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Dynamic Power Management for Autonomous Shelf-Transport Warehouse Robots

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Abstract **Review Article**

Warehouse automation has become increasingly important as companies work to meet the growing demand for faster shipping and greater operational efficiency. Autonomous shelf-transport warehouse robots have become a key part of this transformation because they can move inventory without direct human involvement. However, these robots rely on limited battery power to operate multiple subsystems, including drive motors, sensors, onboard processors, and wireless communication devices. Most current warehouse robots use fixed power settings that do not adjust to changing operating conditions, leading to unnecessary energy consumption and reduced battery life. As warehouses continue expanding their robotic fleets, improving energy efficiency has become an important engineering challenge. This paper proposes a dynamic power management framework designed specifically for autonomous shelf-transport warehouse robots. Rather than relying on fixed operating parameters, the proposed system continuously monitors battery condition, shelf weight, warehouse traffic, travel distance, processor workload, and sensor activity. Using this information, the framework dynamically adjusts motor power, robot speed, sensing frequency, computing resources, route selection, and charging decisions to maximize battery efficiency while maintaining productivity. Artificial intelligence techniques, including predictive modeling and adaptive decision-making, are also discussed as methods for further improving system performance. Although the proposed framework has not been physically implemented, it is based on current research in robotics, battery management, and intelligent control systems. The design demonstrates how software-based optimization can reduce energy consumption, extend battery life, lower operating costs, and improve the long-term efficiency of autonomous warehouse robotics.

Keywords: Autonomous mobile robots, Warehouse automation, Dynamic power management, Battery health, Intelligent control, Route optimization.

INTRODUCTION

The rapid growth of e-commerce has changed the way warehouses operate. Customers now expect orders to be processed and shipped within hours instead of days, requiring companies to improve both the speed and efficiency of their logistics operations. To meet these expectations, many warehouses have adopted automation technologies that reduce human labor while increasing productivity. One of the most significant developments has been the use of Autonomous Mobile Robots (AMRs), which transport shelves, inventory, and materials throughout a warehouse without requiring fixed tracks or direct human control. These robots have become an essential part of modern fulfillment centers because they improve order accuracy, reduce worker travel time, and allow warehouses to operate continuously.

Despite their advantages, autonomous warehouse robots face an important limitation: battery capacity. Every robot depends on a rechargeable battery to power its drive motors, lifting mechanisms, sensors, onboard computers, and wireless communication systems. Since every subsystem draws energy from the same battery, inefficient power management can shorten operating time and increase the number of charging cycles required each day. Frequent charging reduces productivity because robots cannot transport inventory while connected to charging stations. Over time, repeated charging also contributes to battery degradation, increasing maintenance costs and reducing the overall lifespan of the robotic fleet.

Current warehouse robots typically use fixed power settings and simple rule-based battery management systems. Motors often operate at similar power levels regardless of shelf weight, while sensors and processors remain fully active even when maximum performance is unnecessary. Although these methods are reliable and relatively simple to implement, they do not account for changing operating conditions such as traffic congestion, battery condition, or workload. As a result, robots frequently consume more energy than required to complete their assigned tasks.

Recent advances in artificial intelligence have created new opportunities for improving robotic energy management. Machine learning algorithms can analyze large amounts of operational data to predict battery consumption, estimate future workloads, and recommend energy-efficient operating strategies. Rather than relying solely on fixed programming, AI systems can continuously adapt to changing conditions by making intelligent decisions based on real-time information. These technologies have already shown promise in battery management, route optimization, and predictive control across many types of autonomous robotic platforms.

This paper proposes the design of a dynamic power management framework for autonomous shelf-transport warehouse robots. The framework integrates battery monitoring, adaptive motor control, intelligent route planning, dynamic sensor operation, and AI-assisted decision making into a single energy management architecture. Instead of increasing battery size or changing robot hardware, the proposed system focuses on optimizing the way energy is distributed among the robot's existing subsystems. The primary objective is to improve battery life, reduce energy consumption, increase warehouse productivity, and lower long-term operating costs while maintaining safe and reliable autonomous operation.

