

Remote procedure call communication and control of autonomous mobile robot for indoor smart waste monitoring

Ashaari Yusof¹, Abdullah Man¹, Azmi Ibrahim¹, Mohamed Ashraf Husni Zai¹, Md. Jakir Hossen²

¹Centre for Robotics and Sensing Technologies, Telekom Research and Development Sdn Bhd, Cyberjaya, Malaysia

²Faculty of Engineering and Technology, Multimedia University, Melaka, Malaysia

Article Info

Article history:

Received Dec 9, 2024

Revised Feb 4, 2026

Accepted Feb 21, 2026

Keywords:

Autonomous mobile robot

IoT platform

Remote procedure call

Smart dashboard

Smart waste management

ABSTRACT

The integration of autonomous mobile robots (AMRs) and Internet of Things (IoT) technology has revolutionized various industries, including smart waste management (SWM). In this paper, the implementation of a customized remote procedure call (RPC) methodology was successfully demonstrated. This methodology facilitated control and monitoring of AMRs for smart indoor waste management to collect and dispose waste, monitor bin threshold levels and report relevant parameters to a cloud-based platform. Key operational parameters from the AMR and the smart bins via assembled user smart dashboard ensures seamless user monitoring for indoor waste management. Our findings underscore the relevance of RPC in advancing smart waste management technologies, contributing to operational efficiency and sustainability.

This is an open access article under the [CC BY-SA](https://creativecommons.org/licenses/by-sa/4.0/) license.



Corresponding Author:

Ashaari Yusof

Centre for Robotics and Sensing Technologies, Telekom Research and Development Sdn Bhd

Cyberjaya, Malaysia

Email: ashaari@tmrnd.com.my

1. INTRODUCTION

Smart waste management (SWM) has emerged as a critical component of urban sustainability initiatives, driven by the increasing volume of waste generated in rapidly urbanizing environments. With projections indicating that global solid waste generation will reach approximately 3.88 billion tonnes by 2050 [1], and global direct cost of waste management estimated to rise up to USD 361 billion by 2050 [2], the need for effective and efficient waste management solutions has never been more pressing. SWM systems leverage technologies such as the Internet of Things (IoT) to facilitate real-time monitoring, data analytics, and optimized collection processes. The integration of these technologies enable operators to enhance operational efficiency, reduce costs, and improve environmental outcomes by integrating smart sensors and data-driven decision-making into waste management practices.

The automation of indoor waste management processes is particularly vital for maintaining hygiene and operational efficiency in environments such as offices, hospitals, and commercial buildings. This contrasts with traditional manual waste collection methods, which are often labor-intensive and prone to inefficiencies. Subsequently, this inefficiency adds up in operational costs, which ranges from around USD35 per tonne in lower-income countries to over USD100 per tonne in high-income countries [3]. By employing autonomous mobile robots (AMRs), organizations can significantly reduce their reliance on manual labor while enhancing speed and accuracy of waste collection operations. As illustrated in Figure 1, AMRs equipped with advanced sensors and navigation systems can autonomously navigate indoor spaces, identify full bins, and transport waste to designated disposal areas, thereby streamlining the entire waste management process.



Figure 1. An illustration of an indoor SWM solution utilizing AMR to autonomously navigate for waste collection and disposal. The solution allows real-time monitoring of key parameters comprising AMR operational status and waste levels

Moreover, recent advancements in cloud-based IoT platforms have further boosted the capabilities of AMRs in SWM applications. These platforms allow robust frameworks for real-time data exchange and monitoring, enabling seamless integration between AMRs and smart waste bins. Among various communication methodologies available, remote procedure call (RPC) presents a viable option for improving the efficiency and reliability of interactions within these systems. RPC facilitates direct communication between the AMR and smart bins, allowing precise control of commands and exchange of status updates in real time.

By addressing the unique challenges associated with waste management automation, this paper aims to contribute to the ongoing evolution of SWM systems in indoor settings. The proposed RPC-based solution not only improves communication robustness but also enables online monitoring capabilities that empower operators to oversee waste collection processes effectively. The main contributions of this paper are:

- Implementation of a customized RPC framework specifically designed for communication and control mechanisms between AMRs and smart waste bins in indoor environment.
- Generation of a real-time monitoring dashboard from data provided by IoT-enabled waste management components.

2. RELATED WORK

To date, there have been no reported studies specifically focusing on RPC methodology for IoT-related indoor SWM utilizing AMRs. Although RPC framework implementations have been extensively studied in other domains, there are significant opportunities to implement this framework within indoor SWM systems.

