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A Novel Visible Light Communication System for Enhanced Control of Autonomous Delivery Robots in a Hospital

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Abstract— **Control systems for Autonomous mobile delivery robots have been described before. However, the control they provide is limited, leaving potential for serious errors. The current mobile robot systems concentrate on position accuracy and operational function but leave open management of safety hazards such as entering the dangerous and not intended areas as stairway. In order to increase the safety of the robot, it is as important to work with sensors installed in the external environment as the sensors installed on the robot. For this purpose, visible light communication (VLC) is a promising device to be used with the robot system. VLC creates an in-house GPS system by installing special LED lights that can replace standard lighting in key locations in the hospital. We have developed an in-hospital transportation robot, called HOSPI in which the control system has been enhanced by combining the navigational sensors of the robot and a VLC using installed lighting in the building. By using VLC, robots can obtain more information about the environment. As the first step for the practical application of VLC to robot system, we use VLC to overcome problems in conventional localization approaches, and to provide an additional line of defense in the case of catastrophic failures. This paper also describes experimental and actual operational results in detail of robots equipped, in an actual hospital, with the described process.**

I. INTRODUCTION

In an environment, such as a hospital, there are many areas an autonomous robot should not go, the robotic system needs to know the robots exact location in the targeted operating area. However the robot must avoid hazardous areas which exist in all target locations such as stairs and escalators. Although, many methods to improve the recognition accuracy have been studied [1], they have proven to not be reliable for actual daily use. The main issue is localization errors because of an ever changing application. [2]. To increase the safety of the robot, it is a effective method to employ robot sensors installed in the target environment that can communicate with the Robot and control system. For this purpose, visible light communication (VLC) is a promising method to enhance the robotic system. VLC creates an in-house GPS tracking system by installing special LED lights that replace standard lighting in key locations in the hospital. There are many research study examples of position recognition using VLC [3]. As the first step for the practical application of VLC to robot system, we use VLC to overcome problems in conventional localization approaches, and to provide an additional line of defense in the case of catastrophic failures. In this paper, we focus on the measures to prevent robot from falling down from the stairs and describe the detailed method to put VLC into practical use in hospital.

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As described above, only using the position recognition to control the robot not to go to prohibited area leave potential errors and this will be the trigger of serious problems such as a fall from the stairs of the robot. Therefore, there are many techniques to prevent the robot from falling down assuming that there is an error in the position recognition. One method is to use sensor installed on robot and know the dumps by this sensor. Another method is to use the sensor installed on external environment to notify the robot of its error status.

If robot is compact and lightweight like a cleaning robot in the home which is popular in recent years, it will be able to stop in front of the bumps even if it is detected just before the bumps by using bump detect sensor [4]. And after that robot can turn and then continue to move. In addition, its harm will be small even if it falls down because it is lightweight. However, if the weight of the robot is the same as human or heavier like delivery robot or cleaning robot in facilities like hospital, it will too late to stop the robot from steps after detecting the bumps which is just before the robot. And it has a possibility of serious hazard if there is a man under the stairs. In fact, if the robot about 100KG moves at a speed of 1 m/s, the braking distance is tens of 10cm. Therefore, the robot needs to detect a step tens of 10cm forward.

There are many research about the detection of the bumps from the front [5][6][7]. Many studies use stereo camera or distance image camera, but these functions are not robust to change of lighting environment or floor conditions.

Recently, many studies try to use 3D range sensor such as SR-3000 (SwissRanger) and Kinect(Microsoft) to recognize 3D environment[8] . But these 3D range sensors tend to have false detections[9][10]. False detection includes false negative and false positive. If there are false negatives, robot cannot detect bumps and there is possibility of falling down from

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stirs.

Another study uses Laser Range Finder (LRF) to detect the bumps [11]. By using a LRF which is robust to change of lighting environment, it is possible to detect the bumps in more stabilized condition. However, it is difficult to secure the safety of the robot which will work for 24 hours for 365 days by only using sensor installed on robot because of the possibilities of unexpected operations such as malfunction of sensor, and a reckless run of PCs.

In order to solve these issues, it is effective to use the combination of sensor installed on robot and sensors installed on external environment. In addition to VLC, there are other sensors such as infrared sensor and RFID for this purpose [12]. However, in many hospitals they tend to avoid the use of equipment that emits radio waves, such as RFID. VLC is also effective in that sense. And another advantage for VLC is that VLC can use the lighting which is already constructed in the environment.

