Proceedings of the 2nd WRC Symposium
on Advanced Robotics and Automation 2019
Beijing, China, August 21, 2019

A Human-Aware Robotic System for Mobile Robot Navigating in Multi-Floor Building with Elevator

Junxin Zhao, Yujing Chen, and Yunjiang Lou, *Senior Member, IEEE*

***Abstract*— The wheel mobile robots navigation between floors inside the building need to take elevator, but the transition between maps and elevator state detection make difficulties for robots, also the safety problem should be consider for elevator space is narrow. In this paper, we introduce the 2D maps align algorithm with multi-map server to accomplish the transition between different maps, and propose a stable elevator state monitor, ensure the stable navigation while robot taking the elevator. Besides, we consider the human-awareness for taking elevator safety. To validate the algorithms, we implement these modules in a system, and deploy in a wheel mobile robot. By experiment in an unmodified building environment, the result shows that our robotic system can make the robot perform stable and safe navigation between different floors.**

(a) (b) (c)

Fig. 1. (a) Robot waiting to take the elevator, (b) robot detect and locate the human in elevator, (c) human location marked on ROS visualization tool.

I. INTRODUCTION

The autonomous mobile robots are becoming widely applied to our daily lives in recent years. Thanks to the good mobility, mobile robots can take place of human in many application such as logistics, household service, surveillance etc. However, for the multi-floor building, which is one of the most common environment in our daily lives, the mobility problem of robot is still unsolved well. As a result, it restricts the operation space but also limits the application scenarios of mobile robots.

For common wheel mobile robots in most of the building environment, taking elevator is the only way to navigate from floor. However, the states of elevator are hard to detect and the space is separated between floors, which add burdens on robot to transfer itself. And with frequent human activities inside the normal buildings, the robot needs to have human-aware ability to ensure human safe and avoid disturbing human.

In this paper, we aimed at solving aforementioned problems, make the common wheel mobile robots without manipulator can move itself safely and stably between floors with the human assist press the elevator button. To solve the maps discontinuous problem, we introduce the 2D maps align algorithm with multi-map server to accomplish the transition between different maps. To detect the door state and floor state of elevator, we propose a stable elevator state monitor, ensure the stable navigation while robot taking the elevator. More over, we consider the human-awareness in the system, by combining the state of art CNN based object detection algorithm with pedestrian detection and tracking pipeline. Finally, the system deployed in a wheel mobile robot and take experiment in a common building environment with unmodified elevator. The experimental results show that the robotic system can make the robot perform stable and human safe navigation between different floors.

This work was supported in part by the NSFC-Shenzhen Robotics Basic Research Center Program U1713202 and in part by the Shezhen Science and Technology Program under Grant JCYJ20180508152226630.

Zhao, Chen, and Lou are with the School of Mechanical Engineering and Automation, Harbin Institute of Technology, Shenzhen

Corresponding author: Yunjiang Lou, mail: louyj@hit.edu.cn

II. RELATED WORKS

Navigation inside the building with elevator is crucial for mobile robots to complete various tasks, there are many researchers have demonstrated the approach or strategy for robot taking elevator. For our robotic system is designed for most of wheel mobile robots without manipulator, we will mainly focus on the multi-floor navigation solution but not the elevator operation part. Kang et. al. [1] developed a strategy for mobile robots to navigate between multi-floor, it can recognize the current floor and the elevator button by vision in a known elevator. Also, it uses the laser scanner to detect the elevator door state. Kunze et. al. [2] using a personal robot 2 (PR2) to carry out search-and-fetch objects and delivery tasks, where it need to take elevator to finish the delivery task. Pratkanis et. al. [3] present a robot system can navigates through an unmodified campus and deliver coffee. In this work, the robot can take the elevator to navigate in an unmodified environment autonomously. Inspired by [3], Troniak et. al. [4] also using PR2 to complete a navigation task between floors, which present some algorithm to detect elevator button and a state machine for task planning, where it discusses some issue not easy to address such as 2d maps alignment problem, presence of door, transparent and reflective surfaces. Zhang et. al. [5] presents a hierarchical path planner for robot navigating in multi-storey buildings,