2.1. Remote procedure call (RPC)

RPC [4] have been a cornerstone of distributed system design since its inception in the early 1980s. Despite its age, RPC remains a reliable method for communication in modern cloud-connected environments. RPC is a distributed computing paradigm that facilitates the execution of procedure calls across different computers. As illustrated in Figure 2, the sequence of operations involved in initiating an RPC call is presented. In essence, the RPC process encapsulates the details of network interactions within stub functions. When an RPC client sends a request to the server, it includes the specific remote procedure to be invoked, along with relevant parameters and metadata. Upon receiving this request, the server parses it, executes the corresponding process, and subsequently returns the results to the client. RPC enables applications to request services from remote servers without necessitating an understanding of the underlying network protocols and intricacies. This abstraction streamlines the programming model, allowing developers to concentrate on application logic rather than the complexities of network communication.

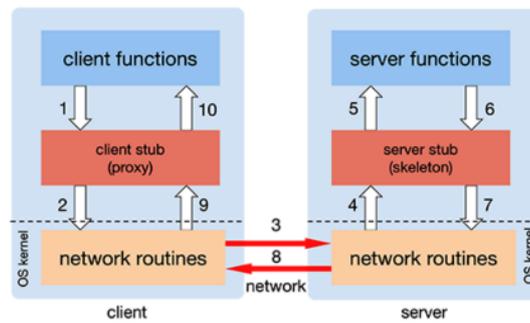


Figure 2. A remote procedure call sequence of operation [5]

In recent times, RPCs have been extensively used in cloud microservice architectures for their scalability and enhanced inter-service communication speed and efficiency. For example, in Zhang *et al.* [6], it is reported that 40k RPC end-points are used in Uber's microservice architecture for its backend service. In other works, Lazarev *et al.* [7] demonstrated throughput and latency improvements via hardware-accelerated RPC deployment in cloud microservice. Similarly, Seemakhupt *et al.* [8] and Chen *et al.* [9] reported significant performance gains in datacenter RPC implementations, while Rao *et al.* [10] evaluated RPC throughput, latency, resource utilisation, and scalability by way of load balancing algorithms. In the field of cloud robotics, Cao *et al.* [11] reported a robot as a service (RaaS) solution that uses microservices and RPC to integrate heterogeneous robots and services, allowing for independent development with scaling of services. However, the intricacies of RPC communication within this RaaS solution were not addressed.

The evolution of RPC, including the introduction of gRPC and RPCX, has revitalized its application, particularly in scenarios requiring efficient remote control [12], [13]. The emergence of these new, high-performance RPC frameworks address limitations of older RPC protocols by offering features such as language neutrality, efficient data serialization, and support for streaming data. While these modern advancements in RPC frameworks are beneficial for specific use cases, this paper focuses on leveraging the core strengths of RPC to develop a robust communication framework tailored within this application domain, addressing the research gap in using RPC for efficient and reliable control of AMRs in indoor SWM systems.

2.2. Robotics and automation in SWM

There exist a large body of knowledge in the scientific literature on the topic of SWM. Sosunova and Porras [14] conducted a systematic review of IoT-enabled SWM systems, identifying various approaches that integrate sensors, data analytics, and communication technologies to improve operational efficiency. Their findings highlight the importance of real-time monitoring and decision-making capabilities in urban waste management. Additionally, the work by Hussain *et al.* [15] provides valuable insights into the dynamics of IoT-enabled systems through a multiagent simulation-based framework. By simulating various aspects of waste generation and collection, the study illustrates how sensor-driven mechanisms significantly outperform traditional approaches in terms of efficiency and cost-effectiveness.

In other works, there are various domains in which SWM automation were applied. Aydin *et al.* [16] present an autonomous vehicle designed for waste collection and fire detection, utilizing machine learning algorithms and computer vision. While this study demonstrates advanced navigation and detection capabilities, it does not explore RPC methodologies for communication between the AMR and waste bins. In another solution, Amaldeep and Arunkumar [17] develop an underwater robot for waste collection, emphasizing the design of hardware and control systems for aquatic environments. Their research, however, does not divulge on the communication details through its tethered ground communication.

There are also studies which have explored outdoor waste management solutions using AMRs, such as Deepak and Davidson's [18] work on a ROS-based waste collection robot. Their approach utilizes GPS for navigation in outdoor environments, which is not applicable to indoor scenarios where GPS signals are often unreliable. Furthermore, their methodology does not incorporate RPC techniques for bin communication. Ushir *et al.* [19] provide a comprehensive review of IoT-based systems for autonomous garbage collection primarily focused on outdoor applications. Their findings highlight the potential of IoT technologies but do not delve into RPC frameworks or indoor waste management scenarios. Miyagusuku *et al.* [20] discuss autonomous garbage collection robots operating in urban environments, emphasizing navigation algorithms and environmental adaptability. However, their research does not consider indoor applications or RPC methodologies for communication. Addas *et al.* [21] propose an IoT-connected smart city waste solution and conduct outdoor field trials utilizing LoRaWAN cloud network. Their work is neither indoor nor using RPC methodologies.