The rest of this paper is organized as follows. The actual operation of HOSPI in a hospital is introduced, followed by descriptions of fall prevention technology. Our actual use of robot transportation system is then described with the experiment results of the method followed by a conclusion.

II. Outline of HOSPI

A. Actual use of HOSPI

HOSPI is an autonomous mobile robot that performs transport operations and other duties in a hospital. HOSPI have been used for actual duties in some hospitals. HOSPI enabled with the technology described in this paper has been transporting medications since January 2011 at the Matsushita Memorial Hospital in Japan.

After receiving the target destination from the hospital staff, HOSPI determines its cruising path based on its stored map information and moves toward the destination. When HOSPI encounters people or obstacles, it continues cruising and avoids obstacles based on information detected by its sensors.

B. HOSPI structure and specifications

HOSPI's appearance and the sensor arrangement are shown in the Fig. 1 and the specifications in Table 1. Four laser range finders (LRF) are built into the robot to recognize its surrounding environment. One of the sensors (LRF1) made by SICK measures the space in the horizontal plane, and three additional sensors (LFR2) made by Hokuyo Electric measure the space to the left and right sides and in the forward direction. The front sensor is positioned high on the robot body and focused down. The receiver for visible light communication is installed on top of the HOSPI.

C. Uniqueness of the hospital environment

There are ideal conditions for the use of a robot in a hospital. Passages have few level differences and this is convenient for a wheel type robot. On the other hand, if hospital has more than two floors, there may be steps or escalators and in most cases these exist near the route in which robot have to move. Because ordinary persons or the hospital staff may use these stairs, it is generally very difficult to install a fence in front of stairs to prevent a robot fall in the case of a failure. As for the other features, the places in which robot moves are passages or near a hospital reception, and not widely open areas like the open space of an airport or a shopping center. Therefore, it is easier for the robot to use the environmental information for self-position recognition which is a basic function of an autonomous mobile robot. Some peculiarities exist in a hospital for example equipment which emits radio waves can interfere with precision healthcare equipment. In comparison VLC installed on HOSPI do not present a hazard, and can be easily installed in a hospital.

Fig. 1 Appearance of mobile robot HOSPI

TABLE I
SPECIFICATION

Item	Quantity
Size	*600 (W)×725 (D)×1345 (H) mm*
Weight	*120 Kg*
Weight capacity	*20 Kg*
Max velocity	*1.0 m/s*
Operation duration	*more than 7 hours*
Controlled axes	*2 axes for driving*
	1axes for head rotating

III. Hazard prevention strategy

The hazard prevention strategy of HOSPI consists of mainly three steps (Fig. 2). First, the robot map is set up so that a robot may not go near a hazard area like stairs. By providing a virtual barrier on a map, HOSPI is prevented from going beyond that position. For this method to operate, HOSPI always needs to maintain its own position. However, in the case of a failure, position recognition may not always function correctly. Therefore, if HOSPI goes to stairs involuntarily for example, it is necessary to detect this situation. The system that detects bumps or uneven surfaces can also detect stairs as long as the sensor installed on the robot is operating correctly. Therefore, it is not safe to only rely on a sensor because of the possibilities of unexpected operation caused by a malfunction of the sensor, or a reckless run because of a PC failure. It is also difficult to detect the robots approach to an escalator since the entry is not sensed to be an uneven surface by a sensor. We enhance the system by the use of VLC which is equipped with an electronic address and has unidirectional communications with the robot. By combining these techniques, the practical management of hazards such as a stairs fall is realized. Below, we will explain these three system elements.

