Robot-Elevator Interaction Through IoT Devices for Autonomous Robot Multi-floor Transition

Zhi Song
School of Mechanical and Aerospace Engineering
Nanyang Technological University
Singapore
zhi005@e.ntu.edu.sg

Runjia Tan
School of Mechanical and Aerospace Engineering
Nanyang Technological University
Singapore
runjia.tan@ntu.edu.sg

Shanhe Lou
School of Mechanical and Aerospace Engineering
Nanyang Technological University
Singapore
shanhe.lou@ntu.edu.sg

Chen Lv
School of Mechanical and Aerospace Engineering
Nanyang Technological University
Singapore
lyuchen@ntu.edu.sg

2024 10th International Conference on Electrical Engineering, Control and Robotics (EECR) | 979-8-3503-7000-3/24/$31.00 ©2024 IEEE | DOI: 10.1109/EECR60807.2024.10607245

***Abstract*—Navigating between floors in a building poses a traditional challenge for robots, often involving manual efforts or complex solutions. This paper addresses the inherent problems focusing on Autonomous Mobile Robots. Presented here is an innovative method for automating conveyor systems, specifically elevators, to facilitate the seamless integration of AMRs into various operations. The proposed robot-elevator integration solution employs a flexible system and an IoT actuator kit that easily integrates with existing elevators, ensuring compatibility with the system already in place. Utilizing imaging sensors and machine learning for real-time object recognition, the system autonomously responds to AMRs in different zones. Proof-of-concept results demonstrate the feasibility and advantages of the proposed approach in terms of safety and operational efficiency.**

***Index Terms*—Robot-elevator interaction, autonomous mobile robot, multi-floor navigation, object recognition, Internet of Things (IoT), adaptable system**

I. Introduction

Autonomous Mobile Robots (AMRs) have become essential in numerous aspects of everyday life, industry, and services. Their applications span from last-mile delivery and service roles in buildings to surveillance and logistics [1]. The growing prevalence of AMRs is attributed to their ability for autonomous navigation and task execution, effectively reducing labor intensity and enhancing productivity.

In many instances, AMRs are employed in environments with multi-floor operations, such as hospitals, offices and warehouses. The effective deployment of AMRs into such complex settings presents challenges [2], particularly in navigating between different floors and utilizing elevators. A key issue lies in the reliance on manual steps for elevator operations, where human assistance is often required to open doors, select destination floors, and facilitate smooth transitions for AMRs. The manual involvement introduces inefficiencies and safety concerns, especially in elevators where humans and robots coexist.

Moreover, existing solutions such as implementing remote control interfaces face practical limitations. Upgrading elevator infrastructure can be cost-prohibitive and may not be feasible for older elevators, limiting the applicability of AMRs in a wide range of environments. Additionally, diverse elevator designs and button layouts compound challenges for AMRs to autonomously recognize and interact [3]. These issues collectively impede the integration of AMRs with elevators, hindering the realization of autonomous floor-to-floor mobility. Addressing them is crucial for unlocking the full spectrum of AMR applications in diverse vertical spaces.

Motivated by identified limitations and driven to achieve seamless autonomy for AMRs, this paper proposes an innovative solution for AMR-elevator integration, focusing on efficient multi-floor navigation. The unique system presented makes key contributions, featuring a novel vision-based recognition system, configurable add-on actuators, and a carefully designed workflow for smooth coordination between elevator operation and AMR movement. This approach enhances AMR autonomy and addresses practical challenges in diverse elevator systems. The paper is structured as follows: Section 2 provides insights into related studies. Section 3 elaborates on the methodology, covering system architecture and components. In Section 4, the proof-of-concept experiment is introduced, along with a discussion of results and observations. The concluding section summarizes findings and outlines potential future research.

II. Related Work

A. Multi-floor Navigation

Navigating through multi-floor environments for autonomous mobile robots involves a series of distinct tasks when interacting with elevators [4]. Initially, the robot must

This study is supported under the RIE2020 Industry Alignment Fund - Industry Collaboration Projects (IAF-ICP) Funding Initiative, as well as cash and in-kind contribution from the industry partner(s).

navigate to the elevator hall, recognize and manipulate the button outside the elevator, wait for the door to open, board the elevator, locate and press the desired floor button, exit the elevator, and finally proceed to the destination on the target floor. This structured flow serves as the foundation for efficient multi-floor navigation. In the realm of the aforementioned tasks, studies often propose cross-floor navigation systems that integrate robot localization, path planning, and utilize the Robot Operating System (ROS). A decision system can be adopted to switch maps for the current floor, employing methods like deep convolutional neural networks [5].

