Automatic Metal Debris Collection Robot for Laboratory Safety: A Review

Sophia Fahima binti Hapizan, Ja'aris Samsudin
Robotics and Automation in Electronic Engineering, Mara-Japan Industrial Institute, 43700 Beranang, Malaysia

Heshalini Rajagopal
Department of Electrical & Electronic Engineering, Mila University, No. 1, Persiaran MIU, 71800 Putra Nilai, Negeri Sembilan Darul Khusus, Malaysia

Takao Ito
Graduate School of Advanced Science and Engineering, Hiroshima University, Japan

Muhammad Amirul Aiman Asri
Department of Electrical Engineering, Universiti Malaya, Malaysia

Anees ul Husnain
Faculty of Engineering, The Islamia University of Bahawalpur, 63100 Pakistan

Email: sophiafahimahapizan22@gmail.com, norrimamokhtar@um.edu.my, heshalini.rajagopal@mila.edu.my

Abstract

Laboratory safety is paramount, especially when managing hazardous metal debris. This review explores advancements in robotics for waste management, emphasizing autonomous sorting and collection systems driven by AI and machine learning. These technologies enhance the precision and adaptability of robots, enabling accurate detection, classification, and handling of metal debris. By integrating advanced sensors and real-time decision-making, such systems improve resource management and safety in laboratory environments. Challenges such as power efficiency and scalability are also discussed, highlighting future opportunities for optimizing robotic solutions in critical waste management applications.

Keywords: Laboratory Safety, Metal Debris, Robotics, Waste Management, Machine Learning, Sensors, Resource Management.

1. Introduction

Laboratories are environments where precision and safety are paramount whether in industrial or research settings such as addressed by Y. Yang et al. [1]. However, the presence of metal debris generated during experiments, fabrication processes or equipment handling can pose significant risks. Such debris may result in physical injuries to personnel, contamination of sensitive experiments, and potential damage to expensive equipment that results in costly repairs or interruptions to critical research. Maintaining laboratory safety is not only about compliance with standards but also creating an environment where experiments can proceed without hazards.

Often, traditional methods of metal waste management often rely on manual handling such as brooms, or manual vacuum systems. While these methods are straightforward, they are labor-extensive, time-consuming, and susceptible to human error, particularly in larger or more complex facilities. In high-tech laboratories, the need for innovative solutions is crucial to address these challenges whereas traditional methods often fall short of meeting the rigorous standards required for operational efficiency and safety. Fig. 1 shows some metal dust after work either in an industrial site or research laboratory, when swept with a broom.

The integration of automation and robotics in laboratory safety has emerged as a revolutionary solution to overcome these challenges. Robots designed for metal debris collection combine advanced technologies such as efficient power systems, smart sensors, and autonomous navigation. These robots are engineered to reduce energy consumption, making them cost-effective and environmentally sustainable. Power-efficient designs, such as low-power processors and optimized motor systems, ensure that these robots can operate for extended periods without frequent recharging, making them ideal for continuous or large-scale applications.

Safety and sustainability are driving forces behind the adoption of these automated solutions. The ability of robots to autonomously detect, collect, and safely dispose of metal debris eliminates the need for manual intervention, thereby reducing the risks of injuries. Furthermore, these robots minimize the contamination risks, especially in laboratories handling sensitive materials or conducting critical experiments. Their consistent performance ensures that no debris is overlooked, enhancing the overall safety and cleanliness of the workspace.

Fig.1 Metal Work Processes [2].

Robots for metal debris collection are equipped with cutting edge technologies:

- Sensors for Metal Detection: Advanced inductive or magnetic sensors allow the robots to identify metal debris accurately, even in mixed material environments. These sensors are designed to work efficiently while consuming minimal power.
- Magnetic Systems for Collection: Electromagnets or permanent magnets are used to collect metal debris such as in Fig. 2. Power-efficient electromagnets can be selectively activated, ensuring energy is used only when necessary.

Fig.2 12V Electromagnet that Can Attract Ferrous Metals Based on Current Input.

- AI and Autonomous Navigation: Artificial Intelligence enables robots to map laboratory layouts, navigate obstacles, and optimize cleaning paths. Machine learning algorithms enhance their ability to adapt to changing environments or debris patterns, ensuring thorough and efficient operations.