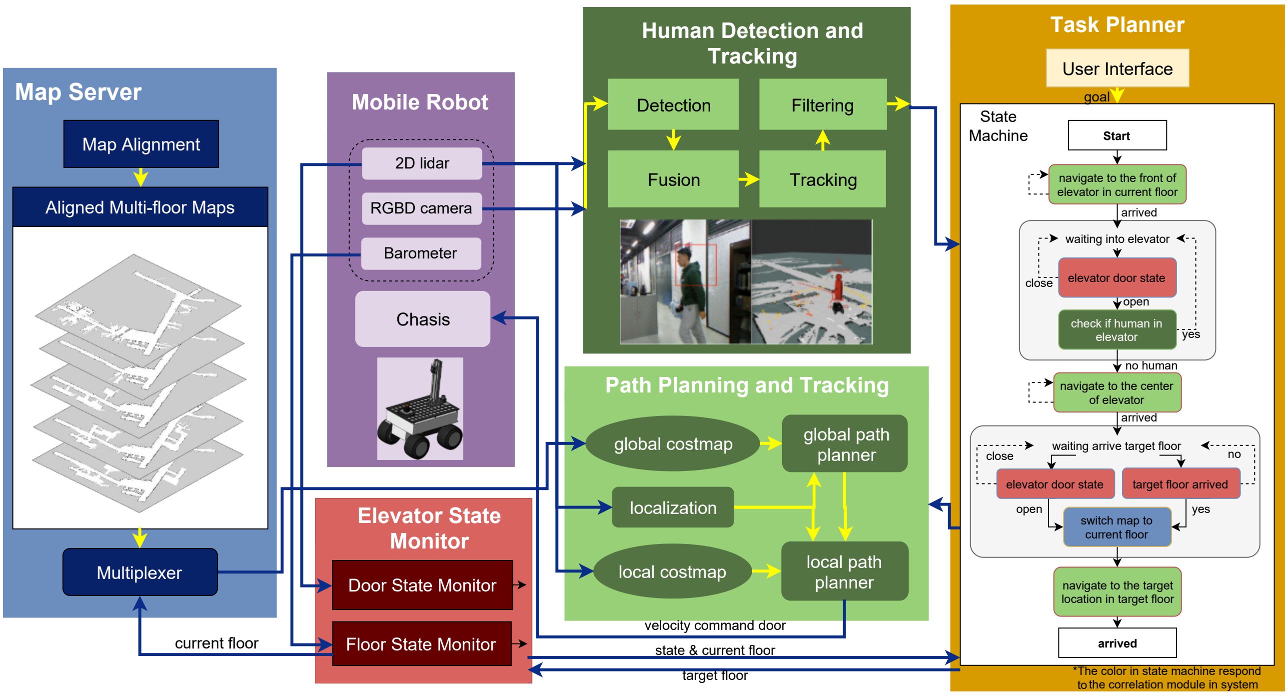


Fig. 2. System overview. Mobile Robot module is the robot with common sensors. Task Planner receiving target and decomposing mission. Map Server provide pre-made aligned map for system. Elevator State Monitor detect the elevator door state and current floor of elevator. Human Detection and Tracking module provide the human location information to keep safe. Path Planning and Tracking module charge for robot localization plan the moving action.

where they mark the staircase as transition point, where the robot can navigate to another floor by climb up stairs. And in recent years, Khandelwal et. al. [6] introduce a novel multi-robot platform with human-robot interaction, where the robot can understand human language requests and recognize human motion. With the multi-map server, it enables the robot to navigate in a building between different floor. Abudulla et. al. [7] presents a mobile robots can control the elevator with after modified the elevator system to transport between multiple floors. where the robot can derive the current floor it locates by pressure sensor. Our goal is similar with the previous works, but inspired by the social-aware robots [8] [9]. Compared with previous works, we consider the human-awareness in our system, and we give out and illustrate the details of our frameworks, present the concise and robust method in elevator state monitoring, and introduce an map alignment algorithm with multi-map server, make the transition between multi-floor more safe and robust.

III. Approach

Figure 2 illustrates the framework of out robotic system. The system is divided into six parts, including mobile robots hardware, task planner, elevator state monitor, map server, human detection and tracking, path planning and tracking modules.