B. Robot-Elevator Interaction

1) Control Panel Recognition: The initial steps of a mobile robot in using an elevator involves recognizing the elevator's buttons and pressing them to call for transportation to another floor. Various methodologies have been proposed on the recognition of buttons and panels. These include approaches using vision algorithms and machine learning, such as optical character recognition (OCR) for button text identification [6], a color-independent contour-based detection approach [7], and a framework utilizing connective-region-based methods and convolutional neural networks [8]. Common limitations across the studies include challenges related to diverse elevator designs [9], variations in lighting conditions [10], and the potential difficulty in detecting elevator buttons due to the small size and complex backgrounds.

2) Remote Control by Wireless Communication: Physically pressing buttons on elevator panels is limited to robots equipped with robotic manipulators. An alternative approach requires access to elevator control system with remote capabilities, utilizing wireless communication for elevator interaction. Ge et al. [11] present an agent-supervised model enabling robotic mobility by developing an IoT-open elevator with ROS-based communication flows. Zhang et al. [12] focus on Modbus TCP protocol to facilitate communication between the elevator's control system and a handling robot, enhancing three-dimensional material transportation in industrial settings without modifying elevator infrastructure.

3) Remote Button Press by External IoT Devices: In contrast to remote control methods, Palacin et al. [13] introduce an distinct solution using an add-on IoT device [14]. This device, uniquely designed for non-intrusive attachment over the original elevator button panel, allows remote elevator control through the building's local area network (LAN). Unlike other IoT devices requiring mechanical or electrical modifications, this solution seamlessly integrates with existing elevator infrastructure. While the mobile robot typically requires additional functions for wireless communication with the IoT device, practical constraints may limit robot modifications in certain applications.

4) Current Floor Detection: Apart from button recognition, determining the current floor in a multistory environment is crucial. Extending computer vision approaches used for button recognition to floor number recognition shows optimistic performance for service robots [10]. Abdulla et al. [15] propose a new system utilizing pressure sensors for floor estimation and door status determination. Krejsa et al. [16] achieve high detection success by combining relative floor changes from an accelerometer with absolute floor numbers detected in vision.

5) Human's Presence in the Operation: Moreover, various studies underscore the significance of human involvement in interactions between autonomous mobile robots and elevators, prompting researchers to enhance workflow and safety in the presence of humans [17]. As we devise a robot-elevator integration methodology, leveraging these findings will contribute to creating a system that adeptly navigates multi-floor environments while prioritizing user safety and robot-human harmony.

III. Methodology

A. Robot-Elevator System Overview

The presented methodology is designed to improve the capabilities of AMRs in vertical mobility, specifically addressing the challenges associated with automating conveyor systems for transporting AMRs within multistory environments. While the methodology is applicable to various conveyor systems, the paper primarily emphasizes enhancing the interaction between AMRs and elevator systems to foster seamless integration.

Focusing initially on the two-story environments, the solution integrates two specialized sensors for visual perception, three mechanical actuators on elevator panels facilitating control actions, and a central control unit hosts vision software and control interfaces. This serves as an introductory example to illustrate the methodology, yet the entire approach is designed to be universally applicable to more complex multistory scenarios. Fig. 1 provides an overview of the system architecture for a two-story application, with cameras symbolizing sensors and Fingerbots representing actuators.

The method utilizes two sensors for real-time monitoring: one observes the AMR waiting zone at the elevator lobby, and the other oversees the elevator cabin. Upon detecting the AMR, the controller initiates a sequence where an actuator activates the elevator, ensuring the AMR's safe entry and exit. Continuous monitoring and actuation maintain control, allowing smooth vertical movement and safe progression through the elevator system.