BACKGROUND

Autonomous shelf-transport warehouse robots are designed to move inventory efficiently throughout warehouses while reducing manual labor and increasing productivity. Unlike traditional automated guided vehicles (AGVs), which follow fixed paths using magnetic strips or predefined routes, Autonomous Mobile Robots (AMRs) navigate independently using onboard sensors, artificial intelligence, and real-time mapping algorithms. This flexibility allows them to adapt to changing warehouse layouts, avoid unexpected obstacles, and coordinate with other robots operating in the same environment. As warehouses continue to expand their use of automation, AMRs have become one of the most important technologies supporting modern supply chain operations.

Warehouse robots begin each task after receiving instructions from a Warehouse Management System (WMS). The WMS stores inventory locations, monitors incoming customer orders, and assigns transportation tasks to available robots. Fleet management software evaluates each robot's location, battery level, and current workload before selecting the most appropriate robot for the assignment. After receiving a task, the robot calculates a navigation path to the storage shelf while considering warehouse maps, obstacles, and traffic conditions. Once the shelf is reached, the robot lifts it slightly off the floor and transports it to a picking station where workers or automated systems retrieve the required inventory before the robot returns the shelf to storage.

The battery system is the foundation of every autonomous warehouse robot because it supplies electrical energy to every subsystem. Most commercial warehouse robots use lithium-ion batteries due to their high energy density, relatively low weight, fast charging capability, and long cycle life. A Battery Management System (BMS) continuously monitors battery voltage, current, temperature, and state of charge to prevent unsafe operating conditions such as overheating, overcharging, or excessive discharge. Although lithium-ion batteries perform well, their capacity gradually decreases after repeated charging cycles, making battery health an important factor affecting long-term operating costs and robot reliability. Researchers continue to investigate improved battery technologies and smarter battery management strategies to extend robot operating time and reduce maintenance costs.

Drive motors represent the largest source of electrical energy consumption within autonomous warehouse robots. These electric motors convert battery power into mechanical motion that allows the robot to accelerate, steer, transport shelves, and stop accurately. The amount of energy consumed depends on several operating conditions, including payload weight, travel distance, acceleration, turning frequency, and floor conditions. Heavy shelves require greater motor torque, while repeated acceleration and braking create large current spikes that reduce battery efficiency. Studies consistently identify locomotion as the dominant contributor to total robot energy consumption, often accounting for more than half of the electrical energy used during normal operation. This makes motor control one of the most important opportunities for improving overall energy efficiency.

Modern warehouse robots depend on multiple sensing technologies to navigate safely and perform autonomous tasks. LiDAR sensors generate three-dimensional maps of the surrounding environment using laser measurements, allowing robots to detect walls, shelving units, obstacles, and nearby workers. Cameras provide additional information through computer vision, enabling robots to recognize barcodes, QR codes, storage locations, and visual landmarks. Wheel encoders measure wheel rotation to estimate robot movement, while inertial measurement units (IMUs) improve localization by measuring acceleration and orientation. These sensors work together through sensor fusion algorithms that combine multiple sources of information to improve navigation accuracy. Although essential for safe operation, continuously running every sensor at maximum performance also increases processor workload and battery consumption.

The onboard computer functions as the robot's central control system by processing sensor data and making navigation decisions in real time. Modern warehouse robots perform simultaneous localization and mapping (SLAM), obstacle avoidance, motion planning, and fleet coordination using increasingly sophisticated processors capable of executing artificial intelligence algorithms. As AI capabilities become more advanced, processor energy consumption also increases. Computer vision models, machine learning algorithms, and real-time optimization require significant computational resources that contribute to total battery usage. Improving software efficiency and dynamically adjusting processor performance according to workload can therefore reduce energy consumption while maintaining reliable robot operation.

Communication systems also play an important role in autonomous warehouse operations. Robots communicate continuously with warehouse servers using industrial Wi-Fi or private 5G networks to receive new assignments, report battery status, update their location, and coordinate with other robots. Fleet management software relies on this communication to prevent collisions, optimize task assignments, and balance workloads across hundreds of robots. Although wireless communication consumes considerably less power than locomotion, continuous networking still contributes to total battery consumption. Researchers have proposed edge computing and distributed processing as methods for reducing communication overhead while maintaining reliable coordination throughout the warehouse.

