points. We regard a valley, continuous bins in the histogram where no beam is observed, as a boundary of objects. The scan points are grouped by the boundaries and the group closest to the door is extracted. Here the groups that include too few scan points are ignored as noise.

2) Estimation of Position and Time of observation: The mean of x-coordinate values of the scan points belonging to the closest group extracted above is considered as the position of the approaching person closest to the door. Also, the mean of the time of them are calculated because one scan takes 0.1 s, and the time varies among scan points depending on the location of people and the direction of scanning. The six latest estimations of the position and the time are always kept for the use in the decision phase.

3) Estimation of Velocity: The velocity of an approaching person is calculated by the least square method based on the position and the time extracted in every radial cell. Fig. 8 shows a graph plotting the position of the closest approaching person against the time in a radial cell. Fitting a line to the points in the graph by the least square method, the velocity of the person is estimated as the slope of the regression line. If the position changes largely from the previous frame, or if no object has been detected for more than two successive frames, the stored data are discarded and the velocity estimation starts over again.

4) Estimation of Number of People: In the decision phase, the width of opening the door is decided depending on whether one person alone approaches the door or more people approach. Thus, the number of people in the scan area is required to be estimated. First, the leftmost and rightmost cells where approaching people exist are extracted and count the number of the cells between them. Next, by comparing the position of people in the leftmost and rightmost cells, the cell where a person is closer to the door is selected and the width of the cell at the position of the person is calculated. Finally, the product of the number and the width is calculated, and if it exceeds a certain threshold, it is judged that more than one person is approaching the door.

C. Estimation of the intention Based on Striped Segmentation

Although the method based on radial segmentation estimates behavior of people approaching a door, it sometimes mistakenly detects people just passing by in front of the door. Thus, it is necessary to discriminate people who enter the door from passing-by people. For this purpose, after the position estimation in radial segmentation method, we examine detected people and select out people who have intention of entering the door. Only the selected people are considered in the successive estimations.

In order to discriminate people approaching the door, we segment the scan area into striped cells as shown in Fig. 6 and estimate the walking direction of people. In our implementation, the width of a striped cell is 100 mm. When a person is first detected in the scan area, the cells within a certain distance to the person are marked as *pending zone*(Fig. 9). People who stay in pending zone are ignored in

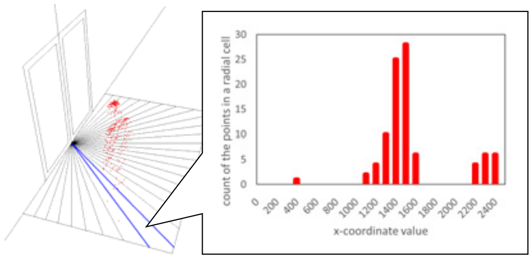

Fig. 7. Histogram of *scan points* in a radial cell

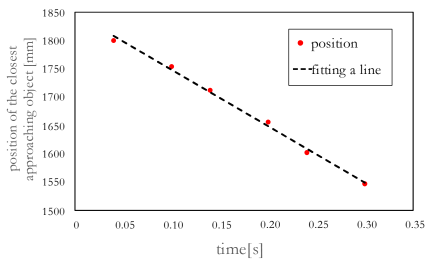

Fig. 8. A transition in the position of the closest approaching a person

the estimation phase. Once a person gets out of the pending zone, the algorithm judges the person is going to enter the door and consider the person in the estimation phase. By focusing only on people approaching the door, we can ignore passing-by people effectively.

D. Decision of Opening Door

The proposed intelligent automatic door controls the timing, speed, and width of opening the door depending on a situation.

1) Timing: The timing of opening the door is determined based on the estimation of arrival time of people. As described above, people approaching the door have been extracted, so the arrival time of approaching people is calculated by the position and the velocity of the people. The command to open the door is issued in the timing that the door finishes opening just in time for the arrival of the person to the door. In addition, this door is designed to open even if a person have stopped at the front of the door suddenly. In this implementation, s-beams are used. When the number of s-beams exceeds a threshold, the instruction to open the door will be issued immediately.

2) Speed: There are two types of speed of opening the door: normal and high speed. Usually, the door opens at normal speed in order to reduce the wear of the drive unit. However, if the estimated time period for arrival is shorter than the time required for opening the door at normal speed, for example in the case a person suddenly changes the direction of walk, the door opens at high speed.

3) Width: The width of opening the door is determined by the estimation of the number of people. When one person alone enters the door, the width is *half-open*. When more than one, it is *full-open*.

