Sensor terminal ”Portable” for intelligent navigation of personal mobility robots in informationally structured environment

Hiroyuki Yamada[1,3], Tomoki Hiramatsu[1], Masato Imai[1], Akihiro Kawamura[2], and Ryo Kurazume[2]

***Abstract*— This study proposes two kinds of systems for building intelligent service robots, namely a sensor terminal named ”Portable” for making various personal mobility robots intelligent and a distributed sensor system for constructing an informationally structured environment consisting of laser range finders and active beacons. The sensor terminal Portable is equipped with a laser range finder and a gyro. Two types of personal mobility robot, namely standing type and wheelchair type, are made intelligent by installing Portable to provide navigation functions such as localization, obstacle detection, and path planning. The sensor system is mainly used to acquire position information about the personal mobility robots, obstacles, and moving objects (e.g., people); this information is used by Portable for navigation. The obtained information is transmitted to the robot, allowing it to operate in a complicated environment. The ability of the proposed system to navigate personal mobility robots is verified in two real environments.**

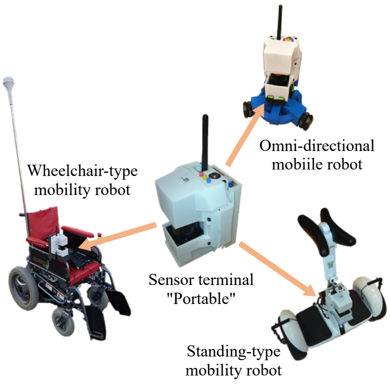

Fig. 1. Concept of sensor terminal ”Portable”. Portable can be installed in various mobile robots to make them intelligent.

I. INTRODUCTION

The development of service robots, which support daily activities, has expanded to prepare for an aging society. Among such robots, the personal mobility vehicle (PMV), which is expected to have high demand and contribute to preventive care, extends the physical ability of the elderly and disabled people, giving them the opportunity to move their own bodies more easily. The essential function of a PMV is to take the user to the target location without harming anyone. This is done by detecting obstacles, determining PMV location using multiple kinds of sensors, and conducting path planning for complicated environments. The faster a PMV can move, the more frequently these processes must be performed. PMV control involves a lot of complicated processing and requires high reliability. One solution is to perform these processes on a controller with high processing capability mounted on the PMV, and another is to make the environment intelligent. An intelligent environment is referred to here as an informationally structured environment (ISE).

An ISE refers to a framework that supports mobility robots. The sensors and processors are in the environment rather than on the robots. An ISE acquires, analyzes, and manages environment information such as maps, obstacles, and the locations of moving bodies, and gives this information to the robots. An ISE reduces the burden on robots of acquiring various information about the surrounding environment, leaving robot processing capacity to other tasks. This allows robots with a smaller processing capacity to be used or the robots can perform more sophisticated tasks. In addition, development resources can be allocated to robot-specific tasks, and it becomes easy to introduce a robot into a real environment. The present authors previously developed an ISE hardware platform named Big Sensor Box [1] and an ISE software platform named ROS-TMS [1][2].

However, some information cannot be acquired using sensors installed in the environment. For instance, the location of a moving object, which is essential environmental information for a PMV, can be occluded by other moving objects and the PMV itself, and thus not detected by sensors in the environment. It is thus necessary for a PMV to acquire information about objects in its surroundings that may possibly move, even in an ISE.

The main task of a PMV is navigation. The main functions necessary to achieve this are moving object detection, path planning to the target location, and path following control. Among these, detection and planning do not depend on the PMV and are common technologies. With an ISE, a PMV can be made intelligent by installing a general-purpose terminal that acquires information from environmental sensors, detects some (but not all) moving objects, and plans a path based on this information (Fig. 1). A PMV requires some hardware and software to move itself along the planned path. Furthermore, an ISE lowers the required processing capability of the general-purpose terminal.