Most commercial warehouse robots currently rely on relatively simple power management strategies. Motors often operate with fixed power settings, sensors remain continuously active, and charging begins once the battery reaches a predetermined threshold. While these approaches are reliable and easy to implement, they rarely account for changing warehouse conditions such as traffic congestion, shelf weight, remaining battery capacity, or processor workload. Recent research suggests that dynamic power management systems capable of continuously adapting robot behavior could significantly improve battery life, reduce electricity consumption, and increase warehouse productivity. These findings provide the foundation for the dynamic power management framework proposed in this paper.

Sources of Energy Consumption and Challenges in Current Systems

Understanding how warehouse robots consume energy is essential for designing a more efficient power management system. Although every subsystem within an autonomous robot requires electricity to function, not all components consume the same amount of power. Research consistently shows that locomotion is the largest contributor to energy consumption, while sensing, computing, and wireless communication make up the remaining portion of the robot's electrical demand. By identifying where energy is being used, engineers can develop strategies that reduce unnecessary consumption without decreasing robot performance.

The drive motors are responsible for moving the robot, transporting shelves, accelerating, turning, and stopping accurately throughout the warehouse. Because these tasks require mechanical work, the motors consume more electrical energy than any other subsystem. Studies have shown that locomotion can account for more than half of an autonomous mobile robot's total energy consumption, making motor control one of the most important areas for optimization. Motor power demand increases significantly when transporting heavier shelves, accelerating quickly, climbing ramps, or repeatedly stopping and starting in congested areas. As a result, improving motor efficiency offers the greatest opportunity for extending battery life without changing the robot's hardware.

Another challenge is downtime. When a turbine stops working because of mechanical problems, it cannot generate electricity. Every hour that a turbine is out of service reduces the amount of clean energy produced and decreases company revenue. Repair crews must travel to the turbine, inspect the damage, order replacement parts if necessary, and complete the repairs before electricity production can continue. This process may take several days or even weeks, especially for offshore wind farms that are located far from land.

Sensors represent another important source of energy consumption. Warehouse robots depend on LiDAR sensors, cameras, wheel encoders, and inertial measurement units (IMUs) to navigate safely and accurately. LiDAR continuously scans the surrounding environment by emitting laser pulses, while cameras capture images that support computer vision algorithms for obstacle detection and localization. Although these sensors are essential for autonomous operation, operating every sensor at maximum performance throughout every delivery consumes unnecessary energy. In many situations, such as traveling through open warehouse aisles with little surrounding activity, the robot does not require the same sensing performance that it would need in a crowded intersection. Researchers have suggested that adaptive sensor scheduling could reduce processor workload and battery consumption while maintaining safe navigation.

The onboard computer also contributes significantly to total energy usage. Modern autonomous warehouse robots perform simultaneous localization and mapping (SLAM), obstacle avoidance, route planning, and fleet coordination while processing large amounts of sensor data in real time. Artificial intelligence algorithms, especially computer vision and machine learning models, require additional computational resources that increase processor power consumption. As processors become more powerful, computing energy becomes a larger percentage of total battery usage. Improving software efficiency and adjusting processor performance according to workload can therefore reduce electrical demand without reducing robot capability.

Several external factors also influence robot energy consumption. Shelf weight directly affects the amount of motor torque required to move inventory. Heavier shelves require higher electrical current during acceleration and transportation, while lighter shelves could often be transported using considerably less power. Travel distance also influences battery usage because longer routes require motors, sensors, processors, and communication systems to remain active for a greater period of time. Assigning tasks without considering expected energy consumption may cause some robots to deplete their batteries much faster than others, creating unnecessary charging interruptions throughout the fleet.

Warehouse traffic and congestion create additional inefficiencies. During busy operating periods, robots frequently stop to avoid collisions or wait for other robots to clear intersections. Every stop requires the robot to accelerate again, producing large current spikes that consume considerably more energy than maintaining a constant speed. Congestion also increases delivery time because sensors and processors continue operating while the robot waits. Recent research has shown that energy-aware routing algorithms that consider traffic conditions can significantly improve both battery efficiency and warehouse throughput.