The mobile robots module is the hardware part of the system with chassis and some common sensors include 2D lidar, RGBD camera, barometry, odometer. The task planner decomposes complete mission into many states, requesting information from different modules and control the subtask for robot to execute. The robot can arrive the destination set by user interface after finishing the transformation though all the states . The elevator state monitor contains door state and floor state monitor, in charge of monitoring elevator door open or close by processing the information of laser scanner, and the current level of elevator from the barometer respectively. The map server module provides the pre-made map information of current floor by multiplexer according to the message from the floor state monitor. The human detection and tracking module detect and track multiple pedestrian near the robot according the vision information from RGBD camera. The path planning and tracking divided into two stages. In the global stage, planner makes use of pre-made map information published by map server, searching for global path to a destination in current floor. In the local stage, the planner derives linear and angular velocities command and executed by the robot to follow the global path while avoiding obstacles detected by laser scanner. The human detection and tracking module make use of RGBD camera and lidar information, detect then track pedestrian in building to ensure navigation strategy safe enough.

A. Task Planner

Every module in system corresponding to some actions of mobile robots. For the navigation mission in building is a complex and high-level task that can be divide into many states, each state comprises of one or more subtasks with actions. We integrate these states and subtasks by using the hierarchical state machine to control the tasks transition.

The state machine we proposed is illustrated in Figure 2, each subtask marked by the color of corresponding module, and can basically split into the five sub-states sequences as follow:

1) Navigate to the front of elevator in current floor.
2) Wait for elevator arrive current floor.
3) Navigate inside the elevator.
4) Taking elevator until arrive target floor.
5) Navigate to the destination in target floor.

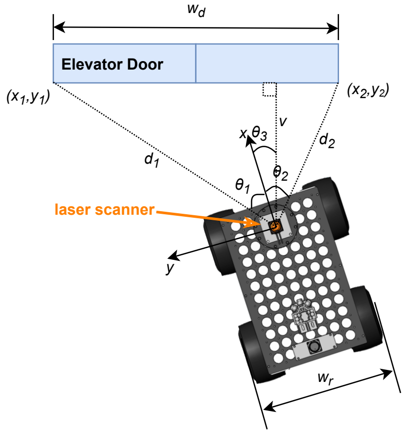


Fig. 3. Elevator door state monitor.

B. Elevator state monitor

As shown in Figure 2, the elevator state monitor contains two sub function modules, monitoring the door state and elevator floor state respectively.

For the illumination changed rapidly while the elevator door opening and closing, the door state will be hard to detect by the camera. Consider the location and the shape of elevator door is known by the robot from pre-made map, we use 2D laser scanner to check whether elevator door is opened or closed stably, and is illustrated in Figure 3, can be computed as follows:

$$\theta_1 = \arctan(y_1/x_1) \qquad \theta_2 = \arctan(y_2/x_2) \tag{1}$$

$$\theta_3 = \theta_2 + (\frac{\pi}{2} - \arccos(\frac{l^2 + d_2^2 - d_1^2}{2ld_2})) \tag{2}$$

$$v = |d_2 * \cos(\theta_2 - \theta_3)| \tag{3}$$

$$\gamma = \frac{\sum_{i=\theta_2}^{\theta_1} sgn(l_i * |\cos(i)| - v - 0.15)}{\sum_{i=\theta_2}^{\theta_1} 1} \tag{4}$$

$$\sigma = 1.2 * w_r / w_d \tag{5}$$

where θ_1 and θ_2 compose the range of laser ray angle that can detect the elevator door. θ_3 is the angle between the line of v and the forward of robot. v is the vertical distance from the laser scanner to the elevator door in meter, which is used to be the minimum distance compare with the other laser data l_i. γ is the door opened level in the range of 0 to 1, and we subtract 0.15 as the thickness of door for removing noise from laser scanner. σ is the threshold, calculated by w_d and w_r corresponding to the width of door and the robot respectively. The door state can be determined by comparing the γ and σ. When γ is larger than σ, means the elevator door is opened, v.v.

For elevator floor state monitor, considering the illumination in elevator changed rapidly and various for different elevator, the view of visual sensor is easy interrupted when there are other people in elevator, and the elevator floor indicator location and pattern also have great differences for diverse elevator. To make the robotic system can easy implemented and adapt to most of environment and robots, we use the barometer (air pressure sensor) to detect the current located floor while the robot inside the elevator. The barometer is sensitive to the change of altitude that have enough resolution to distinguish continuous floors, but have the shortcoming of wide range daily pressure variation [7] in the same place because of the change of temperature, humidity, etc. To overcome this shortcoming, we present a state correlate floor monitor, as presented in Figure 4.