Safety is ensured through imaging sensors and a machine learning model, providing detailed system feedback and precise object detection, including AMRs and humans. The methodology's adaptability is a key strength, seamlessly integrating with diverse elevator systems using a mechanical actuator, minimizing the need for extensive reprogramming or system modifications. It offers a practical solution for efficient deployment across diverse elevator infrastructures.

B. Vision-Based Recognition

The imaging sensors proposed in the methodology refers to a vision-based recognition system. This system is equipped with IP cameras inside and outside the elevator cabin, employing advanced computer vision techniques. The vision software loaded in the host control unit, is designed with intelligence

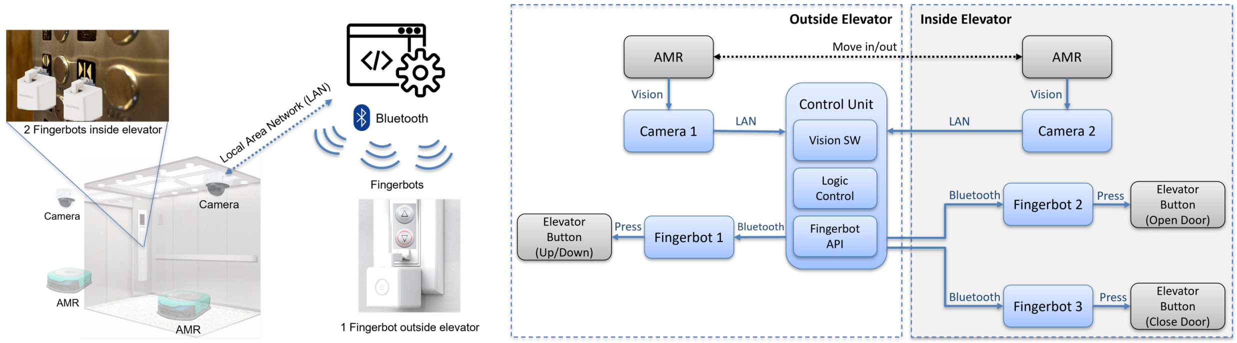

Fig. 1. System overview of the proposed methodology for a two-story AMR application (camera - sensor, Fingerbot - actuator)

of object recognition, to detect the presence and position of the AMR. The object recognition approach is based on a template-based model which can detect the new and unknown object without re-training by utilizing several template images [18]. Template images of the object with various views are to be captured as the input for the NeRF (Neural Radiance Fieldview) synthesis process. The resulting synthesized views, derived from these new templates, act as extensions to enhance the detector's generalizability across various viewpoints. It then leverages a multi-scale convolutional neural network to learn the correlation between the template and the captured image to propose several possible bounding boxes, then a similarity evaluation model is utilized to find out the most possible one as the final detection result. This machine learning model facilitates object recognition to detect AMRs and other relevant objects, ensuring real-time feedback for needed information from the monitored zones.

C. Remote Button Pressing with Fingerbot

A key hardware component, the mechanical actuator, serves as the link between the virtual and physical realms of elevator control. These actuators can be selected from IoT devices, for instance, Fingerbot. They are strategically positioned next to elevator control buttons, enabling remote operation via wireless communication such as Bluetooth. The actuator units can be triggered to press the designated control button, correspondingly initiating the elevator's actions. This add-on hardware components allows for precise and controlled interactions with the elevator system, without the need to access the inner circuit or software of the elevator system. Additionally, the device provides a separate touch-button interface for manual presses as an option, ensuring that it doesn't impede manual usage by other users.

D. Host Control Unit

The host Control Unit serves as the central intelligence hub orchestrating the seamless integration of hardware and software components. Housed within this unit is the machine learning model, a pivotal element for advanced object recognition. The Control Unit receives video signals from the vision system, processed over a wireless LAN, and makes real-time decisions based on the AMR's state. It dictates the operational logic, ensuring precise control actions, such as the pressing and holding of elevator buttons through the Fingerbot. The host Control Unit is the brain behind the adaptive and secure operation of the elevator system, making it a crucial component in the proposed methodology. For optimal data communication quality, installing a dedicated Control Unit for each floor is recommended. This approach helps mitigate potential signal interference issues that could arise when using a single Control Unit for multiple floors, ensuring reliable wireless communication with the Fingerbots.

