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Evolving Field of Autonomous Mobile Robotics: Technological Advances and Applications

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Abstract

The field of autonomous mobile robotics is rapidly evolving, driven by significant technological advances and expanding applications across various sectors. Autonomous mobile robots (AMRs) leverage sophisticated sensors, artificial intelligence (AI), and machine learning algorithms to navigate and perform tasks independently in dynamic environments. These technological breakthroughs have enhanced AMRs' capabilities in perception, localization, mapping, and decision-making. Key advancements include improved sensor technologies such as LiDAR, cameras, and ultrasonic sensors, which provide detailed environmental data. AI and machine learning facilitate real-time data processing, enabling robots to make intelligent decisions, adapt to changes, and optimize performance. Additionally, advancements in robotic hardware, including more efficient power systems and lightweight materials, contribute to enhanced mobility and endurance. AMRs are increasingly applied in industries such as manufacturing, logistics, healthcare, and agriculture. In manufacturing and logistics, they streamline operations, reduce costs, and improve safety by automating repetitive and hazardous tasks. In healthcare, AMRs assist in patient care, medication delivery, and sanitation. In agriculture, they enhance precision farming practices, improving crop management and yield. This abstract highlights the rapid evolution of autonomous mobile robotics, emphasizing technological advancements and diverse applications. The continued development of AMRs promises to revolutionize various industries by increasing efficiency, safety, and productivity, ultimately transforming how tasks are performed in dynamic environments.

Keywords: Artificial Intelligence; Autonomous Mobile Robots; Industrial Applications; Machine Learning; Sensor Technologies; Technological Advances

Abbreviations: AGV: Automated Guided Vehicles, AMR: Autonomous Mobile Robots, ASR: Autonomous Security Robots, SLAM: Simultaneous Localization and Mapping, VLM: Vertical Lift Module

1. Introduction

The field of mobile robotics has witnessed remarkable advancements, paving the way for autonomous systems capable of navigating complex environments without human intervention. Autonomous Mobile Robots (AMRs), at the forefront of this revolution, are transforming industries by streamlining logistics, enhancing safety, and optimizing operational efficiency [1]. These intelligent robots leverage cutting-edge technologies like simultaneous localization and mapping (SLAM), control systems, numerical methods, and signal processing to autonomously navigate and perform tasks. From unmanned ground vehicles in logistics to robotic assistants in healthcare, the applications of mobile robotics are diverse and rapidly evolving, promising to reshape the way we approach automation

and autonomy (Fig. 1) [2].

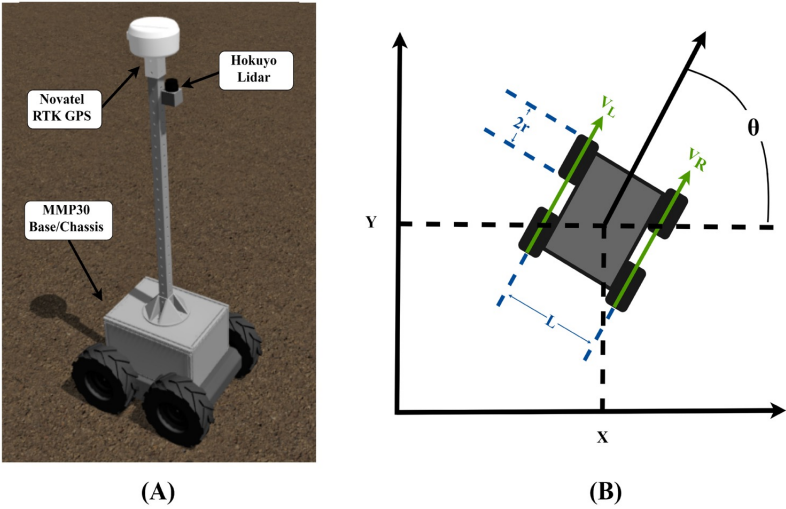


Figure 1. Simulated rover Phenotron.

Autonomous Mobile Robots (AMRs) represent a significant advancement over traditional Automated Guided Vehicles (AGVs). Unlike AGVs that rely on predefined tracks or paths, AMRs leverage sensors, artificial intelligence (AI), machine learning, and advanced mapping/navigation capabilities to interpret and adapt to their surroundings dynamically. AMRs have evolved from AGVs, with advancements in AI, machine learning, and computing power enabling them to navigate complex environments autonomously. Key components of AMRs include.