[1]Hiroyuki Yamada, Tomoki Hiramatsu, and Masato Imai are with Graduate School of Information Science and Electrical Engineering, Kyushu University, Fukuoka 819-0395, Japan {yamada, hiramatsu, imai}@irvs.ait.kyushu-u.ac.jp

[2]Akihiro Kawamura and Ryo Kurazume are with Faculty of Information Science and Electrical Engineering, Kyushu University, Fukuoka 819-0395, Japan {kawamura, kurazume}@ait.kyushu-u.ac.jp

[3]Hiroyuki Yamada is with Transportation System Control Research Department, Center for Technology Innovation - Controls, Hitachi, Ltd. Research and Development Group, Ibaraki 312-0034, Japan hiroyuki.yamada.qt@hitachi.com

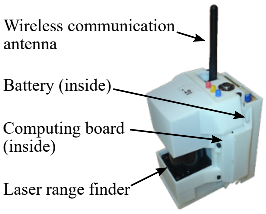

Fig. 2. Portable.

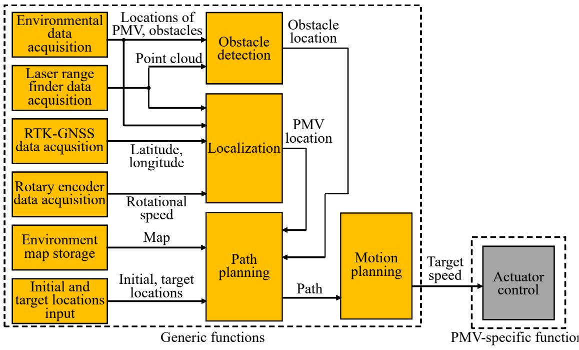

Fig. 3. Logical architecture of Portable.

The present study develops obstacle detection and path planning functions for various kinds of PMV operating in an ISE, and makes two PMVs intelligent using small sensor terminals. These PMVs are evaluated in an ISE that uses laser range finders (LRFs) and active beacons.

II. Related Work

The goal of this study is to realize a robot that acts effectively in a real environment and supports daily activities. We focus on two scenarios for the robot: supporting the movement of people who need nursing care in an indoor living space and guiding visitors to the desired location in an outdoor theme park. The experimental environments were thus a room that simulates an actual living space and the premises of an actual theme park.

One feature of real environments is the occurrence of congestion, such as that caused by pedestrians. Methods for dealing with such congestion have been reported [3][4][5][6][7]. Kümmerle et al. proposed the SLAM system, which accurately creates large-scale urban area maps; SLAM was able to navigate over a distance of more than 3 km using LRFs and GPS in a crowded urban environment [3]. In order to achieve long-term operation even in cases where the data from two-dimensional LRFs are insufficient in busy situations, Pérez et al. extended Monte Carlo localization by integrating image information [4]. Jafari et al. proposed a method for people detection and tracking with a low processing load by effectively utilizing depth information obtained using RGB-D sensors [5].

Although satellite signals (e.g., those from GPS) are important when navigating a robot outdoors, in urban areas, such signals are often obstructed by buildings and trees. In such areas, for robust navigation, localization is often achieved by matching precise maps with data from laser scanners or vision sensors [8]. Schwesinger et al. demonstrated autonomous navigation over a distance of more than 12 km that was achieved by creating a large-scale high-resolution map and detecting three-dimensional (3D) landmarks and obstacles using 3D LIDAR [8]. Map information is important for robots in a real environment, and thus map updating and maintenance methods for large-scale real environments have been proposed [9][10][11]. Pomerleau et al. mapped dynamically changing environments, and by identifying dynamic objects using a 3D laser scanner, extracted static geometry, allowing long-term maintenance with accurate updating of the map [9].

Some studies have attempted to make robots run outdoors using existing published maps, under the assumption that the cost of creating and maintaining large-scale maps is prohibitive [12][13]. When using such two-dimensional maps, an alternative scan matching method is required because there is no map information that can be used for matching.

The present study proposes an approach that makes the development and implementation of PMVs easier. Existing techniques for autonomous navigation are implemented on a sensor terminal, which can be installed to easily make various robots intelligent. Furthermore, the processing required by the sensor terminal is made as simple as possible by placing sensors in the environment.