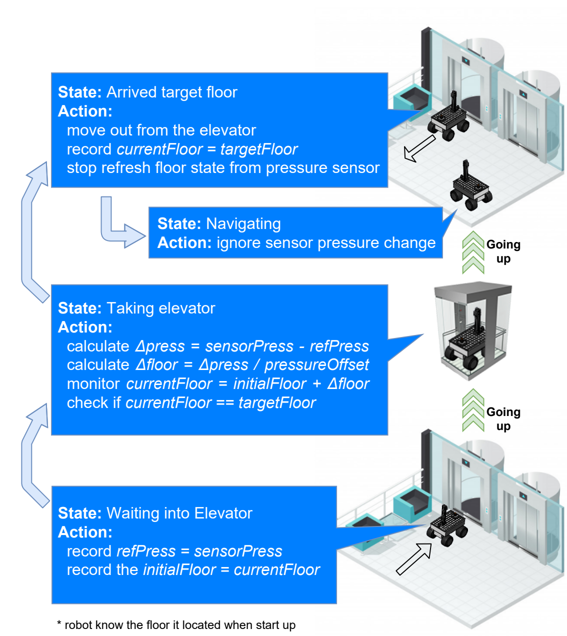


Fig. 4. Elevator floor state monitor.

the $pressureOffset$ need to be determined through experiment and will be mention in section IV.

C. Map server

To complete the navigation task autonomously between different floor in a building, the robot need to store the maps of multiple floors, plan global path from a pre-made map in current floor, transfer and locate itself after taking the elevator to the target floor, so we need to have a map server that use to provide the pre-made maps data for robot to navigate, but traditional standard map sever is design for single floor navigation and only provide single floor data, which is not sufficient for such situation. Here we present an improved approach of map server with a

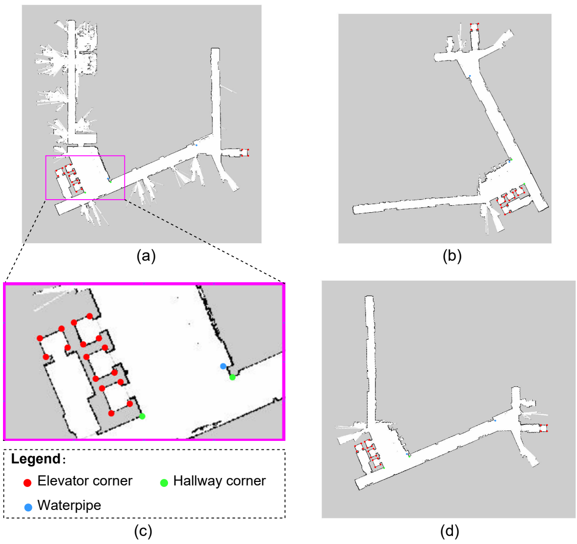


Fig. 5. Map align example: (a) target align map, (b) feature points with legends, (c) the map needs to align, (d) map after align.

multiplex mechanism similar with [6] and multi 2D maps align algorithm to solve multiple maps problem.

For standard map server merely store and provide single floor data, it need to restart server while the robot taking elevator arrive different floor, that will cause the map server break down for a short period before the new map server startup. As a result, it will cause the system create error of no useful map and bring extra instability to the system. With multiplex mechanism as shown in Figure 2, the map server pre-load all the map in the same building, republish the specific map data according to the command send by elevator state monitor. For the republish process with no latency, the break down problem cause by standard map server be overcome by using the multiplex mechanism, and it enable the map server display the maps of whole building simultaneously, which is crucial for multi-robot application in the same building.

In navigation part, the pre-made maps is used to estimate drivable path in an environment, those maps in map server can be built by using laser-based simultaneous localization and mapping (SLAM) algorithms such as Cartographer [10], Gmapping [11] or build by 3D vision-based algorithms. For environment inside the building, the surface is on the same level and the feature is more consistence in height compared with outdoor, 2D SLAM is efficient and sufficient to complete the navigation task for wheel robots, so we use 2D SLAM algorithm[11] to build our maps. For 2D SLAM need to build multiple maps for each floor in building separately, maps in different floor will not align with each other which cause the transition between multiple maps and semantic marking tediously. Here we align the maps of multi-floor by choosing the feature points in different floor, the feature points consist of those points pass through the same place between multiple floors, such as elevator corner, waterpipe, hallway corner which shown in Figure 5. Then by using particle swarm [12] optimization algorithm, the transformation relation between maps can be computed and the optimization algorithm is as follows.