- **Sensors** (e.g., lidar, cameras) to perceive the environment
- **Software** to process sensor data and control the robot
- **Actuators** to physically move the robot

The rapid growth of AMRs is primarily driven by advancements in technologies like computing power, sensors, vision, and analytics, which enable real-time connection to the environment. AMRs leverage technologies such as given in Table 1.

Table 1. AMRs can be categorized into three main types

Type	Description
Inventory/ Product Movers	Automate the movement of inventory and products within a facility, reducing non-value-added tasks and increasing inventory visibility.
Order Picking Assistants	Bring products to the picker, either through zone picking or goods-to-person systems, increasing picking productivity by up to 450%.
Flexible Sortation Solutions	Handle high-speed parcel sortation, ecommerce order fulfillment, returns handling, and short-term sortation.

1. **Simultaneous Localization and Mapping (SLAM).** To understand and adjust to changes in their environment, enabling flexibility across applications.
2. **Advanced Mapping.** To create detailed maps of their surroundings and plan efficient routes.

3. **Machine Learning.** To achieve optimum efficiency and accuracy, even in new situations.

With their self-steering and self-thinking capabilities, AMRs offer greater independence and flexibility compared to traditional AGVs. They can be equipped with secure storage compartments and utilize advanced technologies like LiDAR, visual computing, and mapping for navigation [3, 4, 5].

2. Benefits of AMRs

The integration of Autonomous Mobile Robots (AMRs) offers numerous benefits that streamline operations, enhance productivity, and improve safety across various industries. Here are some key advantages of adopting AMR technology (Fig. 2) [6, 7].

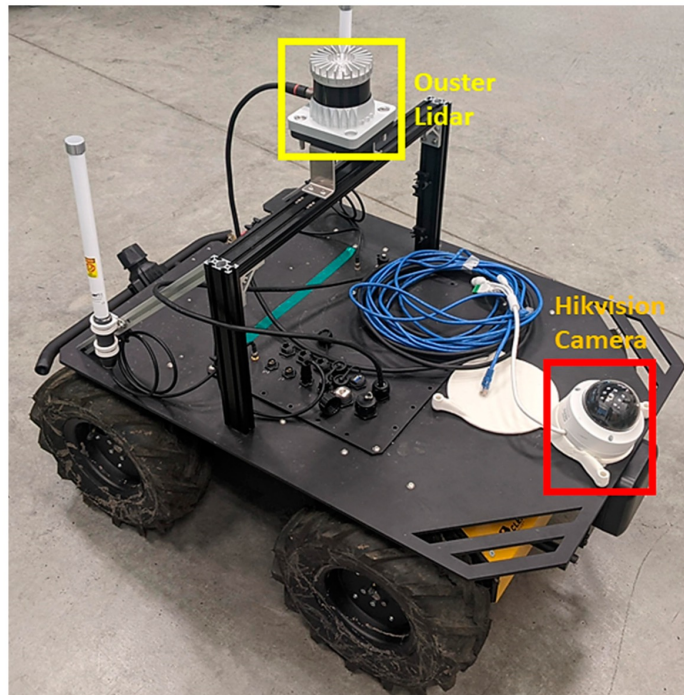


Figure 2. Husky robot setup with a Lidar sensor and Hikvision camera.

1. **Increased Storage Capacity and Efficiency:** AMRs can leverage vertical storage solutions like Modula's Vertical Lift Modules (VLMs), optimizing space utilization and enabling more compact, organized storage. This results in improved storage capacity and reduced clutter within facilities.
2. **Employee Safety and Task Automation:** AMRs can handle dangerous or physically demanding tasks, minimizing risks to human workers. Additionally, they automate mundane and repetitive operations, allowing employees to focus on more valuable, complex duties.
3. **Productivity Gains and Error Reduction:** By supporting employees with tasks like picking, locating, and moving inventory, AMRs enhance overall efficiency and productivity. Their precision and AI-driven software minimize errors, reducing the chances of accidents and order returns.
4. **Flexibility and Adaptability:**
 - AMRs require no guiding infrastructure and can navigate autonomously, adapting to changes in equipment and materials around the facility.
 - They can operate in unstructured environments, quickly adjusting to new routes, warehouses,

and workflows without the need for robotics experts.