III. Development of Small Sensor Terminals and Intelligentization of Various Robots

A. Small sensor unit Portable

We developed Portable, a small sensor terminal that can be mounted on various robots to easily make them intelligent. Portable consists of an LRF (UST-20LX, Hokuyo), an inertial measurement unit (myAHRS+, Hardkernel), a battery, a wireless communication system, and a computing board (ODROID-XU4, Hardkernel). Portable is designed to be compact so that it can be installed on any robot. Its dimensions are 114 × 100 × 240 mm and its weight is approximately 800 g. Portable is shown in Fig. 2.

Figure 3 shows the logical architecture of Portable. Portable has generic functions that do not depend on the type of PMV and a PMV-specific function. The generic functions include acquisition of sensor data from the LRF, rotary encoder, and RTK-GNSS (Real-time kinematic global navigation satellite system) module directly connected to Portable, acquisition of environment information, map storage, input of initial/target locations, obstacle detection, localization, path planning, and motion planning. The PMV-specific function is for controlling the actuators of the PMV and thus depends on PMV hardware. Because there was a constraint that the hardware on the PMV hardware cannot be changed, PMV-specific function is implemented in Portable. However, it is also possible to have PMV-specific function performed by the PMV. Ideally, the interface between Portable and the PMV, such as that for target speed, would be defined and PMV developers would implement the actuator control

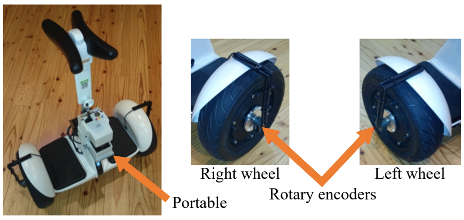

Fig. 4. Standing type PMV and rotary encoders installed on wheels.

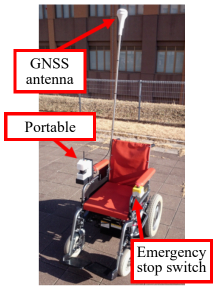

Fig. 5. Wheelchair-type PMV with Portable and GNSS antenna installed.

function. By operating according to the instructions from Portable, a PMV can be guided to the target location without hitting obstacles. PMV developers would no longer need to develop basic guidance functions, giving them time to focus on developing more unique functions that would increase value for users.

Each function is developed based on ROS. We use an occupancy grid map for the environmental map, a particle filter for obstacle detection, the extended Kalman filter for localization, and the Dijkstra method based on a costmap created from the environmental map and obstacle locations for path planning. For a given path, the target velocity (translational and rotational speeds) of the PMV is determined using the dynamic window approach.

B. Intelligentization of standing-type PMV by Portable

In this study, two kinds of PMV are made intelligent, namely standing type and wheelchair type. We targeted the Ninebot by Segway miniPRO (Segway-Ninebot) as the standing-type PMV (Fig. 4). In this PMV, the user can induce translational motion by moving their own center of gravity forward and backward, and can induce rotational motion by tilting the handle held by the feet to the left or right. We attached rotary encoders to the left and right wheels of the miniPRO (Fig. 4), the Portable on the front of the handle (Fig. 4), and a microcontroller for controlling the rotation of the miniPRO at the lower part of the handle. The target rotational speed is sent from the Portable to the microcontroller to control rotation. Due to the characteristics of a standing-type PMV, there is a safety concern if the robot moves forward or backward against the user's intention, and thus the user directly manipulates the PMV to control translational speed. Therefore, in the Portable, the target rotational speeds obtained from the generic functions are ignored and the target rotational speed is computed by the PMV-specific function based on the translational speed set by the user. Only the target rotational speed is sent to the PMV.

C. Intelligentization of wheelchair-type PMV by Portable

We targeted ChairBot (Sustainable Robotics) as the wheelchair-type PMV (Fig. 5). ChairBot is a modified electric wheelchair (MC 3000U, Suzuki) that controls the left and right wheels via digital signals. In the actuator control, which is a PMV-specific function, Portable calculates the target rotational speeds of the left and right wheels from the target translational and rotational speeds, and transmits the appropriate commands to the PMV. For use in an outdoor environment, we installed an RTK-GNSS module and a GNSS antenna. Using a base station placed at a known location, the RTK method eliminates errors caused by ionospheric delay. Excellent position measurement results can thus be obtained. In this study, RTK-GNSS is used to improve robustness by integrating different types of sensor data for localization (wheel odometry and LRF data).