In indoor settings, Khan *et al.* [22] propose a low-cost Arduino-based garbage basket waste monitoring for university using ultrasonic sensors that keep tracks of waste levels and notify the sweeper or further action. However, this system is still dependent on manual labor to empty the garbage basket. In another work, Vincent *et al.* [23] introduce an automated robotic system that replaces traditional bins with smart bins capable of moving when full, using line follower mechanism. While this system integrates IoT technologies, it is only using IR sensors and signaling for waste detection and disposal process between the robot and the smart bin. Also, Carcamo *et al.* [24] propose an AI-powered cleaning robot that employs deep learning for waste detection and classification. Although this research improves performance under varying conditions, it does not address communication protocols like RPC but focuses on algorithmic improvements. Chang *et al.* [25] present a smart trash can robot system that integrates IoT with mobile applications for on-demand trash collection. While they utilize deep learning to optimize path selection, there is no mention of RPC methods to facilitate communication between the robot and the trash can. Lastly, Ravindhiran *et al.* [26] explored wavefront algorithm for its tracking algorithm on mobile robot. This indoor waste management system only focuses on Zigbee's RSSI value to track filled dustbins and automated trash collection by the robot.

The novelty of this research work lies in the implementation of a customized RPC framework tailored for indoor smart waste management. This approach facilitates efficient communication and control mechanisms between the AMR and smart waste bins, addressing the identified research gaps. By leveraging RPC, the proposed system aims to validate the suitability and effectiveness of such methodology for indoor waste management processes, which has not been previously explored in the existing literature.

3. METHOD

3.1. System setup

The experimental setup for this work is designed to assess the effectiveness of the RPC framework in coordinating the operations of the AMR and the smart waste bins within a controlled indoor environment that simulates a typical office setting. As shown in Figure 3, this architecture is designed to leverage server-side and client-side RPC call capabilities within the IoT-enabled and wireless cloud-connected indoor SWM system.

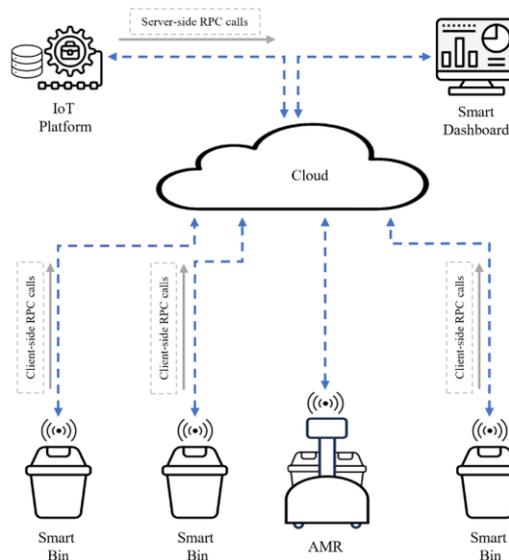


Figure 3. Overall diagram of RPC-based communication and control framework for indoor smart waste collection and disposal via AMR

Central to this solution is the RPC methodology employed through the IoT platform that supports RPC workflows. This allows for precise execution of tasks and automated responses based on specific events, such as when a bin reaches its capacity. The RPC algorithms manage communication between the AMR and the platform's services. For example, a client-side RPC call is invoked when the bin reaches its capacity threshold, while the server-side RPC call ensures synchronization during operations such as opening and closing of the smart bin's flaps.

The smart dashboard provides an intuitive interface for monitoring and visualizing operational data from both AMR and smart bins. Through the dashboard, users can access telemetry data presented in various formats using customized widgets, enabling comprehensive analysis of the SWM processes. This integration of wireless connectivity with cloud-based IoT platforms not only enhances operational efficiency but also allows for scalable solutions adaptable to various indoor environments.

3.2. Hardware setup

There are three main hardware components in this indoor SWM solution, namely AMR, mobile bins and stationary bins as in Figures 4 and 5 respectively. The AMR features advanced navigation components such as LiDAR sensor, 2D camera, ultrasonic sensors and communication modules for precise mapping, obstacle detection and wireless cloud communication within dynamic indoor environments. As shown in Figure 4(a), on top of this AMR also sits the mobile bins as in Figure 4(b) that functions as a temporary transit bin in between the stationary bins and the disposal area during the waste disposal phase. These mobile bins are also equipped with top and bottom flaps that opens and closes as part of the waste collection and disposal process. For the stationary bins shown in Figure 5(a), they are equipped with ultrasonic sensors as in Figure 5(b) to measure waste threshold levels and bin controllers as data collectors and communication mediators. This stationary bin design includes a recessed docking area with an alignment deck for the AMR and mobile bins to align itself to the stationary bins.