- AMRs can get around obstacles, ensuring continuous operation and minimizing downtime.
5. **Scalability and Cost-Effectiveness:**
 - AMRs are highly scalable, allowing businesses to easily add more robots as needed.
 - While the initial investment can be high, AMRs lead to long-term cost savings by reducing labor costs and indirect operating costs.
 - They require less maintenance than traditional systems and can help avoid costly human errors.
 6. **Data-Driven Decision Making:** AMRs can improve data collection, providing businesses with valuable insights for making informed, data-driven decisions to optimize operations further.
 7. **Long-Term Sustainability and Growth:** By reducing human error, enhancing scalability, and adapting to changing business needs, AMRs support long-term sustainability and growth for organizations across various sectors.

In summary, the key benefits of AMRs include enhanced safety for workers, increased flexibility to adapt to changing environments, improved efficiency and productivity by automating tasks and reducing downtime, and cost-effectiveness through 24/7 operation and reduced labor costs [8, 9].

2.1 Applications of AMRs

Autonomous Mobile Robots (AMRs) have found applications across a wide range of industries, including manufacturing, warehousing, logistics, healthcare, retail, banking, hospitality, smart cities, the public sector, and agriculture. Their versatility extends beyond industrial settings, with AMRs providing information to shoppers, delivering room service in hotels, and supporting law enforcement by patrolling city areas [10].

In the manufacturing and logistics sectors, AMRs excel at transporting goods across large warehouse areas more efficiently than human workers. They can handle monotonous tasks like palletization effectively using features like lift plates and robotic arms. Additionally, AMRs are employed for supply delivery, disinfection, and patient navigation in medical facilities, as well as secure transportation of data and samples in data centers and research facilities using lockable boxes or cabinets (Fig. 3) [11].

Some specific applications of AMRs include.

1. **Warehousing and Distribution Centers:**
 - Loading, unloading, transporting, stacking, and retrieving palletized and other large loads
 - Superior to Automated Guided Vehicles (AGVs) for order picking and sortation tasks, which can account for up to 55% of operating costs
 - Automating order picking through goods-to-person, zone picking, and flexible sortation approaches
2. **Cleaning and Disinfection:**
 - Equipped with floor scrubbers, disinfectant sprayers, and UV light emitters for automated cleaning and disinfection
 - Critical during the COVID-19 pandemic for maintaining hygiene in facilities
3. **Security and Surveillance:**
 - Autonomous Security Robots (ASRs) can patrol facilities, provide constant video monitoring, and respond to events using autonomous navigation and AI capabilities
4. **Healthcare:**
 - Automating internal transport of items like meals, linens, drugs, and waste, reducing potential for human-borne spread of viruses and bacteria

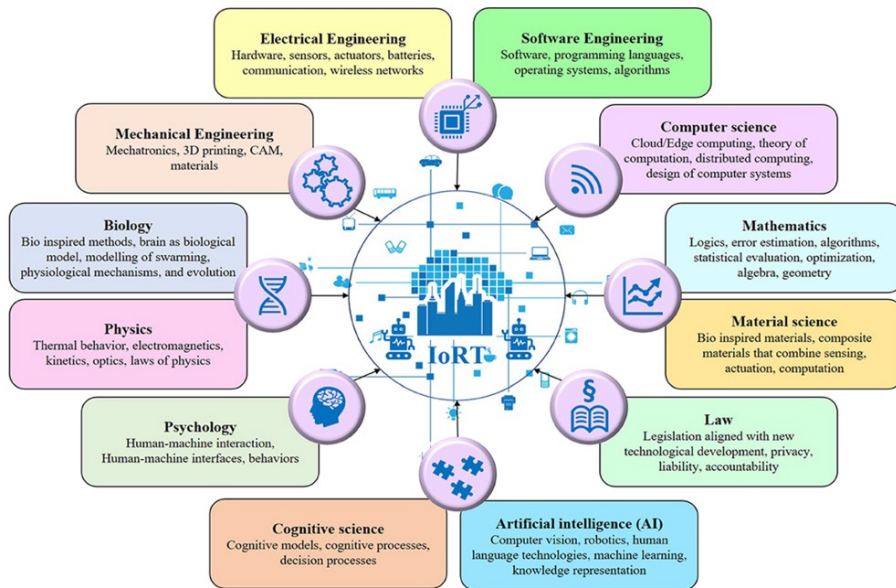


Figure 3. Outline of different fields of study and research perspectives on mobile robots.