IV. Informational Structuring of Real Environment

A. Development of P^2-sen and building ISE

We developed the Petit Petit Sensor Box (P^2-sen) (Fig. 7), which consists of an LRF and a computing board. A P^2-sen can track moving objects. The locations of moving objects in an environment can be determined by arranging multiple P^2-sen devices and integrating their data.

We constructed an ISE that can track moving objects using the LRF of a P^2-sen. The following tracking algorithm was used:

1) Apply background subtraction based on a Gaussian distribution to the scan data obtained from the LRF, and extract data that may contain moving objects.
2) Clustering scan data by determining adjacent data as the same object
3) Apply a particle filter to each cluster and estimate the locations of moving objects

The above process was performed by a control PC to which multiple P^2-sen devices were connected. The locations of moving objects obtained from P^2-sen were sent to Portable from the control PC and used for navigation control of the PMV.

B. Building ISE using active beacons

Active beacons (Pozyx, Pozyx Labs), each comprising a base station and a mobile station, were used. By arranging multiple base stations at known locations in the environment and measuring the distance between a mobile station and the base stations via wireless communication, an active beacon can estimate the location of the mobile station based on the distance from multiple known locations with an accuracy of about 10 cm. The mobile station was installed in the PMV and transmitted its location to Portable. In Portable, the Kalman filter was applied to the position output by the beacon to improve stability.

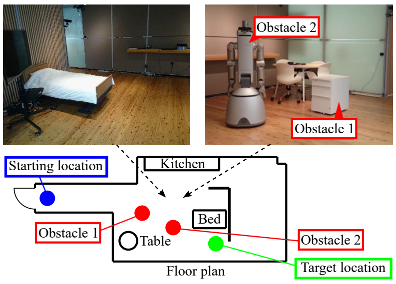

Fig. 6. Indoor experimental environment (Big Sensor Box)[1] and obstacles.

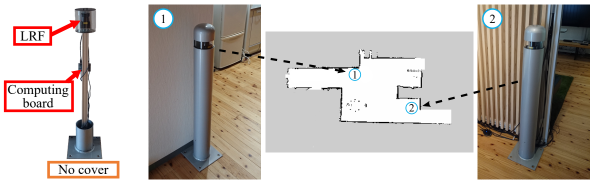

Fig. 7. P^2-sen, environmental map, and locations of two P^2-sen devices in experimental environment.

V. Experiments

A. Navigation experiment of standing-type PMV using Portable and P^2-sen

We constructed an ISE in a real environment and conducted experiments to navigate a PMV using Portable. This section presents the results of constructing an ISE using P^2-sen in an indoor environment that reproduces an actual living space and navigating the standing-type PMV. Figure 6 shows the experimental environment, named Big Sensor Box [1], the obstacles placed in the environment, and locations of the obstacles. The ISE was constructed by placing two P^2-sen devices in the environment, as shown in Fig. 7. The control PC was collected to these devices and processed their data, and then wirelessly transmitted the results to Portable on the PMV. In this experiment, Portable estimated the PMV location by integrating the locations obtained by the rotary encoders and that transmitted from the control PC using the extended Kalman filter. Portable also detected obstacles using its own LRF. The goal of the experiment was to navigate the PMV from the initial location to the target location; however, obstacle 1 was at a height that made it not detected by P^2-sen.

Figure 8 shows the navigation results. First, the PMV is at the initial location and there are no obstacles in the detection range of the LRF mounted on Portable (Fig. 8 ①). However, Portable knows the position of obstacle 2, obtained from the ISE, and plans a path to avoid it. Next, Portable detects obstacle 1 and re-plans the path to avoid the two obstacles (Fig. 8 ②). The PMV then moves to the target location according to the planned path.