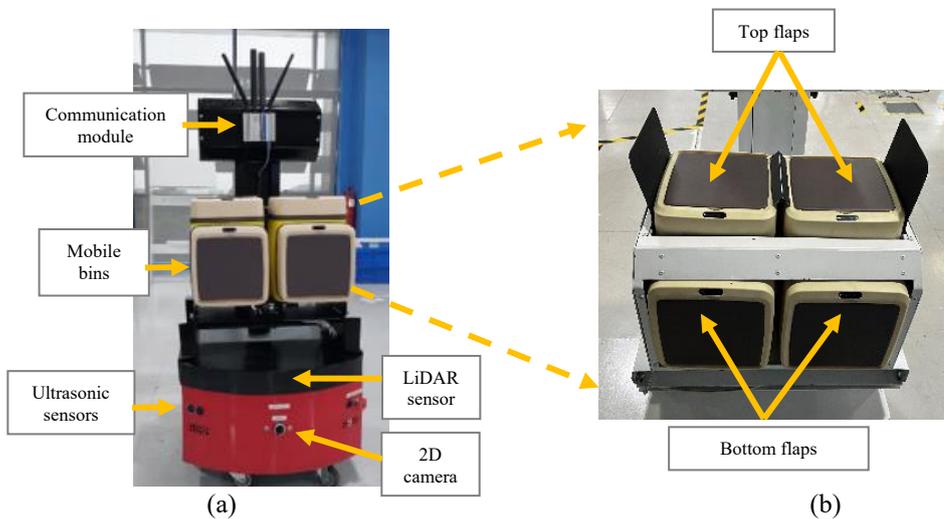


Figure 4. Components of (a) AMR and (b) mobile bins

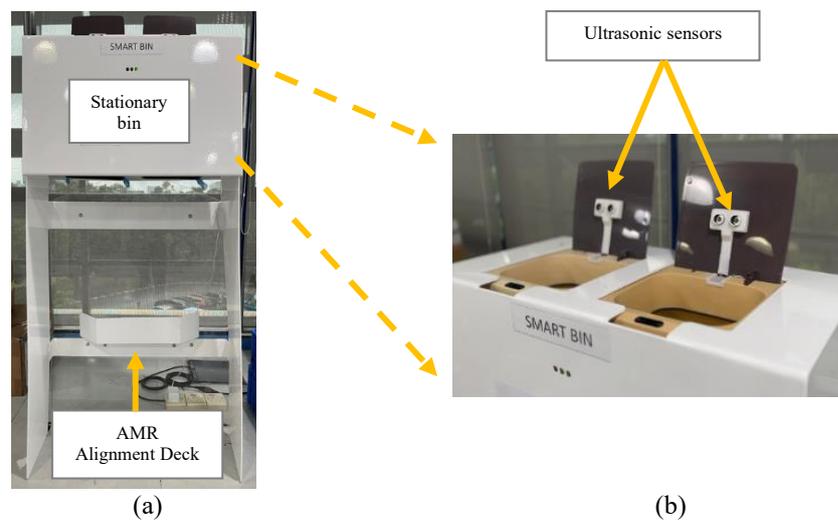


Figure 5. Stationary bin system architecture: (a) stationary bin with recessed docking area and AMR alignment deck and (b) smart bin equipped with ultrasonic sensors for trash level detection

3.3. RPC implementation via ThingsBoard platform

In this study, ThingsBoard CE IoT platform [27] was employed to control, monitor and visualize the operations of the indoor SWM solution using RPC. ThingsBoard platform was selected for its robust features, including real-time data visualization, rule engine for event-based workflows, and support for RPC [28]. The real-time data visualization capabilities of ThingsBoard allowed display of telemetry data from the AMRs and smart bins in various formats as well as customized widgets, facilitating comprehensive monitoring and analysis within a dashboard. The RPC capabilities of ThingsBoard are particularly advantageous for indoor waste management systems. They allow for precise execution of tasks and the ability to configure RPC rule chains within ThingsBoard further enhances the system's responsiveness, allowing automated workflows to trigger actions based on specific events like bin capacity thresholds being reached.

The RPC algorithms are implemented in Python and its communication and control flow is summarized in Figures 6 and 7. This involves several key steps, starting with stationary smart bins detection of waste threshold level. The stationary bin controller then interacts with ThingsBoard's RPC service to send commands to the AMR for trash collection, initiating RPC calls to instruct the AMR to navigate to the bin, align itself and collect the trash. This process involves sending the appropriate command and parameters through ThingsBoard's RPC service. The AMR's main controller also handles the synchronization for opening and closing of bin flaps. This includes controlling the mobile bin mechanism, based on telemetry data from the RPC calls. After the waste collection procedures, the AMR then transports the collected waste to designated box for disposal or recycling. This process is repeated as necessary, ensuring continuous and efficient indoor SWM system.