- Improving traceability of materials and equipment

5. **Hospitality:**

- Delivering food, drinks, and goods to hotel guests
- Automating back-of-house material handling tasks
- Enabling contactless service and reducing labor costs

6. **Retail:**

- Detecting spills, retrieving items for online orders, and scanning shelves for inventory management in grocery stores

7. **Last-Mile Delivery:**

- Autonomous delivery vans, sidewalk pods, and drone pods can help reduce the high costs associated with the last mile of package delivery

3. **AMR Technologies**

Intel offers a range of technologies and solutions to support the development and deployment of Autonomous Mobile Robots (AMRs) [12, 13].

1. **Edge Computing:** Intel's edge-ready compute solutions provide the processing power required for AMRs to perform tasks such as real-time data processing, decision-making, and autonomous navigation.
2. **Computer Vision:** Intel RealSense depth cameras and the OpenVINO toolkit enable AMRs to perceive their environment accurately, detect obstacles, and navigate safely.
3. **Connectivity:** Intel's connectivity solutions ensure reliable and secure communication between AMRs, cloud services, and other devices within the ecosystem.
4. **Artificial Intelligence (AI):** Intel's AI technologies, such as deep learning and machine learning, power the intelligent decision-making capabilities of AMRs, enabling them to adapt to dynamic environments and optimize their performance.

5. **Software Tools:** Intel's Edge Software Hub and DevCloud provide a comprehensive suite of software tools and resources for developing, testing, and deploying AMR applications and solutions.

Several key companies are at the forefront of AMR development and deployment, leveraging these technologies from Intel and other providers. These include.

- ABB
- Aethon
- Blue Ocean Robotics
- Dusty Robotics
- Fetch Robotics

And many others, each contributing to the advancement of AMR capabilities and applications across various industries.

3.1 AMR Implementation

When implementing Autonomous Mobile Robots (AMRs), it's crucial to evaluate existing processes and identify areas that could benefit from automation. Common initial applications include material transport, line-side delivery, end-of-line transport, and tasks involving heavy manual labor (Fig. 4). Factors to consider when selecting an AMR include its physical size, payload capacity, runtime per charge, support requirements, integration with other AMRs, and necessary certifications [14, 15].

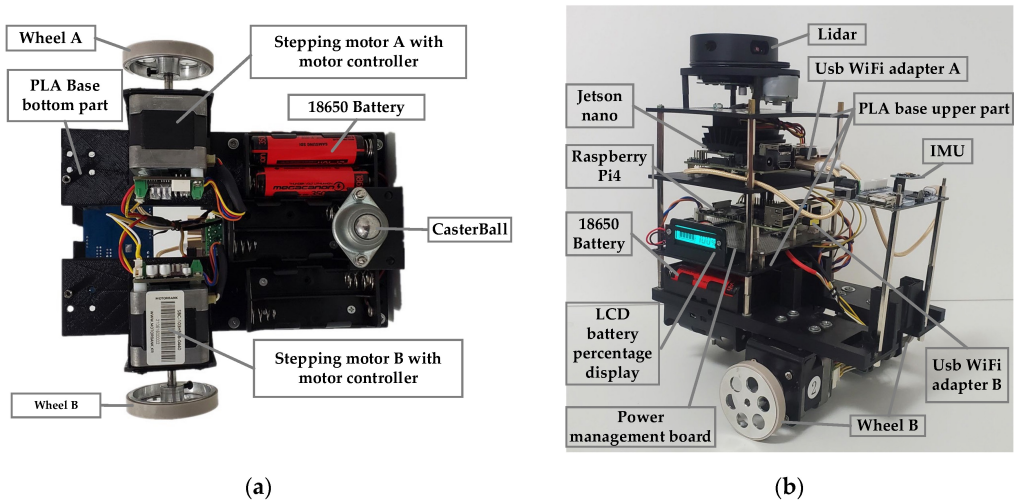


Figure 4. Owlbot robot and its components.