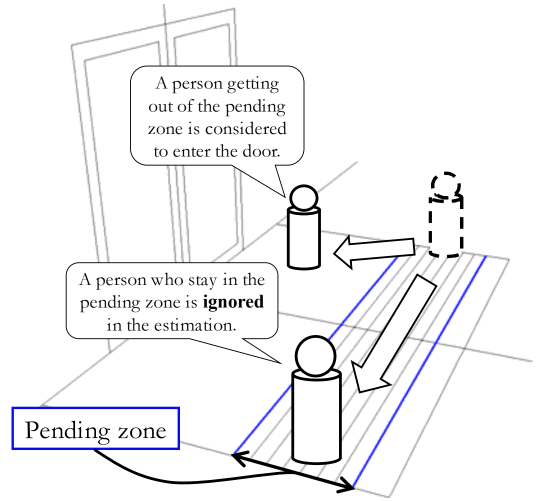

Fig. 9. Pending zone

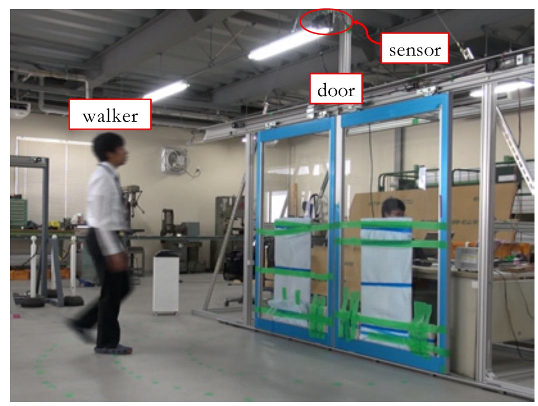

Fig. 10. Experimental environment

V. EXPERIMENT

In order to evaluate the proposed sensor, developed sensor was installed to an experimental doorway, and the following three experiments were conducted. Fig. 10 shows the experimental setup. The parameters of the door and the door sensor are set as shown in Table III.

A. Timing of Opening Door

In this experiment, one subject entered the door from several directions. For every trial, the position and velocity of the subject was recorded at the time the command to open the door was issued. The entering directions were 0 deg, 22.5 deg, and 45 deg to the x-axis (Fig. 11), and the subject entered the door 30 times for each direction. Additionally, to obtain the true position and velocity of the subject, we set a two-dimensional laser scanner (UTM-30LX) behind the subject and recorded the subject's position at 10 Hz. We use the position and velocity calculated from these data as true values.

The result is shown in Fig. 12. The horizontal and vertical axes are the position and the velocity of the subject when the door began to open, respectively. The dotted line shows

TABLE III
SETUP OF THE INTELLIGENT AUTOMATIC DOOR SYSTEM FOR EXPERIMENTS

Parameter	
Mounting height of the sensor	3,000 mm
Mounting angle of the sensor	21 deg
Width of opening the door (*half-open*)	800 mm
Width of opening the door (*full-open*)	1,100 mm
Speed of opening the door (*normal speed*)	800 mm/s
Speed of opening the door (*high speed*)	1,100 mm/s
Time required to open the door (*half-open*)	1.0 sec
Time required to open the door (*full-open*)	1.375 sec
Width of pending zone	700 mm
Threshold of the number of people estimation	800 mm

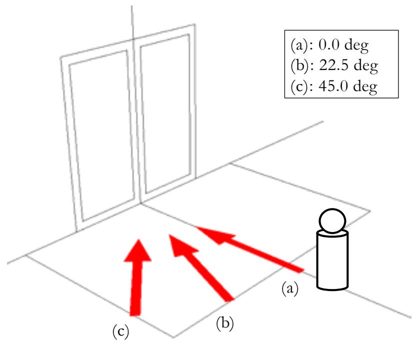

Fig. 11. Entering direction in Experiment A.

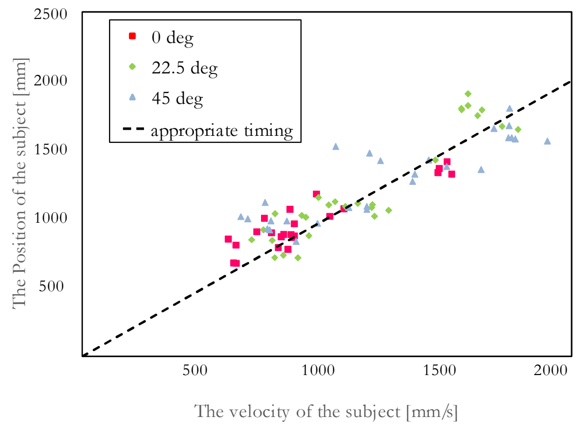

Fig. 12. Relationship between the position and the velocity of the subject

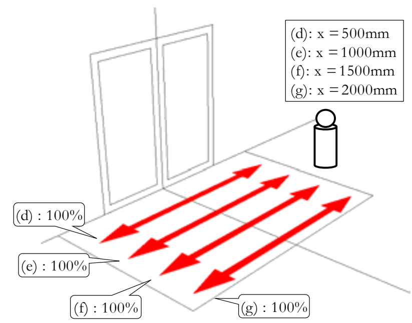

Fig. 13. The percentage of correct judgement in experiment B ((d)–(g)).

the proper timing to start the door opening. If opening instructions are issued at this time, people approaching the door can pass through the doorway without either contacting the door or slowing down.