Figure 9 shows the results of localization obtained using P^2-sen and the rotary encoders and using only the rotary encoders. As shown in Fig. 9, these localization results are not smooth. This is considered to be due to the insufficient number of particles used in the particle filter for moving

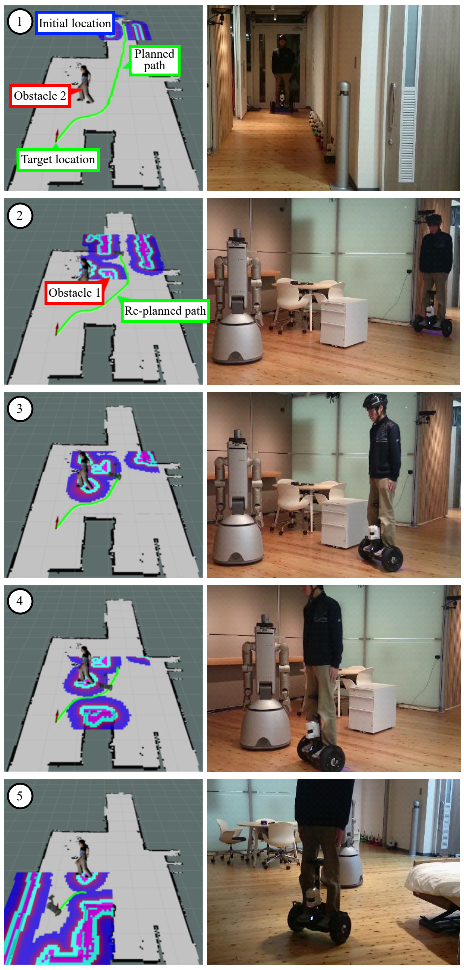

Fig. 8. Navigation of standing-type PMV using P^2-sen and Portable in ISE.

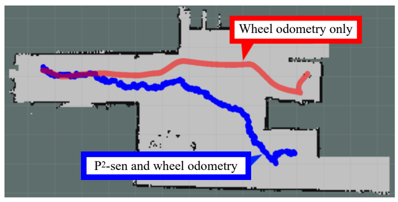

Fig. 9. Localization results of standing-type PMV in ISE.

object tracking by P^2-sen. However, this did not cause practical problems in navigating the PMV. The accuracy of localization was improved by using information from P^2-sen compared to that obtained using only wheel odometry.

B. Navigation experiment of standing-type PMV using Portable and active beacons

We conducted a PMV navigation experiment in a real outdoor environment to simulate visitor guidance at a theme park. In this experiment, we constructed an ISE with eight active beacons placed at the entrance open space of the theme park. The goal was for the PMV to navigate from the entrance gate to the first building. Portable performed localization using wheel odometry and the active beacons.

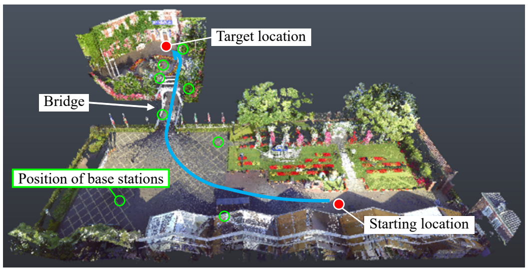

Fig. 10. Experimental environment in theme park entrance area.

Fig. 11. Navigation of standing-type PMV using active beacons and Portable in ISE.

Figure 10 shows the experimental environment and the navigation path of the PMV. There is a bridge with a width of about 4.5 m along the path. An accuracy of 20 to 30 cm is required to pass over this bridge safely. The environment map used in this experiment was precisely constructed using a laser scanner at a time when there were no visitors.

In this experiment, PMV passed over the narrow bridge and was able to navigate to the target location (Fig.11). Figure 12 shows the actual movement path of the PMV and the locations of the base stations of the active beacons. Part of the path is meandering because the speed set by the user and the rotational speed calculated by Portable did not match. It is thus necessary to review the algorithm used for calculating rotation speed.

Figure 13 shows the results of localization from the entrance gate to the front of the bridge in the cases where only wheel odometry is used, only the active beacon are used, and both are used. Using only wheel odometry, it was not possible to reach the bridge due to error accumulation. Integrating information from the active beacons increased accuracy. However, using only active beacons, the information was acquired intermittently or the values jumped in some situations. There seems to have been a problem with the installation locations of the base stations. Various noise sources in the environment, such as metal objects and radio sources, should also be considered. In this environment, the locations and intervals of the base stations greatly affected measurement accuracy.