Proper planning and preparation are essential to avoid common pitfalls during AMR deployment, such as.

1. Improper mapping and map setup
2. Exceeding the robot's payload capacity
3. Lack of modifications to support the automated process
4. Failure to test compatibility with existing systems
5. Inadequate safety protocols and worker training

AMRs can be seamlessly integrated with existing automation systems and warehouse management software (WMS) to create an efficient workflow. When implementing AMRs, it's crucial to.

- Assess your specific needs and requirements
- Evaluate your work environment and existing infrastructure
- Ensure compatibility with your current systems
- Determine your budget and analyze the return on investment (ROI)

Training is a critical component of successful AMR implementation. This includes.

- Training workers on how to supervise and interact with the AMRs
- Training maintenance staff on robot upkeep and troubleshooting

Additionally, implementing a system for real-time monitoring of AMR performance, collecting and analyzing data to identify areas for improvement, and scheduling routine maintenance and inspections can help optimize AMR use and reduce operational costs.

Overall, successful AMR implementation requires integrating AMR software with the warehouse management/execution system, taking a holistic view of how AMRs will fit into the overall operation, and adopting a structured implementation strategy in collaboration with the AMR supplier [16, 17].

4. Safety Considerations

Ensuring the safe operation of Autonomous Mobile Robots (AMRs) is crucial for their successful integration into various industries. Several key considerations must be addressed (Fig. 5).

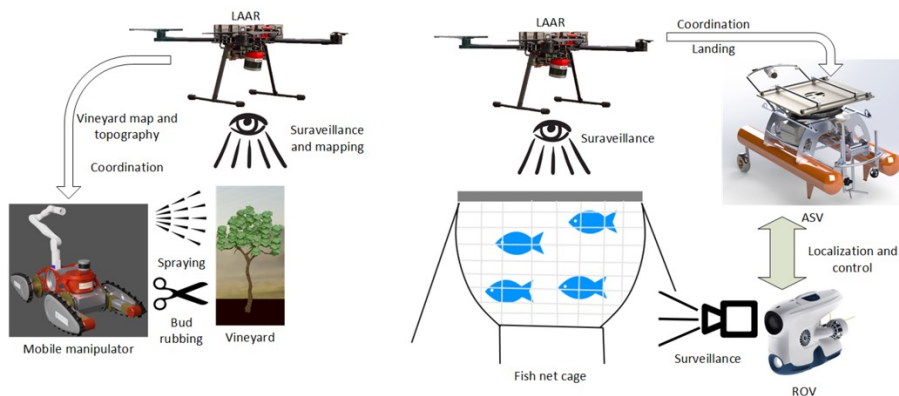


Figure 5. HEKTOR system overview.

1. Emergency Preparedness:

- AMRs must allow a clear path for humans to reach exit doors during emergencies.
- The external alarm system should be tied to the AMRs' internal messaging system, enabling them to respond appropriately by getting out of the way.

2. Payload Stability:

- Proper payload positioning is essential to maintain stability and prevent the AMR from tipping over.
- The payload weight should be positioned as close as possible to the AMR's center of gravity.

3. Obstacle Detection and Stopping Ability:

- Laser-based area scanners and other sensors help AMRs detect obstacles in time to stop smoothly.
- Stopping distances can be calculated based on the AMR's speed and the time needed to stop.
- The surface the AMR travels on can impact its balance and stopping ability, so factors like incline, decline, and surface irregularities should be considered.

4. Communication and Coordination:

- AMRs need to communicate with other equipment, such as when loading or unloading parts.
- They may need to mute their area scanner and reduce approach speed to avoid potential collisions with people.

5. Functional Safety:

- Functional safety is an engineering methodology used to design the overall safety of a system and ensure an acceptable level of risk for AMRs.
- Certified Functional Safety Engineers (CFSE) and Certified Functional Safety Professionals (CFSP) undergo extensive training and testing to obtain certification for ensuring functional safety.

6. Safety Standards and Compliance:

- The new ANSI/RIA R15.08-1-2020 standard provides technical requirements for the design and integration of industrial mobile robots, including AMRs.
- Using a third-party expert can help mobile robot OEMs avoid costly rework and focus on their unique value proposition.