For feature points chosen from the map needs to rotate, have the following linear transformation

$$\begin{bmatrix} \hat{x}_i \\ \hat{y}_i \\ 1 \end{bmatrix} = \begin{bmatrix} \cos\alpha & \sin\alpha & \delta_x \\ -\sin\alpha & \cos\alpha & \delta_y \\ 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} x_i \\ y_i \\ 1 \end{bmatrix} \tag{6}$$

where the x_i and y_i is the feature point of the map needs rotate, $\overline{x_i}$ and $\overline{y_i}$ is the feature point of target map, α is the parameter of rotation, δ_x, δ_y are the translation parameters.

Can define the cost

$$J(\alpha,\delta) = \sum_{i=1}^{N}\left((\hat{x}_i - \overline{x_i})^2 + (\hat{y}_i - \overline{y_i})^2\right) \tag{7}$$

N is the number of feature points.

To optimize the objective as

$$\min J(\alpha,\delta) \tag{8}$$

$$s.t. -\pi \leq \alpha < \pi \tag{9}$$

$$-2\lambda_x \leq \delta_x \leq 2\lambda_x \tag{10}$$

$$-2\lambda_y \leq \delta_y \leq 2\lambda_y \tag{11}$$

where λ_x and λ_y are the resolution of the map along the x-axis and y-axis respectively.

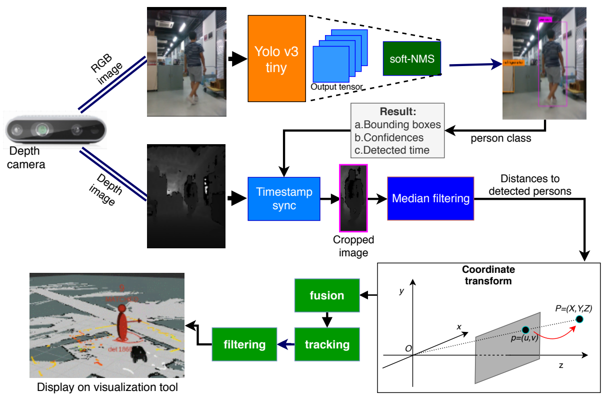


Fig. 6. Detection and tracking pipeline.

D. Human detection and tracking

There are frequent human activities inside the buildings, which needs the robot sensing and avoiding people while navigate to ensure human safe and keep human activities normally. In this paper, we use the pedestrian detection and tracking framework proposed by [13], which present a complete pipeline composed of four sub-module: people detection, multi-sensor fusion, tracking, filtering module. And we deploy the detection module with YOLO-v3 tiny [14], a state of art lighten convolutional neural networks based detection algorithm and train with Pascal VOC data sets [15], to enhance the stability of the human detection and tracking module. The pipeline of this module is illustrated as Figure 6. The detection and tracking result as shown in Figure 1(b)(c).

E. Path planning and tracking

The path planning and tracking module follow the design of ROS navigation stack and divided into 5 sub-modules. In this paper, we use adaptive monte carlo localization (AMCL) [16] for the localization, layered costmap [17] for global and local costmap, djikstra's algorithm for global planner, timed-elastic-band trajectory optimization [18] method for local planner sub-module. This module start with the global desired destination appointed by state machine. Then use global planner to plan the high-level path to destination upon global costmap. Finally, the local planner output velocity command for robot chassis based of local costmap and global path, which ensure the robot approximate follow the global while avoiding obstacle.

IV. Experiment

To verify the mobility of the proposed robotic system, we first label the maps need to navigate with feature points as Figure 5(a), here we choose third and ninth floor for experiment. Then start to derive the alignment parameters $(\alpha, \delta_x, \delta_y)$. For PSO algorithm, we specify the upper bound $(-\pi, -4000; -4000)$ and the lower bound $(\pi, 4000, 4000)$ with 100 particles. The variation of objective function value as shown in Figure 7. Can see the value decrease rapidly in the beginning but stop decreasing before it almost reaches the zero. For the feature points were chosen manually, and the map error cause by SLAM, which is normal for the Because of the normal feature points error by manual label and the map error during SLAM. After optimization, the two map succeed align as Figure 10.