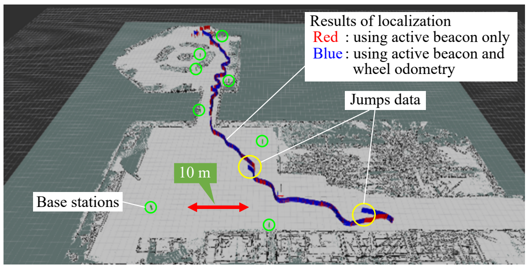

Fig. 12. Localization results of standing-type PMV in ISE.

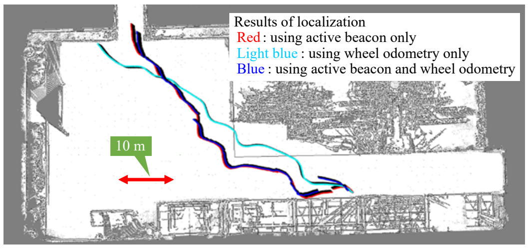

Fig. 13. Localization results of standing-type PMV up to the bridge.

C. Navigation experiment of wheelchair-type PMV using Portable with RTK-GNSS

We conducted a navigation experiment of the wheelchair-type PMV in an outdoor space to evaluate the localization by Portable using rotary encoders and RTK-GNSS without using environmental sensors. The experiment was conducted in an area with an open view of the sky that was sufficient to obtain GNSS satellite signals. We set up the RTK base station in the environment to receive correction data. Figure 14 shows the experimental environment. In this experiment, a map with virtual walls (red lines in Fig. 14) was used. An obstacle was placed in the center of the environment, as shown in Fig. 15. Portable planned a path from the starting location to the target location that avoided the virtual walls and the obstacle.

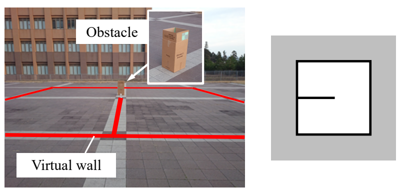

Fig. 14. Left: Experiment environment for wheelchair-type PMV. Right: Map with virtual walls

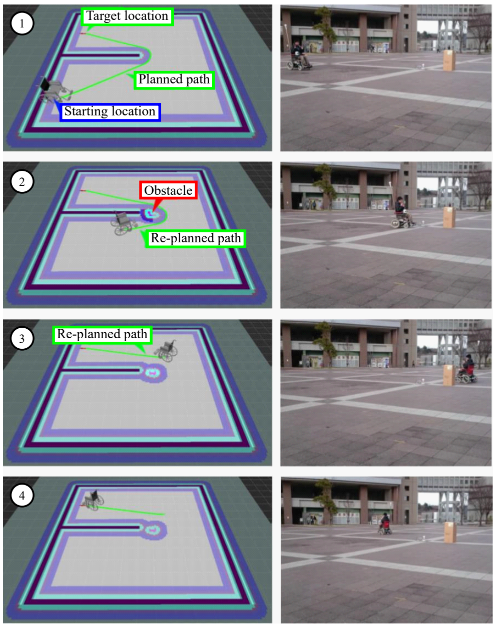

Fig. 15. Navigation experiment of wheelchair-type PMV using Portable.

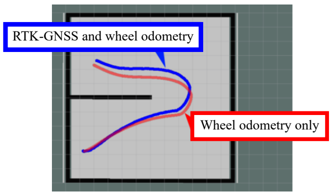

Fig. 16. Trajectories of wheelchair-type PMV using RTK-GNSS.

Figure 15 shows the navigation results. First, the PMV was at the starting location. Since there were no obstacles in the detection area of the mounted LRF, the shortest target path that avoided the virtual walls was planned (Fig. 15 ①). Next, the obstacle was detected by the LRF, and the target path was re-planned to avoid it (Fig. 15 ②). The PMV then moved to the target location according to the planned path (Fig. 15 ③ $\sim$ ④).

Figure 16 shows the results of localization obtained using the RTK-GNSS module and the rotary encoders and using only the rotary encoders. The two sets of results are similar since ChairBot has a relatively small slip between the ground and the tires and its travel distance was short. However, by integrating RTK-GNSS, it is possible to estimate the target location more accurately. RTK-GNSS is thus beneficial for long-distance movement.