7. Speed and Separation Monitoring (SSM):

- The goal is to use SSM to enable collaborative applications where humans and robots can work as close to each other as possible, while minimizing the necessary safety distances.
- This approach involves dynamically generating a 'robot safety space' and a 'person safety space' based on camera-based detection and tracking of humans in the workspace.
- The robot safety space is generated using a voxel-based discretization and a braking model, considering both static and dynamic collision objects.
- The person safety space is constructed by projecting the 2D human silhouette onto the ground plane and adding safety margins, considering the person's potential movement during the robot's reaction and braking time.

8. ANSI/RIA R15.08-1-2020 Standard:

- This standard defines the safety requirements for Industrial Mobile Robots (IMRs), including both Automated Guided Vehicles (AGVs) and Autonomous Mobile Robots (AMRs).
- It classifies IMRs into three types. Type A (basic AMR), Type B (AMR with passive or active attachments), and Type C (AMR or AGV with a robotic manipulator attached).
- Key safety considerations covered include hazard identification and risk assessment, design requirements and risk reduction measures, verification and validation of risk reduction measures, and information for use and markings.
- The standard aims to ensure the safe design, manufacture, and installation of industrial mobile robots to protect the 'safety-trained' personnel working around them.

5. Data and Analytics

Autonomous Mobile Robots (AMRs) generate a wealth of data that can provide valuable insights for optimizing operations and decision-making. By leveraging advanced analytics, businesses can unlock the full potential of AMRs and drive continuous improvement. Here are some key aspects of

data and analytics in the context of AMRs [18, 19, 20].

1. Data Collection and Integration:

- AMRs are equipped with various sensors, such as LiDAR, cameras, and odometry sensors, that collect data about their environment, movements, and operations.
- This data can be integrated with other systems, such as warehouse management systems (WMS), enterprise resource planning (ERP) systems, and manufacturing execution systems (MES), to provide a comprehensive view of operations.

2. Real-Time Monitoring and Optimization:

- By analyzing real-time data from AMRs, businesses can monitor their performance, identify bottlenecks, and make informed decisions to optimize operations.
- For example, data on AMR traffic patterns, task completion times, and battery levels can be used to adjust routes, schedules, and charging cycles for improved efficiency.

3. Predictive Maintenance:

- AMRs generate data on various components, such as motors, sensors, and batteries, which can be analyzed to predict potential failures or maintenance needs.
- Predictive maintenance algorithms can be applied to this data, enabling proactive maintenance and reducing downtime.

4. Safety and Compliance:

- Data from AMRs can be used to monitor safety conditions, such as detecting obstacles, identifying potential hazards, and ensuring compliance with safety regulations.
- Advanced analytics can be employed to identify patterns and trends that may indicate potential safety risks, allowing for preventive measures to be taken.

5. Simulation and Scenario Planning:

- AMR data can be used to create digital twins or simulations of the operational environment, enabling businesses to test different scenarios and optimize their AMR deployment strategies.
- Simulation tools can help identify potential bottlenecks, evaluate the impact of layout changes, and optimize AMR fleet sizes and configurations.

6. Performance Benchmarking and Continuous Improvement:

- By analyzing AMR data over time, businesses can establish performance benchmarks and identify areas for continuous improvement.
- Comparative analysis of AMR performance across different facilities or operations can help identify best practices and opportunities for optimization.

7. Data Visualization and Reporting:

- AMR data can be presented through intuitive dashboards and reports, providing stakeholders with real-time insights and enabling data-driven decision-making.
- Visual representations of AMR performance, utilization, and operational metrics can facilitate better understanding and communication across teams.

To fully leverage the potential of AMR data and analytics, businesses should adopt a comprehensive data strategy that includes data governance, security, and privacy measures. Additionally, investing in advanced analytics tools, such as machine learning and artificial intelligence, can further enhance the insights derived from AMR data and drive continuous improvement in operations (Fig. 6).

6. Industry Examples

Several companies are leading the way in the development and deployment of Autonomous Mobile Robots (AMRs) across various industries. Here are some notable examples.