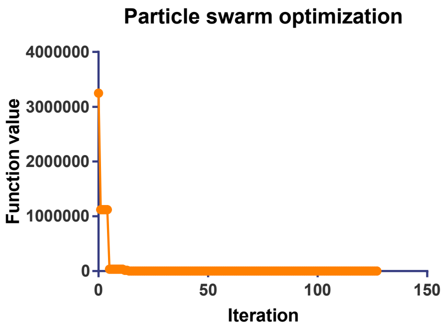


Fig. 7. Derive translate value for map alignment by PSO.

For the elevator state monitor, the pressure offset between two continuous floors needs to be obtain. We use the mobile robot to take elevator six times in different day through a month as Figure 8. Can prove the basic pressure will change daily, but the difference of two continuous floors remain constant with some sensor error. Also, the barometer can distinguish two continuous floors. After pressure variation experiment, we choose 48Pa as the pressure offset between continuous floors. And we validate the elevator door state monitor while the robot inside and outside the elevator as Figure 9, experiment shown that the elevator door state can be detecting in real time (affected by the scanning rate of

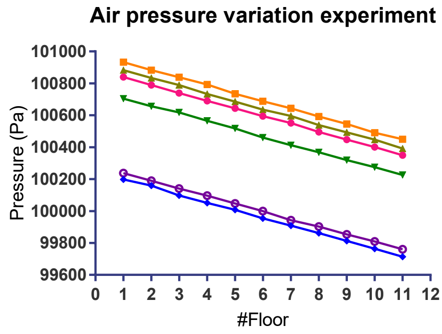
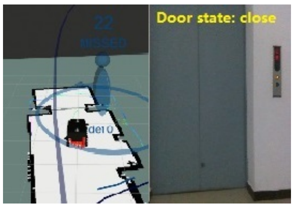


Fig. 8. Air pressure variation due to floor change in different day.

laser scanner, but for most of 2D scanner have scanning rate larger than 10Hz) and stable by using our algorithm with 2D laser scanner.



(a)

(b)

(c)

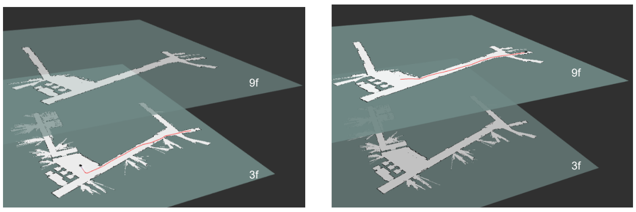
(d)

Fig. 9. Door state monitor experiment. the left side of subfigure is the view of visualization tool, the right side is the view of robot. (a) and (b) shown robot outside the elevator, can check the door is closed and opened respectively, Robot in (c) and (d) is inside the elevator, check the door is closed and opened.

Finally, we test our system between third and ninth floor of the building G at the Harbin Institute of Technology, Shenzhen. The whole system implements based on robot operating system (ROS) in a wheel mobile robots equipped with two laser scanners and a front depth camera as Figure 1(a). As shown in our demonstration video, the robot navigates to elevator like Figure 10(a), taking elevator while it is empty, and navigate to the destination in target floor like Figure 10(b). The robot can distinguish each floor clearly while taking elevator, and will not move out the elevator until it arrives target floor.

V. Conclusion

In this paper, we propose a human-aware robotic system, make the common wheel mobile robot can fully navigate in a multi-floor building by taking the elevator with human pressing buttons. The system we propose leverages the advanced



(a) (b)

Fig. 10. Multi-floor navigation experiment. Robot in (a) carry on navigation task to the elevator in 3rd floor, (b) is navigating to destination in 9th floor.

CNN object detect algorithm to improve the human detection and tracking module, which make the robot can take elevator safely. With the elevator state monitor we present, the robot can take the elevator more stable. And we further investigate the maps align method to make the transition of robot more intuitive for user. The system was final implemented by ROS in a wheel robot and performs as expected as the robot can navigate stably and safety from floor to floor in experiment.

REFERENCES

[1] Jeong-Gwan Kang, Su-Yong An, and Se-Young Oh. Navigation strategy for the service robot in the elevator environment. In *2007 International Conference on Control, Automation and Systems*, pages 1092–1097. IEEE, 2007.

[2] Lars Kunze, Michael Beetz, Manabu Saito, Haseru Azuma, Kei Okada, and Masayuki Inaba. Searching objects in large-scale indoor environments: A decision-theoretic approach. In *2012 IEEE International Conference on Robotics and Automation*, pages 4385–4390. IEEE, 2012.