E. Operation Procedure and Multi-Floor Expansion

The step-wise procedure illustrates the controlled and secure transportation of AMRs within a confined space. A typical two-story operation scenario is detailed in Fig. 2:

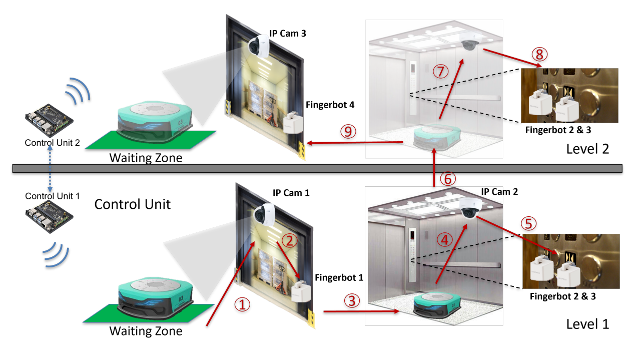

Fig. 2. Workflow for a two-story AMR application
1) AMR at waiting zone 2) AMR detected and Fingerbot 1 opens Elevator door 3) AMR moves into Elevator 4) AMR status monitored 5) Fingerbot 2 closes door 6) Elevator moves to upper level 7) AMR and Elevator status monitored 8) Fingerbot 3 opens door 9) AMR exits Elevator

The adaptability of the proposed methodology extends to multi-floor scenarios. With the vision-based recognition system and remote button-pressing capabilities as the universal approach, the elevator system can seamlessly navigate between different levels, accommodating the vertical mobility needs of AMRs.

In the context of multi-floor expansion, certain adjustments are needed for the proposed approach. Firstly, the increased number of floors demand additional Fingerbots to accommodate the expanded array of options, ensuring the capability to access buttons on different floors. Secondly, a strategic framework is devised to enable the AMR to comprehend the current arrived floor number. This crucial piece of information forms the basis for the AMR's decision-making process, determining whether it should exit the elevator at the current floor or continue its vertical journey. To achieve this, the vision recognition system is extended to monitor and identify the displayed floor number from the elevator. The recognized floor number is then transmitted to the host for determining the stay or exit.

IV. Experiment

The initial experiment was conducted through a proof-of-concept, with the primary goal of assessing the feasibility and functionality of the developed approach in a real-world setting. This chapter presents the details and a demonstration of the proposed method.

A. Experimental Setup

The proof-of-concept demonstration took place in a multi-floor university research building, focusing on a two-story scenario. An AMR prototype, two webcams for vision-based monitoring, three IoT Fingerbots (Fig. 3) for remote elevator control, and a laptop as the host controller were strategically positioned. A universal four-wheel AMR navigated between floors, while webcams and Fingerbots facilitated vision-based monitoring and remote elevator control. The demonstration involved the AMR traveling from level 3 to level 2, showcasing the system's capabilities in a simplified scenario. In real deployment, dedicated controllers for each floor would ensure stable network communication.

Fig. 3. Fingerbots as add-on actuator attached to the elevator buttons

B. Implementation

Building on the proposed methodology, the proof of concept incorporates a real-time detection algorithm for AMR recognition. This template-based vision technique is versatile, allowing it to be applied to various types and brands of AMRs without the requirement for pre-training. The vision system comprising web cameras detects the AMR's presence and position. Remote elevator control button pressing is executed by triggering Fingerbots through the Bluetooth protocol. The host computer determines actions based on input information derived from camera views and its recognized AMR states.

The operational procedure implemented for the demonstration is outlined in accordance with the established workflow illustrated in Fig 2, incorporating a customized configuration for transitioning from level 3 to 2.

C. Results

In the demonstration, the detailed procedures are classified into four AMR tasks. For each task, specific checkpoints were established to monitor and assess the completion and success of key actions (Table I). The primary focus was on determining whether each checkpoint within a task was executed and completed (indicated as "Completed") and if the associated actions were correct and successful (indicated as "Successful"). This structured approach allowed us to systematically evaluate the effectiveness and efficiency of the proposed methodology at a granular level.