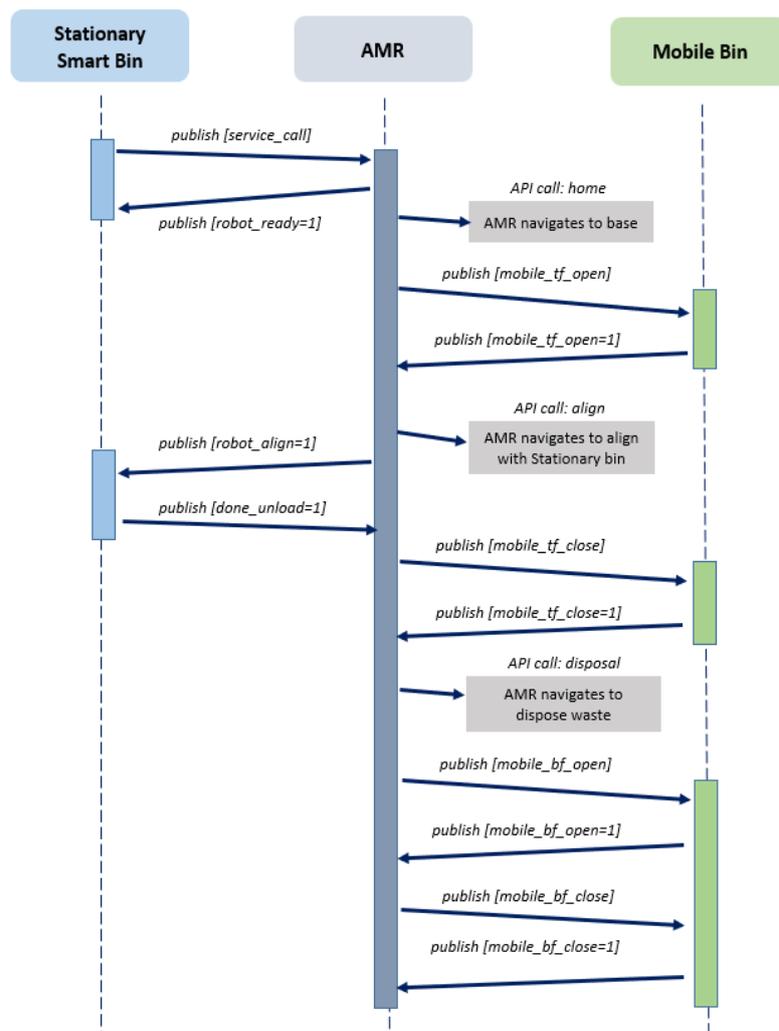


Figure 6. RPC communication flow

```

#call AMR to unload
print("[SB]-- Call AMR for Unloading Service")
rpc("stationary_unload","RPC")
http_rpc_data={"method":"stationary_unload","params":{"mode":"RPC"}}
http_post_rpc_to_rb(http_rpc_data)
while (robot_ready == 0):
    print("[SB]-- Waiting for AMR Ready Acknowledgement")
    print("[SB]-- Resend Service Call")
    rpc("stationary_unload","RPC")
    http_rpc_data={"method":"stationary_unload","params":{"mode":"RPC"}}
    http_post_rpc_to_rb(http_rpc_data)
print("[SB]-- AMR Ready Acknowledgement is Received")
while (robot_align == 0):
    print("[SB]-- Waiting for AMR Alignment")
print("[SB]-- AMR Aligned Acknowledgement is Received")
#open Stationary bin bottom flap to unload
bin_bottom_open()
data = {"stationary_bf":"1"}
http_post_tb(data)
time.sleep(10)
#close Stationary bin bottom flap
bin_bottom_close()
data = {"stationary_bf":"0"}
http_post_tb(data)
#rpc AMR to acknowledge unloading done
print("[SB]-- Send Done Unloading to AMR")
rpc("done_unload","RPC")
http_rpc_data={"method":"done_unload","params":{"mode":"RPC"}}
http_post_rpc_to_rb(http_rpc_data)
#close top flap
bin_top_close()

```

Figure 7. Python code snippet on RPC-based waste collection and disposal process

4. RESULTS AND DISCUSSION

Based on the RPC methodology described in Figures 6 and 7, telemetry data was continuously sent back from both the smart bins and AMR to ThingsBoard platform. The data includes information on bin fill levels, operational status of AMRs, and any anomalies detected during operation. The platform processed this telemetry data through its rule-chain configuration, which allows users to define automated workflows based on specific events or conditions, such as triggering alerts or automated requests for collection when telemetry data indicates a bin is nearing full capacity. Along this process, all related data pertaining to waste management process were collected for visualization and monitoring.

A smart dashboard within the Thingsboard platform was created that serves as a comprehensive visualization that aggregates critical parameters essential for effective indoor SWM, as depicted in Figure 8. This visualization from real-time data stream is facilitated via the RPC methods discussed in Section 3. As end users of this solution such as facilities management or building officer, this capability enhances SWM visibility and allows quick decision making, at the same time reduces dependency from manual labor to monitor the current hygienic condition in indoor environments.