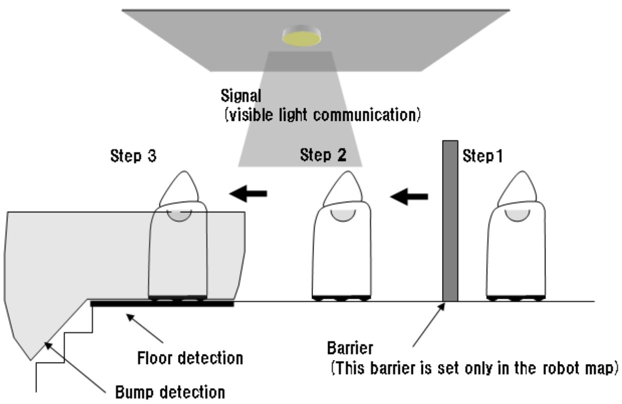


Fig. 2 Strategy for fall prevention

A. Barrier in the map for avoiding the stairs.

The first strategy is to set up the robot map so that a robot may not go to a hazardous area in first place. By providing a virtual barrier on a map, HOSPI is prevented from going beyond that place. Although this function is easily implemented, the robot always needs to know its own position correctly to function properly. In this section, the position recognition technology of HOPSI is described. Position recognition uses the output of an inner sensor, and an external sensor. The method of using an inner sensor involves dead reckoning. In HOSPI, odometry and a gyroscope are performing dead reckoning. Since an error is accumulated only with dead reckoning, the compensation of a position using an external sensor becomes indispensable. There are established ways of using an external sensor, for example an absolute position can be acquired from a GPS or the position can be assumed with reference to the sensor and robot map. If robot moves outdoors, GPS can be used, but there is no sensor which can determine a position in accurately and reliability indoors. As mentioned before, an indoor GPS device which may affect precision instruments cannot be used.

In our system the determining of an absolute position using VLC mentioned can be used in a hospital. However, an exact position cannot be determined by this method alone. To determine a more exact position, we have implemented a matching method using the robot sensor and robot map[13][14]. In consideration of the uniqueness of the hospital environment, HOSPI has wall information stored as map information, and has adopted the technique of matching the wall information acquired from the sensor and map information. The places in which the robot moves in the hospital are basically passages or near a hospital reception, it is easier for the robot to detect a wall in almost all the cases. Therefore the HOSPI performs matching which uses the wall information (Fig. 3) to determine it's exact position.

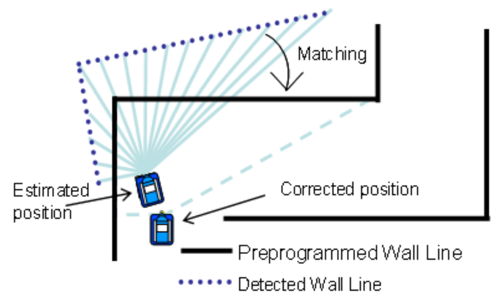


Fig. 3 Localization with line segments detection

B. External Environment sensor

The 2nd strategy is the method of stopping a robot using the sensor installed on the external environment.

In a hospital, it is generally very difficult to install a physical barrier in front of stairs for the purpose of the preventing a robot fall. Since a person may stumble, it is not safe even if a small height difference is installed. Therefore, the safest approach is to warn the robot of the existence of a step using a wireless device. However, there are few means to report the information reliably using a wireless system which does not interfere with precision instruments. So HOSPI system adopted the strategy of warning HOSPI using VLC. The lights are equipped with an electronic address and have unidirectional communications with the HOSPI. Since signal is generated by the light on and off, it has no influence on other apparatuses. Moreover, if the LED light is an emergency light , it can operate during a power failure. VLC equipment consists

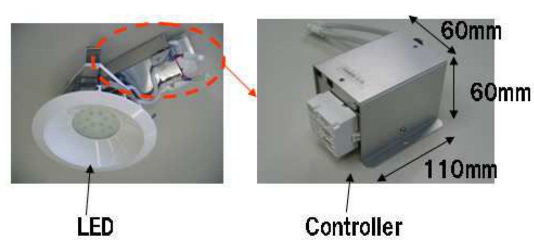


Fig.4 Appearance of trial product of LED device

of ordinary LED lighting and a device which adds signals to light (Fig. 4).

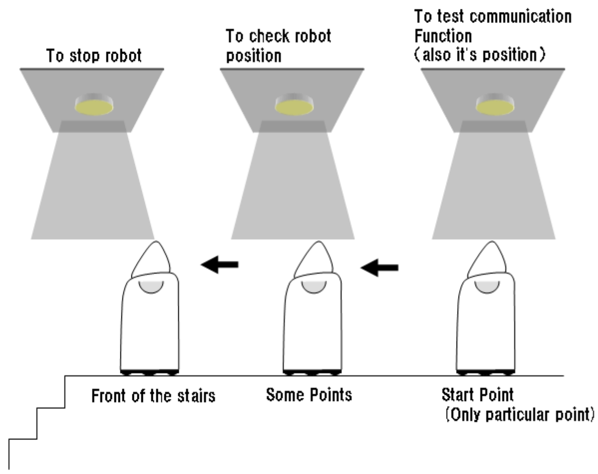


Fig.5 VLC functions

VLC is used for the three purposes as shown in Fig .5. The whole system containing the VLC is shown in Fig. 6.