VI. CONCLUSION

This study proposed the Portable framework that provides functions required for an ISE and makes it easy to make various PMVs intelligent. The effectiveness of Portable was confirmed by basic experiments using two types of PMV, namely standing type and wheelchair type. In addition, we confirmed that a standing-type PMV equipped with Portable can navigate a real environment that was made into an ISE. Navigation in an ISE was also possible with the wheelchair-type PMV.

This study focused on evaluating the effectiveness of Portable and thus congestion was not considered in the experiments. Performance in a congested environment will be evaluated in future experiments.

ACKNOWLEDGMENT

The authors would like to thank Y. Kawauchi, T. Nakamura, T. Inoue, and O. Toyama at Living Robot Inc. for technical assistance with the experiments. This research was supported by the Japan Science and Technology Agency (JST) through its ”Center of Innovation Science and Technology based Radical Innovation and Entrepreneurship Program (COI Program)” and was supported in part by a Grant-in-Aid for Scientific Research (A) (26249029).

REFERENCES

[1] R. Kurazume, Y. Pyo, K. Nakashima, T. Tsuji, and A. Kawamura, “Feasibility study of iort platform ”big sensor box”,” in *Proc. IEEE International Conference on on Robotics and Automation (ICRA2017)*, pp. 3664–3671, 2017.

[2] Y. Pyo, K. Nakashima, S. Kuwahata, R. Kurazume, T. Tsuji, K. Morooka, and T. Hasegawa, “Service robot system with an informationally structured environmen,” *Robotics and Autonomous Systems*, vol. 74, no. Part A, pp. 148–165, 2015.

[3] R. Kümmerle, M. Ruhnke, B. Steder, C. Stachniss, and W. Burgard, “A navigation system for robots operating in crowded urban environments,” in *2013 IEEE International Conference on Robotics and Automation*, pp. 3225–3232, May 2013.

[4] J. Pérez, F. Caballero, and L. Merino, “Integration of monte carlo localization and place recognition for reliable long-term robot localization,” in *2014 IEEE International Conference on Autonomous Robot Systems and Competitions (ICARSC)*, pp. 85–91, May 2014.

[5] O. H. Jafari, D. Mitzel, and B. Leibe, “Real-time rgb-d based people detection and tracking for mobile robots and head-worn cameras,” in *2014 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 5636–5643, May 2014.

[6] Y. Morales, E. Takeuchi, A. Carballo, W. Tokunaga, H. Kuniyoshi, A. Aburadani, A. Hirosawa, Y. Nagasaka, Y. Suzuki, and T. Tsubouchi, “1km autonomous robot navigation on outdoor pedestrian paths ”running the tsukuba challenge 2007”;,” in *2008 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 219–225, Sept 2008.

[7] G. Ferrer, A. Garrell, and A. Sanfeliu, “Social-aware robot navigation in urban environments,” in *2013 European Conference on Mobile Robots*, pp. 331–336, Sept 2013.

[8] Dylan, Schwesinger, Armon, Shariati, Corey, Montella, and J. Spletzer, “A smart wheelchair ecosystem for autonomous navigation in urban environments,” *Autonomous Robots*, vol. 41, pp. 519–538, Mar 2017.

[9] F. Pomerleau, P. Krüsi, F. Colas, P. Furgale, and R. Siegwart, “Long-term 3d map maintenance in dynamic environments,” in *2014 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 3712–3719, May 2014.

[10] B. Suger, G. D. Tipaldi, L. Spinello, and W. Burgard, “An approach to solving large-scale slam problems with a small memory footprint,” in *2014 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 3632–3637, May 2014.

[11] F. Ferri, M. Gianni, M. Menna, and F. Pirri, “Dynamic obstacles detection and 3d map updating,” in *2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 5694–5699, Sept 2015.

[12] P. Ruchti, B. Steder, M. Ruhnke, and W. Burgard, “Localization on openstreetmap data using a 3d laser scanner,” in *2015 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 5260–5265, May 2015.

[13] K. Irie, M. Sugiyama, and M. Tomono, “A dependence maximization approach towards street map-based localization,” in *2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 3721–3728, Sept 2015.