TABLE I
Results of the two-story use case demonstration

Tasks and Checkpoints	Completed	Successful
1. Elevator Call		
1.1 AMR detected at waiting zone	Yes	Yes
1.2 AMR initiates elevator call	Yes	Yes
1.3 Elevator arrived at AMR's level	Yes	Yes
2. Entering Elevator		
2.1 Elevator door opening	Yes	Yes
2.2 AMR enters the elevator	Yes	Yes
3. Floor Selection		
3.1 Button pressing for selected floor	Yes	Yes
3.2 Elevator transits to selected floor	Yes	Yes
4. Exiting Elevator		
4.1 Elevator door opening	Yes	Yes
4.2 AMR exits the elevator	Yes	Yes

The outcome of the two-story use case demonstration (Fig. 4) confirms the practicality and efficiency of the proposed methodology in seamlessly integrating AMRs with elevator systems. The implemented vision-based recognition system demonstrated significant capability, accurately detecting the AMR's presence at the waiting zone for initiating elevator calls, and monitoring its status within the elevator cabin. Notably, the vision approach demonstrated its adaptability by successfully recognizing an unknown AMR model without the need for pre-training, emphasizing its efficiency in real-world scenarios. The controlled and precise operation of Fingerbots further contributed to the success of each task, showcasing their ease of use and effectiveness in activating elevator buttons. The designed workflow, particularly the measure of holding the door open until the AMR reaches its target zone, ensured safe and efficient entry and exit from the elevator. The completion of each checkpoint underscores the meticulous design and practicality of the technical solutions implemented. The overall success of the demonstration highlights the feasibility of the proposed methodology and sets the foundation for future developments and refinements.

D. Challenges and Considerations for Future Works

While the presented methodology demonstrates promising results, certain limitations and challenges were identified during the experiment. Addressing these issues provides avenues for future research and solution refinement.

Fig. 4. Two-story (level 3 to 2) use case demonstration

Scaling to tall buildings with numerous floors poses a challenge, requiring exploration of alternative button control mechanisms for efficient multi-button triggering. Seamless integration into environments with human occupants necessitates enhanced object recognition. This ensures precise AMR actions amidst multiple users exiting at different levels.

Addressing security measures, such as access card verification, requires additional design considerations. To mitigate IT security concerns, exploring alternatives like RFID systems may be crucial in industrial areas with strict data protection requirements. In enclosed environments like elevator cabins, communication challenges may arise, demanding solutions for reliable data exchange, potentially during the elevator door's open phase. Additionally, RFID tagging offers a direct and reliable alternative to vision recognition, particularly in routine scenarios with consistent entities.

V. Conclusion

The presented methodology seamlessly integrates AMRs with elevator systems, enhancing multistory mobility. Demonstrating successful two-story use, this approach utilizes a vision-based system and Fingerbots, eliminating manual interventions and opening new AMR application possibilities. The theoretical implication emphasizes adaptability, providing a practical foundation for AMR integration with vertical transportation systems. While acknowledging challenges, such as scalability and security, the study suggests exploring alternative actuation mechanisms and enhancing object recognition for future research. Refining and expanding the methodology will contribute to unlocking the full potential of robotic mobility in multistory environments.

References

[1] S. S. Alam, T. Ahmed, M. S. Islam, and M. M. F. Chowdhury, "A Smart Approach for Human Rescue and Environment Monitoring Autonomous Robot," *International Journal of Mechanical Engineering and Robotics Research*, vol. 10, no. 4, pp. 209–215, 2021.

[2] N. T. Thinh, T. P. Tho, and N. D. X. Hai, "Adaptive Fuzzy Control for Autonomous Robot under Complex Environment," *International Journal of Mechanical Engineering and Robotics Research*, vol. 10, no. 5, pp. 216–223, 2021.

[3] J. W. Pyo, K. H. Lee, J. S. Cho, and T. Y. Kuc, "Self-Supervised Button Recognition for Indoor Mobile Robots," *2022 Joint 12th International Conference on Soft Computing and Intelligent Systems and 23rd International Symposium on Advanced Intelligent Systems, SCIS and ISIS 2022*, pp. 1–5, 2022.

[4] K. Iwase, J. Miura, and Y. Shirai, "Teaching a mobile robot to take elevators," *Mechatronics for Safety, Security and Dependability in a New Era*, pp. 229–234, 2007.