Despite advances in autonomous robotics, most commercial warehouse robots continue to rely on relatively simple power management strategies. Motors generally operate using fixed control settings regardless of shelf weight, while sensors remain active throughout every task even when maximum sensing capability is unnecessary. Charging decisions are often based on fixed battery thresholds instead of considering future workload, warehouse traffic, or charging station availability. These rule-based approaches are reliable and easy to implement, but they cannot continuously adapt to changing operating conditions.

Battery limitations present another significant challenge. Lithium-ion batteries gradually lose capacity after repeated charging cycles, reducing robot operating time and increasing maintenance costs. Frequent deep discharges and excessive fast charging accelerate battery degradation, making battery replacement one of the largest long-term expenses associated with autonomous warehouse robots. Because warehouse productivity depends heavily on battery availability, improving battery utilization has become an important area of research for both robotics engineers and warehouse operators.

Charging downtime further reduces warehouse efficiency. Whenever a robot leaves its assigned task to recharge, another robot must either complete the work or the task remains unfinished until charging is complete. If many robots require charging simultaneously, charging stations may become congested, creating additional delays. Traditional charging strategies typically send robots to recharge as soon as battery levels reach a predetermined threshold without considering future warehouse demand. More intelligent charging strategies that predict future workloads and coordinate charging schedules across the entire fleet could significantly improve robot availability while reducing unnecessary waiting time.

These challenges demonstrate that current warehouse robots often use energy inefficiently despite possessing advanced navigation and automation capabilities. Instead of relying on fixed operating parameters, future systems should continuously adapt motor power, processor performance, sensing activity, route selection, and charging schedules according to changing warehouse conditions. The following section presents a proposed dynamic power management framework designed to address these challenges by integrating intelligent energy management into every major subsystem of the robot.

Proposed Dynamic Power Management Framework

The primary objective of this research is to design a dynamic power management framework capable of intelligently distributing electrical energy among the major subsystems of an autonomous shelf-transport warehouse robot. Unlike traditional warehouse robots that operate using fixed control settings, the proposed framework continuously evaluates operating conditions and adjusts power allocation in real time. Instead of simply increasing battery capacity or installing larger motors, this design focuses on using existing hardware more efficiently through intelligent software control. By combining battery monitoring, adaptive motor control, energy-aware routing, dynamic sensing, processor management, and artificial intelligence, the framework aims to maximize battery life while maintaining high warehouse productivity.

The first component of the proposed framework is adaptive motor power control. Since drive motors consume the largest percentage of the robot's electrical energy, optimizing motor operation provides the greatest opportunity for improving overall efficiency. Before beginning each delivery, the robot estimates the weight of the storage shelf using information from force sensors, motor current measurements, or warehouse inventory records. Instead of supplying the same amount of motor power for every task, the controller dynamically adjusts motor torque according to the estimated payload. Light shelves require less torque and therefore consume less electricity, while heavier shelves automatically receive additional power only when necessary. Once the robot reaches its desired speed, motor output is reduced to maintain efficient cruising rather than continuing to operate at maximum power. This adaptive approach decreases electrical current draw, reduces heat generation, minimizes mechanical wear, and extends battery operating time. Similar adaptive power management strategies have demonstrated significant improvements in robotic energy efficiency across multiple autonomous platforms.

The second component is battery-aware speed control. Every autonomous warehouse robot continuously monitors battery condition through its Battery Management System (BMS), which measures battery voltage, current, temperature, and state of charge. Instead of maintaining constant travel speeds throughout every task, the proposed framework gradually adjusts maximum speed according to remaining battery capacity. When battery levels are high, the robot operates at full performance to maximize productivity. As battery capacity decreases, acceleration and maximum speed are gradually reduced to lower motor current draw while maintaining safe transportation of inventory. If battery levels become critically low, the robot automatically evaluates whether it can safely complete its current assignment before navigating to the nearest available charging station. By avoiding sudden battery depletion and excessive current spikes, battery-aware speed control extends operating time while reducing long-term battery degradation.

Another important feature of the proposed system is energy-aware route planning. Traditional warehouse routing algorithms generally select the shortest available path without considering how much electrical energy each route requires. The proposed framework instead estimates total energy consumption by considering travel distance, shelf weight, expected traffic congestion, turning frequency, and current battery condition. For example, a slightly longer route through an open aisle may consume less energy than a shorter route that requires repeated stopping because of heavy robot traffic. Historical warehouse traffic patterns can also be analyzed using machine learning algorithms to predict future congestion before it occurs. This allows robots to proactively select routes that minimize energy consumption while maintaining efficient delivery times. Recent research in warehouse AI has shown that reinforcement learning can improve robot coordination and reduce congestion by dynamically prioritizing robot movement.