The adoption of such automated systems is especially critical in laboratories where human safety and operational precision are non-negotiable. For example, in facilities working with hazardous materials or intricate instrumentation, the introduction of robots not only safeguards personnel but also ensures that research activities are conducted without disruption. This review explores the advancements in robotics and automation technologies for waste management, particularly focusing on their application in laboratory safety. It examines the technological components that enable efficient and intelligent metal debris collection, including power-efficient designs, sensor technologies, and AI-driven navigation. By providing insights into these innovations, this review aims to shed light on how laboratories can enhance safety, improve resource management, and reduce operational risks through the adoption of automated solutions.

2. Key Research Themes

2.1 *Metal Detection and Collection*

The accurate detection and efficient collection of metal debris are essential for ensuring laboratory safety. Numerous studies have explored the use of sensors, such as inductive proximity sensors, metal detectors, and vision systems to identify metallic objects with high precision.

These technologies are particularly suited for laboratory environments, where debris may vary in size and composition. Research has further emphasized magnetic collection systems, noting their ability to attract and retain metallic fragments of various sizes with high efficiency. For instance, Gundupalli [3] highlights the strength of modern magnetic systems and their role in automating waste collection. Such technologies enable safe handling of sharp and hazardous debris, reducing risks for laboratory personnel.

2.2 *Navigation and Obstacle Avoidance*

Autonomous navigation is a critical component for robots operating in confined and cluttered environments like laboratories. Studies have demonstrated the effectiveness of AI-based techniques, such as machine learning algorithms and Simultaneous Localization and Mapping (SLAM), in enabling robots to map their surroundings, detect obstacles, and plan optimal paths. For example, P.Valsalan et al. [2] showed that efficiency of a camera-based system robot from Fig. 3 that takes an image of the room (area of interest) then identifies the metallic scraps: the robot calibrates the coordinate locations of all the scraps. With Scale Invariant Function (SIFT) and Nearest Neighbor Search (NNS) algorithms the robot is able to calculate and provide coordinate position of scrap locations. This is particularly relevant for laboratory applications, where precision in movement is crucial to avoid disrupting sensitive experiments or equipment.

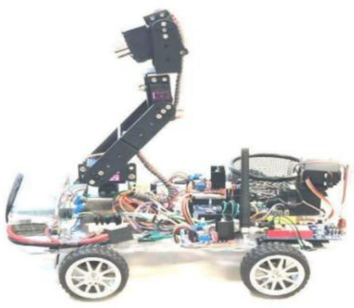

Fig.3 Valsalan's Robot Design for Metallic Scrap Collection Robot [2].

Another example of AI-based techniques robots that use path planning and obstacle avoidance in dynamic environments for cleaning robots is shown by S. Khanna and S. Srivastava [4] that addresses limitations caused by traditional cleaning robots that often rely on predetermined paths and struggle to adapt to changes in environment. To overcome this, they presented a design using advanced path planning algorithms and neural network models for path optimization, and a performance evaluation. Such an approach is important to enhance the adaptability and efficiency of cleaning robots, enabling them to dynamically respond to real-time environmental changes, avoid obstacles effectively, and optimize cleaning paths. This not only improves operational performance but also ensures that robots can function seamlessly in unpredictable and complex environments like laboratories, where maintaining safety and precision is critical.

2.3 *Design and Structural Considerations*

The physical design of a debris collection robot significantly impacts its performance in specialized environments. Compact and modular designs are often highlighted in the literature for their ability to navigate narrow lab spaces and adapt to various tasks. Storage compartments for collected debris are also emphasized, ensuring efficient handling and disposal processes. Case studies, such as those focusing on robots designed for hospitals or manufacturing, provide valuable insights into how design principles can be tailored for laboratory safety applications such as from 5. H. Alsahafi and M. Almaleky [5]. These examples demonstrate the adaptability of robotic systems for different operational needs.

2.4 *Efficiency and Sustainability*

Efficiency and sustainability are key metrics for evaluating the performance of automated cleaning robots. Research highlights the importance of optimizing speed, accuracy, and energy consumption to enhance the robot's effectiveness while minimizing operational costs. Furthermore, the environmental benefits of automated systems are discussed in terms of recycling and waste segregation. For instance, A. Jha et al. (2019) [6] reviews the contribution of autonomous garbage collector robots to resource conservation and pollution reduction. By integrating energy-efficient components and focusing on sustainable practices, these systems align with broader goals of environmental responsibility.