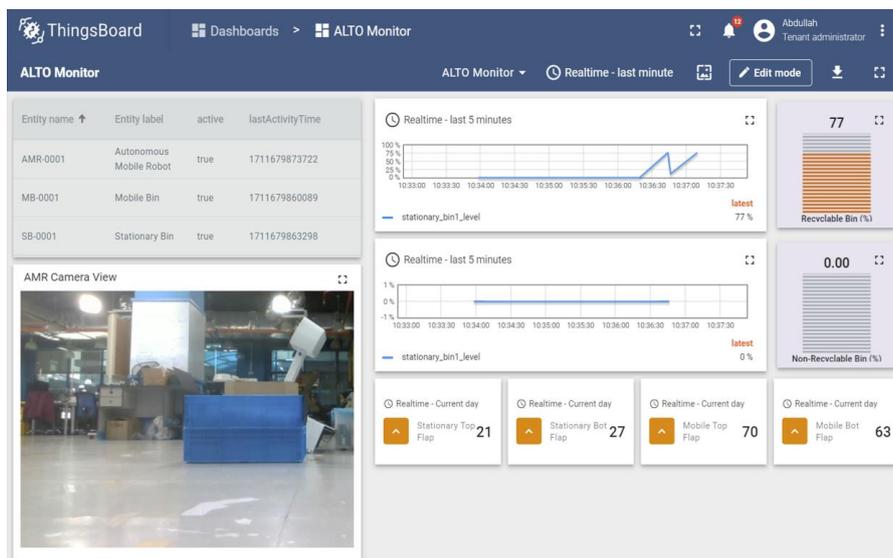


Figure 8. RPC-enabled indoor smart waste monitoring dashboard

The dashboard displays the current operational status of AMRs, mobile bins, and stationary bins, allowing for immediate identification of any anomalies or operational issues. It provides insights into bin levels to optimize AMR trips that can be programmed in planned or ad-hoc mode. The dashboard also tracks usage activity and collection frequency for stationary bins, offering valuable data on waste generation patterns. Monitoring the opening and closing activity of bin flaps provides insights into user interactions with the system. This feature enables the assessment of user engagement and can suggest adjustments to bin designs or placement to improve accessibility. Finally, the inclusion of real-time camera feeds from AMR-mounted cameras enhances situational awareness by providing visual confirmation of bin status and surrounding environments. This capability is particularly beneficial for monitoring areas that may not be easily accessible or visible through traditional monitoring methods.

In addition to the benefits of the RPC-based approach outlined prior, this work significantly enhances the efficiency of the implemented RPC methodology through parameter tuning from ThingsBoard’s RPC setup. Specifically, the timeout request parameter in the default ThingsBoard RPC implementation was adjusted. By changing the request time from 30 seconds to 0.5 seconds, as shown in Figure 9, the RPC call success rate has greatly improved. The RPC server-side call can now be completed in a single attempt instead of multiple tries, improving RPC calls success rate. This adjustment ensures that the RPC request does not cause delays due to unnecessary multiple service calls, as the system design is optimized for a single service call at the smart bin.

```

http_post_rpc_to_sb(data):
try:
    print("Post RPC Telemetry Data")
    headers = {'charset':'utf-8','Content-Type':'application/json', 'Accept':'text/plain'}
    url = "https://" + alto_conf.url_tb + "/api/v1/" + alto_conf.access_token_sb + ".rpc"
    post_response = requests.post(url, data, headers=headers, verify=True, timeout=0.5)
    return post_response
except requests.Timeout:
    pass
except requests.exceptions.ConnectionError:
    return
    
```

Figure 9. Default timeout modification for more efficient RPC implementation

5. CONCLUSION

This paper highlights the successful integration of an RPC-based communication framework within an indoor smart waste management system utilizing AMRs. By leveraging IoT technologies and real-time data visualization through ThingsBoard, the proposed system enhances operational efficiency while reducing dependence on manual labor. The customized RPC methodology enables seamless communication between stationary smart bins and AMRs, facilitating timely waste collection based on accurate telemetry data. The findings underscore the importance of effective communication protocols in optimizing waste management processes, demonstrating that such RPC-based control systems can greatly assist towards resource allocation improvement and long-term environmental sustainability. This research not only fills a critical gap in the literature regarding RPC applications in indoor SWM settings but also sets the stage for further automation and optimization related to this framework. As urban areas and modern indoor offices continue to grow, a new paradigm in RPC-based and AMR-based SWM is essential for creating an efficient and sustainable future.

FUNDING INFORMATION

The authors thank Telekom Malaysia for their funding under RDTC241131 project.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Ashaari Yusof	✓	✓		✓	✓	✓	✓		✓	✓	✓		✓	✓
Abdullah Man	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓				
Azmi Ibrahim		✓	✓	✓	✓			✓	✓	✓	✓			
Mohamed Ashraf	✓			✓						✓		✓	✓	✓
Husni Zai														
Md. Jakir Hossen	✓			✓						✓		✓	✓	

C : Conceptualization	I : Investigation	Vi : Visualization
M : Methodology	R : Resources	Su : Supervision
So : Software	D : Data Curation	P : Project administration
Va : Validation	O : Writing - Original Draft	Fu : Funding acquisition
Fo : Formal analysis	E : Writing - Review & Editing	