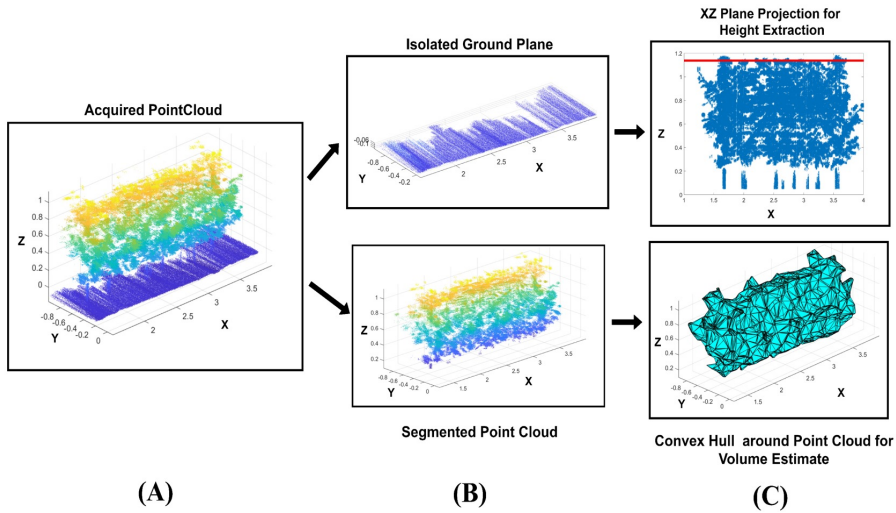


Figure 6. LiDAR phenotyping pipeline to extract phenotypic traits.

- **Material Handling Systems (MHS)** offers AMRs for order fulfillment, kitting, picking, sorting, and inventory management. Their solutions are designed to streamline material handling operations and enhance operational efficiency.
- **Fetch Robotics** provides autonomous mobile manipulators for warehousing, e-commerce, and logistics. Their robots are capable of performing tasks such as picking, transporting, and organizing inventory autonomously.
- **IAM Robotics** specializes in autonomous inventory robots for inventory management, cycle counts, and replenishment. Their solutions help businesses optimize inventory management processes and improve accuracy.
- **NextShift Robotics** offers self-driving forklifts for material handling, pallet movement, and transportation. Their autonomous forklifts are designed to enhance safety and efficiency in material handling operations.
- **Stanley Robotics** provides autonomous valet parking robots for parking space optimization. Their robots can autonomously park and retrieve vehicles, maximizing the utilization of available parking spaces.
- **Robotnik** offers mobile manipulators and collaborative robots for manufacturing, logistics, healthcare, and agriculture. Their robots are designed to work alongside humans, enhancing productivity and safety.
- **SESTO Robotics** specializes in autonomous industrial vehicles (AIVs) for manufacturing, logistics, and healthcare. Their AIVs are designed to automate material handling and transportation tasks in various industrial settings.
- **HAHN Robotics GmbH** focuses on autonomous guided vehicles (AGVs) for industrial material handling and logistics. Their AGVs are designed to optimize material flow and improve operational efficiency.
- **Vecna Robotics** leverages AI-powered AMRs for autonomous mobile picking in warehousing, e-commerce, and retail. Their robots are designed to streamline order fulfillment processes and enhance productivity.

- **AutoGuide Mobile Robots** offers a range of AGVs for manufacturing, logistics, and healthcare. Their AGVs are designed to automate material handling tasks and improve operational efficiency.

These companies are at the forefront of AMR development and deployment, offering innovative solutions that are transforming various industries by enhancing productivity, efficiency, and safety.

7. Conclusion

The remarkable advancements in autonomous mobile robotics have opened up a world of possibilities, reshaping industries and revolutionizing the way we approach automation and efficiency. AMRs, with their adaptive navigation capabilities and seamless integration with existing systems, offer unparalleled flexibility and scalability, enabling businesses to streamline operations, enhance safety, and optimize productivity. As we continue to embrace the power of AMRs, it is crucial to prioritize safety, compliance, and effective implementation strategies. By leveraging data-driven insights, advanced analytics, and continuous improvement methodologies, businesses can unlock the full potential of AMRs and drive sustainable growth. The future holds immense promise for autonomous mobile robotics, and those who embrace this transformative technology will undoubtedly gain a competitive edge in an increasingly automated world.