Communication between the VLC and HOSPI for the purpose of stopping the robot is performed only when HOSPI comes to the area in front of the stairs where a VLC is installed. A functional check of the VLC is performed and is always supervised by the server. To check that the VLC is operating normally a check is performed at each specific point in the system such as the start positions.

To check normal operation of a light receiving section of visible light, the receiver checks the signal from the sample

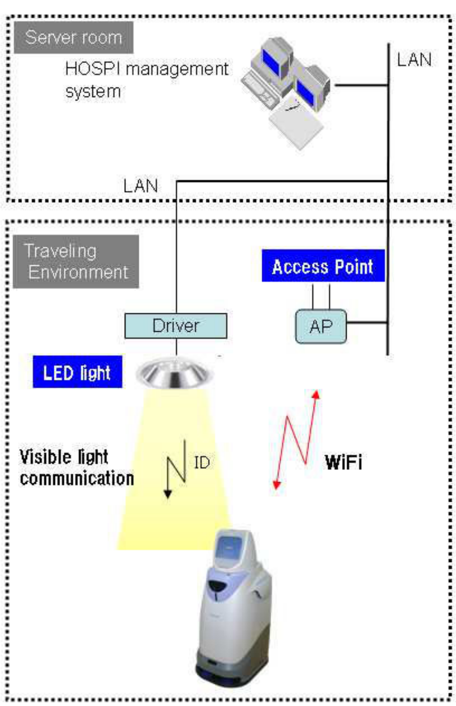


Fig.6 System configuration of HOSPI

visible light which is installed just beside the receiver at the fixed interval. VLC also has the possibility of position recognition because VLC has a unique key. At this time we don't use VLC for this purpose since it is not more accurate than the light-receiving range (1m or more). Therefore we use the VLC only to check the position of the HOSPI.
In the next design it is possible to increase the accuracy and we will consider this function.

Fig.7 shows the range of VLC detection. The blue point shows the detectable limit. In this example, HOSPI can detect visible light in the range of 700mm radius..

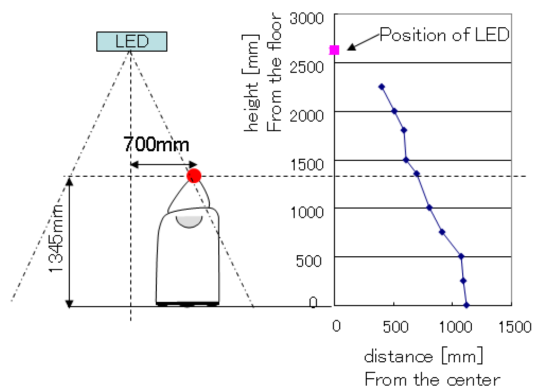
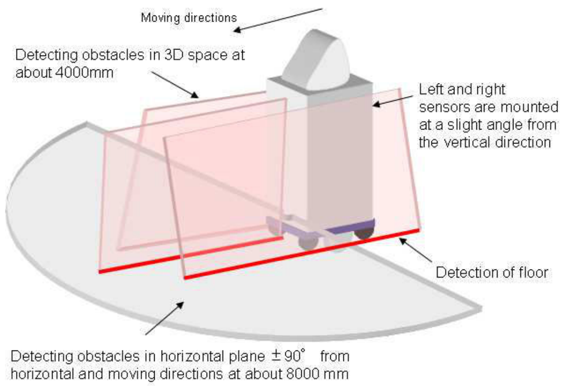


Fig.7 range of VLC detection

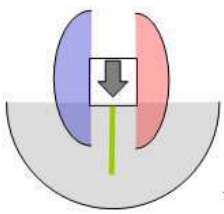
C. *Level difference recognition using the robot's sensor*

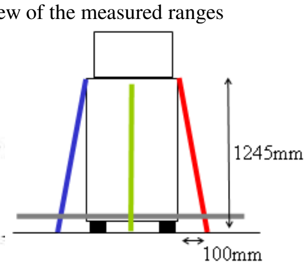
The third strategy is a method of stopping the robot using the sensor installed in the HOSPI. HOSPI has four LRFs and can detect obstacles and also steps in front of the HOSPI.