The framework also introduces dynamic sensor management. Autonomous warehouse robots rely heavily on LiDAR sensors, cameras, and other sensing technologies for navigation and obstacle detection. However, operating every sensor at full performance continuously is unnecessary in many warehouse environments. During travel through open aisles with few nearby obstacles, the robot can reduce camera frame rates or temporarily decrease LiDAR scanning frequency while still maintaining safe navigation. As the robot approaches intersections, workstations, or areas with increased human activity, sensing performance automatically returns to full operation. This adaptive sensing strategy reduces processor workload, lowers battery consumption, and improves overall energy efficiency without compromising safety.

The proposed design also incorporates dynamic computing resource management. Artificial intelligence algorithms, computer vision systems, and navigation software require significant computational resources that increase processor power consumption. Instead of operating the onboard computer at maximum performance continuously, processor speed and computational resources are adjusted according to the complexity of the current task. During routine navigation, processor frequency can be reduced to conserve energy. When obstacle avoidance, computer vision, or complex path planning become necessary, processor performance automatically increases. Dynamic voltage and frequency scaling (DVFS), which has been widely studied in robotics, provides one possible implementation of this concept.

The final component of the proposed framework is fleet-wide intelligent charging management. Rather than waiting until every robot reaches a fixed battery threshold before charging, fleet management software continuously predicts future workloads, charger availability, and battery condition. Robots with lower workloads may recharge earlier, while robots assigned to high-priority deliveries remain operational longer. Opportunity charging during short idle periods further reduces long charging interruptions and decreases congestion at charging stations. Artificial intelligence models can continuously learn optimal charging schedules by analyzing historical warehouse activity, allowing charging decisions to improve over time. Recent reinforcement learning research demonstrates that AI-based charging strategies outperform traditional rule-based scheduling methods in warehouse environments.

Together, these six components form a fully integrated dynamic power management framework capable of continuously optimizing robot energy usage throughout warehouse operations. Instead of treating each subsystem independently, the framework coordinates motor control, battery management, sensing, computing, routing, and charging as a unified energy optimization system. This integrated approach has the potential to significantly improve battery utilization, reduce electricity consumption, lower maintenance costs, and increase warehouse productivity while requiring minimal hardware modifications. As artificial intelligence continues advancing, dynamic power management systems such as the one proposed in this paper may become standard features of future autonomous warehouse robots.

Expected Benefits

The proposed dynamic power management framework could provide several benefits compared with fixed power management. The most direct improvement would be longer operating time per battery charge. Research on autonomous mobile robots shows that locomotion can account for more than half of total energy consumption, which means even relatively small improvements in motor control and route planning could meaningfully affect total energy use. Instead of treating every task the same, the proposed system would match energy use to factors such as payload, route, traffic, and battery condition.

Reducing energy consumption could also decrease charging frequency. This is important because charging is not simply an electrical issue. It directly affects warehouse throughput. Zou *et al.,* (2018) found that battery recovery strategies can significantly affect retrieval throughput in robotic mobile fulfillment systems. Chen *et al.,* (2024) similarly showed that battery management and charging policies affect robotic warehouse performance. A robot that uses its available battery more efficiently could remain productive for longer before leaving its tasks to recharge.

Intelligent charging could further improve this benefit. Instead of sending every robot to charge after reaching the same battery percentage, the system could consider predicted tasks and charging demand. Tomy *et al.,* (2021) developed a charging approach that reasons about predicted future tasks instead of relying only on fixed thresholds. More recent reinforcement-learning research has also investigated dynamically selecting charging stations and charging durations for warehouse AMRs. These findings support including predictive charging in the proposed framework.

Another expected benefit is improved fleet productivity. Energy management should not be viewed only at the individual robot level because hundreds of robots may share the same warehouse. Recent research on robotic mobile fulfillment systems specifically considers energy consumption alongside throughput and robot fleet decisions. The proposed system could distribute heavy or distant assignments toward robots with sufficient battery capacity while directing lower-battery robots toward shorter tasks or charging opportunities. This would help balance energy use throughout the fleet.