References

- [1] Mary B Alatise and Gerhard P Hancke. "A review on challenges of autonomous mobile robot and sensor fusion methods". In: *IEEE Access* 8 (2020), pp. 39830–39846.
- [2] Thomas Howard, Mihail Pivtoraiko, Ross A Knepper, and Alonzo Kelly. "Model-predictive motion planning: Several key developments for autonomous mobile robots". In: *IEEE Robotics & Automation Magazine* 21.1 (2014), pp. 64–73.
- [3] Vladimir F Filaretov and Valentin E Pryanichnikov. "Autonomous mobile university robots AMUR: Technology and applications to extreme robotics". In: *Procedia Engineering* 100 (2015), pp. 269–277.
- [4] James Kramer and Matthias Scheutz. "Development environments for autonomous mobile robots: A survey". In: *Autonomous Robots* 22 (2007), pp. 101–132.
- [5] Francisco Rubio, Francisco Valero, and Carlos Llopis-Albert. "A review of mobile robots: Concepts, methods, theoretical framework, and applications". In: *International Journal of Advanced Robotic Systems* 16.2 (2019), p. 1729881419839596.
- [6] Gregor Klancar, Andrej Zdesar, Saso Blazic, and Igor Skrjanc. *Wheeled mobile robotics: from fundamentals towards autonomous systems*. Butterworth-Heinemann, 2017.
- [7] Ulrich Nehmzow. *Mobile robotics: a practical introduction*. Springer Science & Business Media, 2012.
- [8] Roland Siegwart, Illah Reza Nourbakhsh, and Davide Scaramuzza. *Introduction to autonomous mobile robots*. MIT press, 2011.
- [9] Lynne E Parker. "Current state of the art in distributed autonomous mobile robotics". In: *Distributed autonomous robotic systems* 4 (2000), pp. 3–12.
- [10] Elena Garcia, Maria Antonia Jimenez, Pablo Gonzalez De Santos, and Manuel Armada. "The evolution of robotics research". In: *IEEE Robotics & Automation Magazine* 14.1 (2007), pp. 90–103.
- [11] Carlotta A Berry. *Mobile robotics for multidisciplinary study*. 4. Morgan & Claypool Publishers, 2012.
- [12] Alexandre Gabriel, Claude Charles, Louis Andre, and Charlotte Antoine. "Navigating the Future of Wearable Devices with Flexible Electronics". In: *Fusion of Multidisciplinary Research, An International Journal (FMR)* 1.2 (2020), pp. 63–72.

- [13] Abdelghani Chibani, Yacine Amirat, Samer Mohammed, Eric Matson, Norihiro Hagita, and Marcos Barreto. “Ubiquitous robotics: Recent challenges and future trends”. In: *Robotics and Autonomous Systems* 61.11 (2013), pp. 1162–1172.
- [14] Andreas Birk and Stefano Carpin. “Rescue robotics—a crucial milestone on the road to autonomous systems”. In: *Advanced Robotics* 20.5 (2006), pp. 595–605.
- [15] Ranbir Singh Batth, Anand Nayyar, and Amandeep Nagpal. “Internet of robotic things: driving intelligent robotics of future-concept, architecture, applications and technologies”. In: *2018 4th international conference on computing sciences (ICCS)*. IEEE. 2018, pp. 151–160.
- [16] Vito Trianni. *Evolutionary swarm robotics: evolving self-organising behaviours in groups of autonomous robots*. Vol. 108. Springer Science & Business Media, 2008.
- [17] Adam Jacoff, Elena Messina, and John Evans. “Performance evaluation of autonomous mobile robots”. In: *Industrial Robot: An International Journal* 29.3 (2002), pp. 259–267.
- [18] Michael Schneier, Michael Schneier, and Roger Bostelman. “Literature review of mobile robots for manufacturing”. In: (2015).
- [19] Alonzo Kelly. *Mobile robotics: mathematics, models, and methods*. Cambridge University Press, 2013.
- [20] Matthew Dunbabin and Lino Marques. “Robots for environmental monitoring: Significant advancements and applications”. In: *IEEE Robotics & Automation Magazine* 19.1 (2012), pp. 24–39.