Although research of a three-dimensional laser sensor is promising in recent years, there are very few practical sensors [11]. This study [11] describes a method of producing 3D obstacle and environment maps by rotating a 2D sensor. But in this method, the laser scanning cycle is 0.8 sec., and obstacles or bumps hidden in the undetectable area during this period are missed. Because HOSPI is designed to cruise at 1 m/s moves 0.8 m in 0.8 sec, this delay cannot be tolerated. So HOSPI arranges the sensor as shown in Fig. 8(a) for the detection of the obstacle position and detection of a level difference ahead of a robot. Four laser range finders (LRF) are built into the robot to recognize its surrounding environment. One of the sensors (LRF1) made by SICK measures the space in the horizontal plane, and three sensors (LFR2) made by Hokuyo Electric measure the space of the left and right sides and the front direction from high position on the body of the robot and positioned pointing down. The overhead view of the measured ranges is shown in Fig. 7(b), and the view from the front in Fig. 7(d). The obstacle detection example viewed from the side is shown in Fig. 7(d). LRF1 detects obstacles in front of the robot by measuring the horizontal plane, and LRF2 detects obstacles and steps in the front, sides, and back

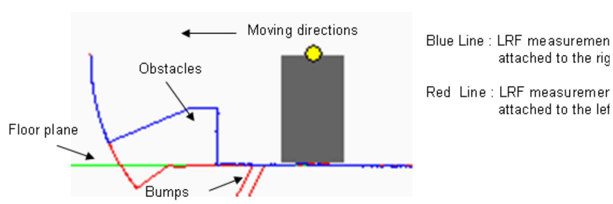


(a) The overhead view of the measured ranges





(b) The view from the top (c) The view from the front



(d) Obstacle detection viewed from side
(d) Obstacle detection viewed from side

Fig.8 The measured ranges of four LRFs

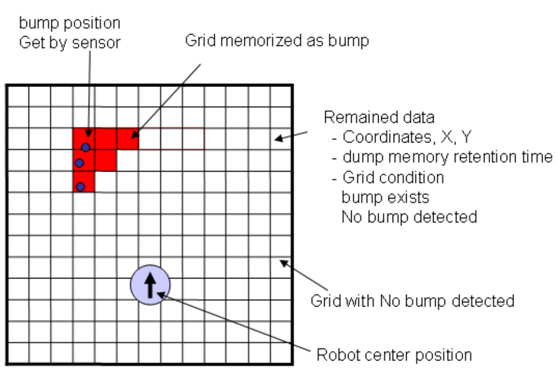


Fig.9 appearance of grid map with bumps

of the robot. The data obtained by LRF2 is converted to three-dimensional positions in the robot navigational system. The positions are recognized as obstacles when the data indicates they exist above the floor surface or as a step when the data indicates that it exists below the floor level. When a level difference is detected ahead, HOSPI will stop, or move to avoid the step. Since there is a margin of error in a sensor, level difference detection and robot stop function cannot be always used. For example, if HOSPI might stop because of the detection of the small crevice between an elevator car and floor or tiny bump in a floor. In this case HOSPI has a map grid which records the bump. If a level difference is detected, this information such as the position of the bump is memorized in the corresponding grid. If more than a given number of regions of this memory are filled HOSPI senses an error and stops. In the case of a step, HOSPI recognizes that there is a step in front of HOSPI. Fig. 9 shows the appearance of grid map.

IV. RESULT OF REAL OPERATION

By applying the above algorithm, four HOSPIs are actually used for conveyance in Matsushita memorial hospital. two HOSPIs are real-working from January 2011, and other two HOSPIs from October 2011. We will describe the condition about the above-mentioned strategy and its result below.

A. *Operation task , Operating areas*

The main duty of HOSPI in the Matsushita memorial hospital is conveyances of medications and blood samples, etc. Conveyance of medication from the pharmaceutical department which exists in B1 to each ward from 1F to 6F, and collection of blood samples are performed. HOSPI uses the lift automatically and can go to all floors in this hospital. There are steps and escalators near the route HOSPI moves. The length of the route HOSPI moves in one floor is about 100m.