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

REFERENCES

- [1] "Solid waste management," *World Bank Group*. <https://www.worldbank.org/en/topic/urbandevelopment/brief/solid-waste-management> (accessed Oct. 05, 2024).
- [2] United Nations Environment Programme, "Global waste management outlook 2024." <https://www.unep.org/resources/global-waste-management-outlook-2024> (accessed Oct. 05, 2024).
- [3] "Trends in solid waste management." https://datatopics.worldbank.org/what-a-waste/trends_in_solid_waste_management.html (accessed Oct. 13, 2024).
- [4] A. D. Birrell and B. J. Nelson, "Implementing remote procedure calls," *ACM Transactions on Computer Systems (TOCS)*, vol. 2, no. 1, pp. 39–59, Feb. 1984, doi: 10.1145/2080.357392.
- [5] "Remote procedure calls." <https://pk.org/417/notes/rpc.html> (accessed Oct. 05, 2024).
- [6] Z. Zhang, M. K. Ramanathan, P. Raj, A. Parwal, T. Sherwood, and M. Chabbi, "CRISP: Critical path analysis of large-scale microservice architectures," *Proceedings of the 2022 USENIX Annual Technical Conference, ATC 2022*, pp. 655–672, 2022.
- [7] N. Lazarev, N. Adit, S. Xiang, Z. Zhang, and C. Delimitrou, "Dagger: Towards efficient RPCs in cloud microservices with near-memory reconfigurable NICs," *IEEE Computer Architecture Letters*, vol. 19, no. 2, pp. 134–138, Jul. 2020, doi: 10.1109/LCA.2020.3020064.
- [8] K. Seemakhupt *et al.*, "A cloud-scale characterization of remote procedure calls," in *SOSP 2023 - Proceedings of the 29th ACM Symposium on Operating Systems Principles*, Oct. 2023, pp. 498–514, doi: 10.1145/3600006.3613156.
- [9] J. Chen *et al.*, "Remote procedure call as a managed system service," *Proceedings of the 20th USENIX Symposium on Networked Systems Design and Implementation, NSDI 2023*, pp. 141–159, 2023.
- [10] S. S. Rao, S. Mishra, S. Seshadri, and S. Bhaskaran, "Optimizing distributed communication: A comparison of load balancing strategies in gRPC and Apache thrift," in *2024 15th International Conference on Computing Communication and Networking Technologies, ICCCNT 2024*, Jun. 2024, pp. 1–6, doi: 10.1109/ICCCNT61001.2024.10724038.
- [11] F. Cao, C. Fang, X. Qin, X. Jin, and F. Shu, "Towards a cloud-controlled heterogeneous robot system based on microservices," in *2023 9th International Conference on Control Science and Systems Engineering, ICCSSE 2023*, 2023, pp. 202–207, doi: 10.1109/ICCSSE59359.2023.10245035.
- [12] Ritu, S. Arora, A. Bhardwaj, A. Kukkar, and S. Kaur, "A comparative analysis of communication efficiency: REST vs. gRPC in microservice-based ecosystems," in *Proceedings - 2024 International Conference on Emerging Innovations and Advanced Computing, INNOCOMP 2024*, 2024, pp. 621–626, doi: 10.1109/INNOCOMP63224.2024.00107.
- [13] L. Zhang, K. Pang, J. Xu, and B. Niu, "High performance microservice communication technology based on modified remote procedure call," *Scientific Reports*, vol. 13, no. 1, 2023, doi: 10.1038/s41598-023-39355-4.
- [14] I. Sosunova and J. Porras, "IoT-enabled smart waste management systems for smart cities: A systematic review," *IEEE Access*, vol. 10, pp. 73326–73363, 2022, doi: 10.1109/ACCESS.2022.3188308.
- [15] D. I. Hussain, D. A. Elomri, D. L. Kerbache, and D. A. El Omri, "Smart city solutions: Comparative analysis of waste management models in IoT-enabled environments using multiagent simulation," *Sustainable Cities and Society*, vol. 103, Apr. 2024, doi: 10.1016/j.scs.2024.105247.
- [16] O. Aydin, E. Molla, F. Karadağ, B. Guzeltepe, H. U. Ünal, and Ö. N. Gerek, "Design and implementation of an autonomous vehicle for waste material collection and fire detection," *Eskişehir Osmangazi Üniversitesi Mühendislik ve Mimarlık Fakültesi Dergisi*, vol. 31, no. 3, pp. 801–807, Dec. 2023, doi: 10.31796/ogumf.1233759.
- [17] C. Amaldeep and S. Arunkumar, "Design and Development of an Underwater Robot for Effective Waste Collection," 2024, doi: 10.1109/AMATHE61652.2024.10582229.
- [18] U. Deepak and R. Arlene Davidson, "Development of a ROS based waste collection robot for campus use," *INDICON 2022 - 2022 IEEE 19th India Council International Conference*, 2022, doi: 10.1109/INDICON56171.2022.10039752.
- [19] O. M. Ushir, P. R. Jadhav, and N. S. Patankar, "An IoT-based system and method of autonomous robots for garbage collection in smart cities," in *Proceedings - 2024 5th International Conference on Intelligent Communication Technologies and Virtual Mobile Networks, ICICV 2024*, 2024, pp. 871–875, doi: 10.1109/ICICV62344.2024.00143.
- [20] R. Miyagusuku, Y. Arai, Y. Kakigi, T. Takebayashi, A. Fukushima, and K. Ozaki, "Toward autonomous garbage collection robots in terrains with different elevations," *Journal of Robotics and Mechatronics*, vol. 32, no. 6, pp. 1164–1172, Dec. 2020, doi: 10.20965/jrm.2020.p1164.
- [21] A. Addas, M. N. Khan, and F. Naseer, "Waste management 2.0 leveraging internet of things for an efficient and eco-friendly smart city solution," *PLoS ONE*, vol. 19, no. 7 July, Jul. 2024, doi: 10.1371/journal.pone.0307608.
- [22] M. N. Khan and F. Naseer, "IoT based university garbage monitoring system for healthy environment for students," in *Proceedings - 14th IEEE International Conference on Semantic Computing, ICSC 2020*, Feb. 2020, pp. 354–358, doi: 10.1109/ICSC.2020.00071.
- [23] B. Vincent, R. Nidhin, D. R. Thomas, A. E. Anub, A. M. Shibu, and A. Shaji, "An automatic robotic system for efficient replacement of fully filled bins," *2024 1st International Conference on Trends in Engineering Systems and Technologies, ICTEST 2024*, 2024, doi: 10.1109/ICTEST60614.2024.10576094.
- [24] J. Carcamo *et al.*, "AI-powered cleaning robot: a sustainable approach to waste management," *International Conference on Human System Interaction, HSI*, 2024, doi: 10.1109/HSI61632.2024.10613552.