However, some points are plotted under the line, and it means that the subject arrived at the door before the door completely opened. Thus, in practical operation, we should keep a buffer time when issuing the open command. From this experiment, we can estimate appropriate buffer at 0.2 s because the largest error of the timing was 0.2 s.

B. Discrimination of Passing-by People

We had two experiments here. In the first experiment, one subject passed by in front of the door, and recorded whether the system issued the open command or not. The subject walked along seven patterns of straight paths, and the speed of walking varied from 500 mm/s to 1,500 mm/s. Thirty trials were conducted for each path. The percentage of correct judgment for each path are shown in Fig. 13 and 14. In the case of (d)–(i) and (j), the door never opened for the passing-by subject. In the case of (h), the door mistakenly opened in a trial. This is because the walking direction is far from parallel to the door in (h) and the movement along x-axis became large.

In the second experiment, many people walked in front of the door. During five minutes, 103 people passed by in front of the door and six people entered the door. There were at most three people at the same instant in the scanning area. The door never opened for passing-by people. In contrast, it opened with proper timing only four out of six people entering the door. In the other two people's cases, because there were passing-by people in the scan area and the pending zone due to them hid the entering person, the system could not detect the entering person. In practice, for security purpose, we set an additional scanning area around the door to open it soon when any object appeared there (similar behavior to ordinary automatic doors), and it had the door open eventually though the timing was delayed. Since our algorithm does not track people in detecting passing-by people, this problem is unavoidable. However, the door surely opened for all people intending to enter it, even tough the timing is sometimes delayed, this problem would not be very serious for practical use.

C. Width of Opening Door

In the previous experiments, when one person entered the door, the system always issued the half-open command. Thus, we can say the width of opening door is correctly decided for one person.

Next, we examine the case that more than one person enter the door. In this experiment, two people came to the door simultaneously from five different directions. The speed of walking varied from 500 mm/s to 1,500 mm/s. Ten trials were conducted for each direction. Fig. 15 and Fig. 16 shows the percentage of correct decision. In all the cases, the system issued the full-open command for all trials.

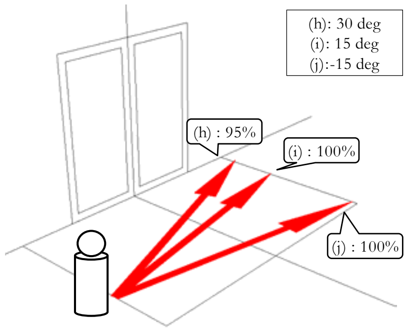

Fig. 14. The percentage of correct judgement in experiment B ((h)–(j)).

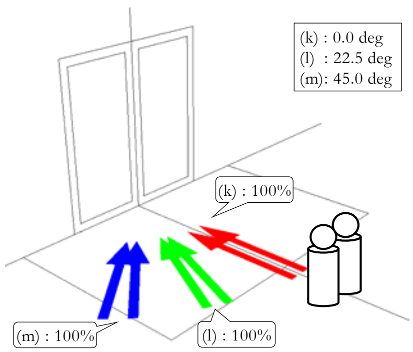

Fig. 15. The percentage of correct judgement in experiment C ((k)–(m)).

D. Discussion

In these experiments, the sensor is mounted at an angle such as it can scan the vicinity of the door for users' safety, so the scan area limited to 2,400 mm from the door and up to 2,000 mm/s walking people can be detected.

However, if the viewing angle of the sensor spread, the limitation would reduce without any change of the algorithm. In order to confirm it, we changed the mounting angle from 21 deg to 51 deg and conducted an additional experiment. As the result, the sensor determined the appropriate timing of door opening for people running at 4,000 mm/s.

VI. Conclusion

This paper describes an intelligent door sensor that achieves the following functions:

- opening a door only for people who intend to enter it,
- controlling the speed, width, and timing of opening a door according to motion of approaching people.

We developed both hardware and software: a novel laser range scanner and a lightweight algorithm for it. The scanner observes an area in front of a door three-dimensionally. The algorithm detects people approaching the door and estimates the speed of them. Also, segmenting the scan area radially, it discriminate passing-by people from people who intend to enter the door.

The experimental results showed that the sensor could control a door depending on the speed of people within the required specifications and that it worked correctly under the situation that people passed by the door.

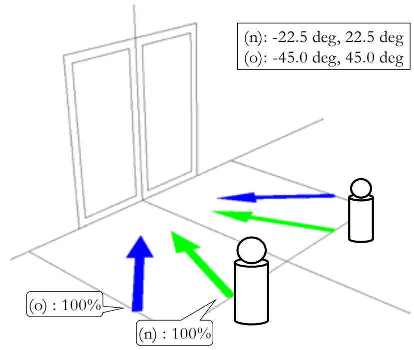

Fig. 16. The percentage of correct judgement in experiment C ((o), (n)).

In future, we plan the field tests. In the tests, we will study effective door opening timing. It is because it has been found that usability is influenced by margin in which the door completes opening. Additionally, we will study energy-saving effect by intelligent door sensor.

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