B. *Setting of barriers in the map and conditions of position correction*

Virtual barriers are set in the robot map before each stairway, escalator, and places we do not want HOSPI to go. The conditions for position correction were set to as follows:

・correction range (offset) : 1m

・correction range (rotation) : 20degree

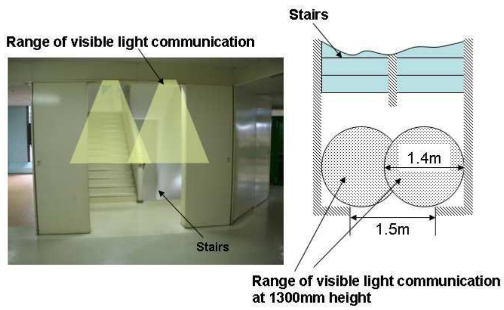
C. *Setting of VLC*

As shown in Fig. 10, visible light was set in front of each stairway and escalator. The range of the detection area of visible light is shown in Fig .10 The number of VLC's installed in this hospital (HOSPI moves from basement 1 to 6th floor) is up to 22

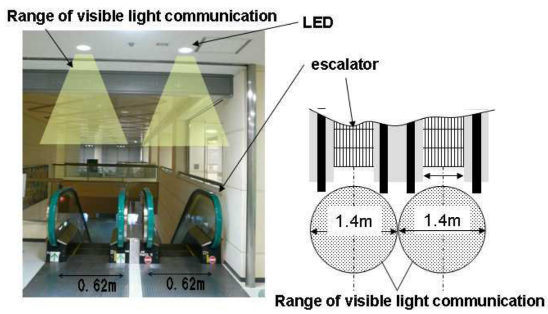
D. *Setting of floor detection function*

HOSPI recognizes the space as a bump when the sensor data is 10cm below the floor. The grid map was set around the HOSPI path. Grid size was set to 3cm square, and HOSPI judges the existence of bump ahead if 10 pieces of grid are filled with the memory of bumps.

operation is shown in Fig. 12.



(a) VLC set in front of stairway



(b) VLC set in front of escalator

Fig.10 VLC setting

E. The result of each function

Each function was evaluated and tested repeatedly at the time of introduction and all systems are checked satisfactorily.

The fall prevention function, after encountering a virtual obstacle, was tested repeatedly and we determined that HOSPI doesn't lose its recognized position in a normal status and doesn't go beyond the virtual barrier.

Furthermore, we tested conditions which would make HOSPI go in the direction of stairs, and checked the function of stopping immediately by visible light detection.

To test the fall prevention function using the robot sensor we did the test to force the HOSPI to go in the direction of stairs and checked the function of stopping immediately by detecting the bump. This situation is shown in Fig. 11. HOSPI stopped 220 mm before the step.

F. The result of real operation

Every HOSPI perform dozens of times transportation everyday in Matsushita Memorial Hospital. There were several times that HOSPI was stopped by VLC through this whole period. The one situation was caused by a position recognition error. This happened because the position error correction was accumulated over a long time movement preventing HOSPI from returning to the original route after evading several obstacles. Although technical improvement to increase the accuracy of position recognition is required, it can be said that it is shown that it is effective to combine two or more navigation functions to prevent robot error. The situation that HOSPI stopped by its own sensor have not occurred during this whole period. The situation of daily operation is shown in Fig. 12.

Fig.11 Step detection by LRFs

Fig.12 Real operation in a hospital

V. CONCLUSION

We proposed hazard management strategy using a novel visible light communication system addition to conventional method which is performed by sensors installed on robot. By using visible light communication, we can enhance the safety of robot system especially for preventing the robot from falling down. We use the visible light communication to create an in-house GPS system and to notify robots the existence of hazards such as stairs or escalators. A robot named HOSPI in which our developed technology has been implemented is actually transporting drugs in a hospital. HOSPI cruises daily among many peoples, and the space where steps and escalators are located near the route. Visible light communication has great potential in the robot system such as in-house GPS and localization and large amount of information exchange between systems and robot. By having put this VLC in practical use this time, it can be said that it has succeeded in verification of one possibility of VLC.

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