3. Applications and Case Studies

3.1 *Existing Implementations*

Robots designed for cleaning and debris collection are already being deployed in industrial and laboratory settings, showcasing their effectiveness in improving safety and efficiency. For instance, automated cleaning roots like HR-Recycler system have been adapted for waste sorting, including metallic components in industrial facilities A.Axenopoulus et al. [7]. The system integrates hybrid human-robot collaboration to ensure accurate separation of hazardous waste, demonstrating their potential for laboratory applications where safety is paramount. Manual, expensive, hazardous and time-consuming tasks of materials pre-processing will be substituted by automatic robotic-based procedures before the materials enter the shredding machine.

In laboratory settings, robots equipped with basic cleaning tools and sensors have been utilized for tasks such as biohazard material handling and spill cleanup such as introduced by H.Prendinger et al. [8]. While these robots may not specifically target metal debris, their success highlights the feasibility of adapting such systems for metal collection. Furthermore, studies have demonstrated the application of magnetic collection systems integrated into robots explained by J.J.Abbott et al. [9], which have proven effective in scrapyards and recycling facilities and can be scaled down for lab use.

3.2 *Innovative Prototypes*

Recent advancements have introduced prototypes tailored for metal debris collection in hazardous and confined environments. For example, S. Khanna and S. Srivastava [4] developed an AI-driven cleaning robot with advanced path planning algorithms and obstacle avoidance capabilities. Their design demonstrates how intelligent systems can optimize cleaning operations in dynamic and unpredictable environments.

Another notable prototype is the Metallic Scrap Collection Robot by P. Valsalan et al. [2], which uses electromagnets and inductive sensors to detect and collect ferrous metals. This system has been trialed in industrial contexts and offers insight into how such designs could be adapted for laboratories. Its compact design and efficient energy management system make it particularly suitable for spaces with limited mobility.

Additionally, research projects have explored robots with modular designs, allowing them to adapt to specific laboratory conditions. These prototypes often include features like interchangeable tools for handling different types of debris and Internet of Things (IoT) systems for remote monitoring and control. Such innovations underline the growing versatility of automated solutions in addressing safety and operational challenges in laboratory environments.

By examining these existing implementations and emerging prototypes, this review highlights the potential for further advancements in robotic solutions for metal debris collection, paving the way for safer and more efficient laboratory operations.

3.3 *Design Suggestion*

The proposed design for an automatic metal debris collection as shown in Fig. 4 is developed to enhance laboratory safety by automating detection, collection, and management of hazardous metallic waste. This system integrates advanced components such as proximity inductive sensors, electromagnets, camera module paired with microcontroller to enable efficient and reliable operations.

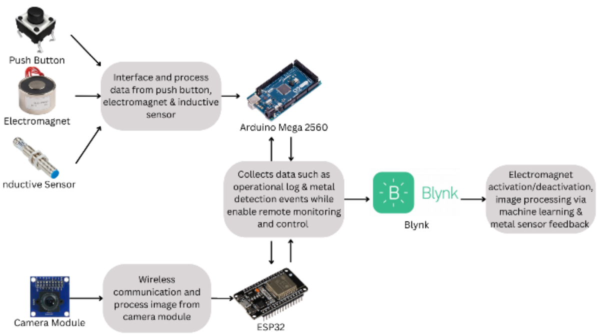

Fig.4 Proposed Design for Metal Debris Collection Robot.

The design aims to address the limitations of traditional manual debris handling methods. By incorporating such features such as autonomous navigation, image processing for precise metal identification, and IoT capabilities for remote control and monitoring, this robot ensures a seamless and effective approach to waste management in laboratory settings.

Moreover, the proposed system is tailored to operate in dynamic environments, leveraging modern robotics technologies and sustainable power solutions to optimize energy usage while maintaining performance.

4. Challenges and Future Directions

4.1 *Current Limitations*

Despite significant advancements, several challenges persist in the development and implementation of automated metal debris collection robots:

- Material Differentiation: One of the major limitations is the difficulty in accurately differentiating between metallic and non-metallic materials, especially when debris consists of mixed or coated substances. Current systems often rely on magnetic detection, which may fail to distinguish between various material types.
- Navigation in Dynamic Environments: Laboratory environments are often crowded and dynamic, with constantly changing layouts and obstacles. Ensuring reliable navigation and obstacle avoidance in such conditions remains a significant technical challenge for robotic systems.
- Maintenance and Durability: Robots operating in harsh laboratory conditions, such as exposure to corrosive chemicals or abrasive materials, face issues with durability and maintenance. Regular wear and tear of components like sensors and electromagnets can reduce operational efficiency over time.