[3] Anthony Pratkanis, Adam Eric Leeper, and Kenneth Salisbury. Replacing the office intern: An autonomous coffee run with a mobile manipulator. In *2013 IEEE International Conference on Robotics and Automation*, pages 1248–1253. IEEE, 2013.

[4] Daniel Troniak, Junaed Sattar, Ankur Gupta, James J Little, Wesley Chan, Ergun Calisgan, Elizabeth Croft, and Machiel Van der Loos. Charlie rides the elevator–integrating vision, navigation and manipulation towards multi-floor robot locomotion. In *2013 International Conference on Computer and Robot Vision*, pages 1–8. IEEE, 2013.

[5] Qun Zhang, Xiaojun Wu, Bingbing Liu, Albertus Hendrawan Adiwahono, Tran Anh Dung, and Tai Wen Chang. A hierarchical topological planner for multi-storey building navigation. In *2015 IEEE International Conference on Advanced Intelligent Mechatronics*, pages 731–736. IEEE, 2015.

[6] Piyush Khandelwal, Shiqi Zhang, Jivko Sinapov, Matteo Leonetti, Jesse Thomason, Fangkai Yang, Ilaria Gori, Maxwell Svetlik, Priyanka Khante, Vladimir Lifschitz, et al. Bwibots: A platform for bridging the gap between ai and human–robot interaction research. *The International Journal of Robotics Research*, 36(5-7):635–659, 2017.

[7] Ali A Abdulla, Hui Liu, Norbert Stoll, and Kerstin Thurow. An automated elevator management and multi-floor estimation for indoor mobile robot transportation based on a pressure sensor. In *2016 17th International Conference on Mechatronics-Mechatronika*, pages 1–7. IEEE, 2016.

[8] Rudolph Triebel, Kai Arras, Rachid Alami, Lucas Beyer, Stefan Breuers, Raja Chatila, Mohamed Chetouani, Daniel Cremers, Vanessa Evers, Michelangelo Fiore, et al. Spencer: A socially aware service robot for passenger guidance and help in busy airports. In *Field and service robotics*, pages 607–622. Springer, 2016.

[9] Nick Hawes, Christopher Burbridge, Ferdian Jovan, Lars Kunze, Bruno Lacerda, Lenka Mudrova, Jay Young, Jeremy Wyatt, Denise Hebesberger, Tobias Kortner, et al. The strands project: Long-term autonomy in everyday environments. *IEEE Robotics & Automation Magazine*, 24(3):146–156, 2017.

[10] Wolfgang Hess, Damon Kohler, Holger Rapp, and Daniel Andor. Real-time loop closure in 2d lidar slam. In *2016 IEEE International Conference on Robotics and Automation*, pages 1271–1278. IEEE, 2016.

[11] Giorgio Grisetti, Cyrill Stachniss, Wolfram Burgard, et al. Improved techniques for grid mapping with rao-blackwellized particle filters. *IEEE Transactions on Robotics*, 23(1):34, 2007.

[12] Russell Eberhart and James Kennedy. A new optimizer using particle swarm theory. In *Proceedings of the Sixth International Symposium on Micro Machine and Human Science*, pages 39–43. IEEE, 1995.

[13] Timm Linder, Stefan Breuers, Bastian Leibe, and Kai O Arras. On multi-modal people tracking from mobile platforms in very crowded and dynamic environments. In *2016 IEEE International Conference on Robotics and Automation*, pages 5512–5519. IEEE, 2016.

[14] Joseph Redmon and Ali Farhadi. Yolov3: An incremental improvement. *arXiv preprint arXiv:1804.02767*, 2018.

[15] M. Everingham, L. Van Gool, C. K. I. Williams, J. Winn, and A. Zisserman. The pascal visual object classes (voc) challenge. *International Journal of Computer Vision*, 88(2):303–338, 2010.

[16] Dieter Fox, Wolfram Burgard, Frank Dellaert, and Sebastian Thrun. Monte carlo localization: Efficient position estimation for mobile robots. *AAAI/IAAI*, 1999(343-349):2–2, 1999.

[17] David V Lu, Dave Hershberger, and William D Smart. Layered costmaps for context-sensitive navigation. In *2014 IEEE International Conference on Intelligent Robots and Systems*, pages 709–715. IEEE, 2014.

[18] Christoph Rösmann, Frank Hoffmann, and Torsten Bertram. Integrated online trajectory planning and optimization in distinctive topologies. *Robotics and Autonomous Systems*, 88:142–153, 2017.