- [25] B. R. Chang, H. F. Tsai, J. L. Lyu, and T. K. Yin, "Smart trash can robot system with integration of internet of things and mobile applications," *Sensors and Materials*, vol. 31, no. 11, pp. 3495–3516, 2019, doi: 10.18494/SAM.2019.2563.
- [26] P. Ravindhiran, P. Gopal, S. J. Gladwin, and R. Rajavel, "Automated indoor waste management system employing wavefront algorithm and received signal strength indicator values-based mobile robot," in *5th IEEE Region 10 Humanitarian Technology Conference 2017, R10-HTC 2017*, 2018, vol. 2018-Janua, pp. 284–289, doi: 10.1109/R10-HTC.2017.8288958.
- [27] "ThingsBoard open-source IoT platform." <https://thingsboard.io/> (accessed Oct. 04, 2024).
- [28] "Using RPC capabilities." <https://thingsboard.io/docs/user-guide/rpc/> (accessed Oct. 04, 2024).

BIOGRAPHIES OF AUTHORS



Ashaari Yusof     is from the Centre for Robotics and Sensing Technologies, TM Research and Development Sdn Bhd, Malaysia. He is currently developing smart use cases focusing on robotics and digital applications. His research interests include IoT intelligent services and computer vision. Ashaari is a senior researcher with 20+ years of academia-industry collaborative experience and can be contacted at ashaari@tmrnd.com.my.



Abdullah Man     is affiliated with the Centre for Robotics and Sensing Technologies at TM Research and Development Sdn Bhd, Malaysia. His current work focuses on developing smart solutions for robotic applications and urban forestry. His research interests include IoT intelligent services, computer vision, and wireless systems. With over 15 years of experience in academia-industry collaborations, he can be reached at abdullah@tmrnd.com.my.



Azmi Ibrahim     is from the Centre for Robotics and Sensing Technologies at TM Research and Development Sdn Bhd, Malaysia. He focuses on IoT front-end development, connectivity solutions including robotics connectivity. His research interests include wireless sensing, intelligent services, sensor technology and edge computing for IoT. With over 15 years of experience in academia-industry collaborations, he can be reached at iazmi@tmrnd.com.my.



Mohamed Ashraf Husni Zai     is currently heading the Centre for Robotics and Sensing Technologies, TM Research and Development Sdn Bhd, Malaysia. As Director of CRST, he drives pragmatic applied research in robotics and IoT for strategic industry domains, using the convergence of AI and next generation computing. Throughout his career, he has held a diverse portfolio of team management, product management and solution development roles. He can be contacted at ashraf.hz@tmrnd.com.my.



Md. Jakir Hossen     is currently working as an associate professor in the Department of Robotics and Automation, Faculty of Engineering and Technology, Multimedia University, Malaysia. He received the master's degree in communication and network engineering from Universiti Putra Malaysia, Malaysia in 2003. He received the PhD degree in smart technology and robotic engineering from Universiti Putra Malaysia, Malaysia in 2012. His research interests are application of artificial intelligence techniques in data analytics, robotics control, data classifications and predictions. He can be contacted at jakir.hossen@mmu.edu.my.