Finally, improved power management could reduce the environmental and financial cost of warehouse automation. Electricity consumption becomes increasingly important as robot fleets grow. Extending battery life could also reduce how frequently batteries need replacement. For warehouse operators, these improvements could reduce operating expenses while increasing the useful working time of existing robots.

Limitations and Future Research

The proposed framework is a design concept rather than an experimentally validated system, which is an important limitation of this paper. No physical warehouse robot was constructed or tested as part of this research. Therefore, this paper does not claim a specific percentage improvement in battery life or energy efficiency. Instead, the design combines approaches supported by existing research into one proposed architecture for future testing.

Another challenge is that optimizing energy use involves tradeoffs. Reducing motor speed may conserve battery power but increase delivery time. Lowering camera or LiDAR activity may reduce electrical consumption but could also reduce perception performance if it is done at the wrong time. Reducing processor frequency may save power but increase computation time. A successful controller therefore cannot simply minimize energy consumption. It must balance energy efficiency, productivity, navigation accuracy, safety, and battery health. Reviews of intelligent robotic power management similarly describe this as a multi-objective control problem rather than a single energy-minimization problem.

Artificial intelligence also creates its own energy cost. Running a larger neural network on a robot requires processor power, meaning an AI system could theoretically consume more energy than it saves if it is poorly designed. The AI component should therefore be lightweight enough that its optimization benefits exceed its computational energy requirements. Current research identifies this balance between intelligent control and AI computation as an important area for continued study.

The framework would also require large amounts of accurate data. Battery state, motor current, payload, robot location, traffic, sensor demand, and task information would need to be collected continuously. A prediction model trained on one warehouse might not perform equally well in another warehouse with different floors, shelves, layouts, robot models, or workloads. The system would therefore need additional training and validation before deployment in different environments.

Future research should begin with simulation rather than immediately implementing the framework on a commercial robot. A digital model could compare a baseline robot using fixed control settings against the proposed dynamic system while keeping warehouse conditions identical. Researchers could measure energy consumed per delivery, average state of charge, distance traveled, charging time, task completion time, and total throughput. Existing warehouse research already uses simulation and optimization to investigate charging and battery-management strategies, providing useful methods for designing this type of study.

After simulation, the framework could be tested on a small physical mobile robot. Motor current, battery voltage, payload, speed, and sensor activity could be recorded during repeated routes. Eventually, multiple robots could be tested together to determine whether fleet-wide optimization produces additional improvements. Reinforcement learning would be particularly interesting at this stage because recent research suggests it can learn charging and navigation strategies in changing warehouse environments.

CONCLUSION

Autonomous shelf-transport robots have transformed warehouse operations by allowing inventory to move quickly between storage areas and picking stations. However, their performance remains limited by the amount of electrical energy available onboard. Batteries must simultaneously power locomotion, sensing, computing, communication, and other robot systems. Research on autonomous mobile robots indicates that locomotion alone can represent more than half of total energy consumption, while charging policies can significantly influence warehouse throughput.

This paper proposed a dynamic power management framework that treats energy as a resource that should be continuously allocated rather than passively consumed. The system would combine adaptive motor control, battery-aware speed adjustment, energy-aware routing, dynamic sensing, computing resource management, intelligent charging, and fleet-level coordination. An AI decision system could analyze real-time and historical information to determine how these components should operate under different conditions.

The most important feature of the proposed framework is that it does not depend on simply installing a larger battery. Instead, it attempts to extract greater performance from the energy already available. Recent research in intelligent robotic power management supports approaches including dynamic power management, dynamic voltage and frequency scaling, predictive control, machine learning, and reinforcement learning. Warehouse-specific research also demonstrates that battery management, charging strategy, and energy consumption can directly affect system performance.

Future testing would be necessary before determining exactly how much energy the proposed framework could save. However, existing research provides strong support for studying power management as an integrated system rather than optimizing each robot component separately. As warehouses continue adopting larger autonomous robot fleets, intelligent energy management could become increasingly important for extending operating time, reducing charging interruptions, lowering electricity consumption, and improving productivity.

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