[5] W. H. Wang, Y. H. Chien, H. H. Chiang, W. Y. Wang, and C. C. Hsu, "Autonomous Cross-Floor Navigation System for a ROS-Based Modular Service Robot," *Proceedings - International Conference on Machine Learning and Cybernetics*, vol. 2019-July, pp. 1–6, 2019.

[6] A. A. Abdulla, H. Liu, N. Stoll, and K. Thurow, "A robust method for elevator operation in semi-outdoor environment for mobile robot transportation system in life science laboratories," *INES 2016 - 20th Jubilee IEEE International Conference on Intelligent Engineering Systems, Proceedings*, pp. 45–50, 2016.

[7] D. A. Dewi, E. Sundararajan, A. S. Prabuwono, and L. M. Cheng, "Object detection without color feature: Case study Autonomous Robot," *International Journal of Mechanical Engineering and Robotics Research*, vol. 8, no. 4, pp. 646–650, 2019.

[8] S. Li, Y. Chen, Y. Meng, and Y. Lou, "Autonomous elevator button recognition and operation framework for multi-floor mobile manipulator navigation," *IEEE/ASME International Conference on Advanced Intelligent Mechatronics, AIM*, vol. 2021-July, pp. 383–388, 2021.

[9] S. Jiang, W. Yao, M. S. Wong, M. Hang, Z. Hong, E. J. Kim, S. H. Joo, and T. Y. Kuc, "Automatic Elevator Button Localization Using a Combined Detecting and Tracking Framework for Multi-Story Navigation," *IEEE Access*, vol. 8, pp. 1118–1134, 2020.

[10] K. T. Islam, G. Mujtaba, R. G. Raj, and H. F. Nweke, "Elevator button and floor number recognition through hybrid image classification approach for navigation of service robot in buildings," *2017 International Conference on Engineering Technology and Technopreneurship, ICE2T 2017*, vol. 2017-Janua, no. September, pp. 1–4, 2017.

[11] H. Ge, M. Matsui, and N. Koshizuka, "An open-IoT approach on elevator for enabling autonomous robotic vertical mobility," *LifeTech 2021 - 2021 IEEE 3rd Global Conference on Life Sciences and Technologies*, no. LifeTech, pp. 139–141, 2021.

[12] P. Zhang, H. Chen, Q. Lv, and X. Shen, "Application and Research of Elevator Internet of Things-Lifting Robot Using Elevator Scheme," *Journal of Physics: Conference Series*, vol. 2246, no. 1, 2022.

[13] J. Palacín, R. Bitriá, E. Rubies, and E. Clotet, "A Procedure for Taking a Remotely Controlled Elevator with an Autonomous Mobile Robot Based on 2D LIDAR," *Sensors*, vol. 23, no. 13, 2023.

[14] E. Rubies, R. Bitriá, E. Clotet, and J. Palacín, "Non-Contact and Non-Intrusive Add-on IoT Device for Wireless Remote Elevator Control," *Applied Sciences (Switzerland)*, vol. 13, no. 6, 2023.

[15] A. A. Abdulla, H. Liu, N. Stoll, and K. Thurow, "A secure automated elevator management system and pressure sensor based floor estimation for indoor mobile robot transportation," *Advances in Science, Technology and Engineering Systems*, vol. 2, no. 3, pp. 1599–1608, 2017.

[16] J. Krejsa, S. Vechet, K. S. Chen, M. Havelka, and M. Černil, "Mobile Robot in the Elevator: What Floor Am i On?" *Proceedings of the 2022 20th International Conference on Mechatronics - Mechatronika, ME 2022*, 2022.

[17] W. T. Law, K. S. Li, K. W. Fan, T. Mo, and C. K. Poon, "Friendly Elevator Co-rider: An HRI Approach for Robot-Elevator Interaction," *ACM/IEEE International Conference on Human-Robot Interaction*, vol. 2022-March, pp. 865–869, 2022.

[18] Z. Hu, R. Tan, Y. Zhou, J. Woon, and C. Lv, "Template-Based Category-Agnostic Instance Detection for Robotic Manipulation," *IEEE Robotics and Automation Letters*, vol. 7, no. 4, pp. 12 451–12 458, 2022.