4.2 *Research Gaps*

Several areas require further exploration to improve the effectiveness of automated metal debris collection robots:

- Multi-functional Robots: There is a need for robots capable of handling both metallic and non-metallic waste to provide comprehensive cleaning solutions. Integrating advanced sensors and adaptive tools could enable robots to address this challenge.
- Energy Efficiency: While energy-efficient designs are emerging, optimizing power consumption, especially in portable robots with limited battery capacity remains an area of active research.
- Scalability for Laboratory Use: Many existing designs are tailored for industrial applications. Adapting these systems to the compact and intricate nature of laboratory environments requires further innovation.

4.3 *Emerging Trends*

The field is witnessing exciting trends that promise to address current limitations and expand the capabilities of robotic systems for laboratory safety:

- IoT Integration: The incorporation of IoT technology allows for real-time monitoring, remote control, and data-driven optimization of robot operations. Such systems enable better oversight and improved decision-making in dynamic lab environments.
- AI and Machine Learning Advancements: The use of AI for enhanced material recognition, path planning, and adaptive learning is a transformative trend. Machine learning algorithms can enable robots to become more efficient and autonomous over time, adapting to specific lab conditions.
- Miniaturization of Robots: The development of compact and lightweight robotic systems is particularly important for laboratory settings. Miniaturization designs enable robots to navigate narrow spaces, access hard-to-reach areas, and operate with greater precision.

By addressing these challenges and leveraging emerging trends, future robotic systems can significantly enhance laboratory safety and efficiency, setting a benchmark for automated waste management solutions in critical environments.

5. Conclusion

This review highlights the advancements and challenges in the development of automated robots for metal debris collection in laboratory environments. The reviewed literature emphasizes significant progress in key areas, such as material detection using advanced sensors, navigation through dynamic environments powered by AI-based techniques, and the integration of magnetic systems for efficient debris collection. Additionally, trends like IoT-enabled monitoring, machine learning for enhanced autonomy, and compact robotic designs are crucial to revolutionizing laboratory safety protocols. The importance of developing robust, efficient and sustainable robotic solutions cannot be overstated, particularly in laboratory settings where precision and safety are utmost. Automated systems not only mitigate risks posed by hazardous metal debris but also improve operational efficiency and reduce manual intervention. Such advancements add to creating safer and more sustainable working environments for researchers and personnel.

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Authors Introduction

Ms. Sophia Fahima Binti Hapizan

She is currently pursuing study in Electronics Engineering at Mara-Japan Industrial Institute, MJII.

Mr. Ja'aris Samsudin

He is the head of department of Robotic and Authomation at Mara-Japan Industrial Institute, MJII. His research interests include Microcontrollers and Pneumatic & Hydraulics.

Dr. Heshalini Rajagopal

She received her PhD and Master's degree from the Department of Electrical Engineering, University of Malaya, Malaysia in 2021 and 2016, respectively. She is an Assistant Professor in the School of Engineering and Computing, Mila University. Her research interests include image processing, artificial intelligence and machine learning.

Dr. Takao Ito

He is Professor of Management of Technology (MoT) in Graduate School of Engineering at Hiroshima University. He is serving concurrently as Professor of Harbin Institute of Technology (Weihai) China. He has published numerous papers in refereed journals and proceedings, particularly in the area of management science, and computer science.

Mr. Muhammad Amirul Aiman Bin Asri

He received the B.E (Electrical) from the Department of Electrical Engineering, University of Malaya, Malaysia in 2020 Currently, he is a Research Assistant in University of Malaya, Malaysia. His research interest includes image processing, artificial intelligence and machine learning.

Dr. Anees ul Husnain

Anees received his Doctoral in Electrical Engineering at University of Malaya, Malaysia. He holds a master's degree in computer engineering from UET Taxila, Pakistan. He is working on autonomous path generation of UAVs to monitor fugitive emissions. Currently, he is an Assistant Professor at Faculty of Engineering, The lslamia University of Bahawalpur, Pakistan.