Exploring the use of Quadruped Robots in Construction Environments: The Case of Small Item Transportation

Abudurrahman Baru[1], Mariam Tomori[2], and Javier Irizarry[3]

[1] Georgia Institute of Technology, Atlanta GA 30332, USA
[2] Georgia Institute of Technology, Atlanta GA 30332, USA
[3] Georgia Institute of Technology, Atlanta GA 30332, USA
javier.irizarry@gatech.edu

Abstract

The construction industry faces significant safety and efficiency challenges, with construction fatalities ranking among the highest in occupational sectors. This paper explores the integration of quadruped robots into construction processes to address these challenges. Quadruped robots offer stability and mobility in dynamic construction environments, potentially enhancing operational efficiency and worker safety. This study investigates the material-carrying capacity of quadruped robots and their applicability in addressing specific construction needs. A Boston Dynamic's SPOT robot was utilized in the research. Strategic approaches are proposed to optimize their use for enhancing safety practices. The methodology involves designing customized paths for robot navigation and developing specialized first aid kits and toolkits. Results suggest that quadruped robots can efficiently transport materials and contribute to safety practices in construction. Future research areas include security and surveillance, safety checks, emergency response, and environmental monitoring.

Keywords
Quadruped Robots, Construction Technology, Safety Improvements, Material Transportation, Fiducial Markers

1. Introduction

The construction industry, vital to global economic development, is characterized by its high-risk environment, leading to significant safety and efficiency challenges. According to the Occupational Safety and Health Administration (OSHA), construction fatalities account for a significant proportion of all occupational fatalities in the United States (OSHA., 2018); it is among the top three industries for workplace fatalities in the United States (BLS, 2023), trailing only behind agriculture and forestry, and transportation and warehousing in terms of danger. It also holds the dubious distinction of having the highest number of worker deaths (NSC, 2023). The construction industry is also known to be the most conservative and rigid in adopting technological advancement in its execution process compared to other industries (McKinsey & Company, 2023). This backdrop underscores an urgent need for innovative solutions to mitigate safety risks and enhance operational efficiency within the construction milieu. This research delves into the potential integration of quadruped robots in construction activities, aiming to transform conventional practices and bolster industry standards.

Quadruped robots, characterized by their four-legged design, offer remarkable stability and mobility in diverse terrains, ideally suited for dynamic and unpredictable construction sites (Afsari et al., 2021; Rowell et al., 2024.) Quadruped robots can address challenges in the construction industry that involve human resource-demanding tasks such as safety monitoring, progress monitoring, and site inspections, (Halder et al., 2022); however, no documented instances or case studies have indicated the utilization of quadruped robots for material transportation purposes. Previous studies on integrating quadruped robots into construction reveal that their primary applications lie in progress monitoring and safety inspections (Afsari et al., 2021). Also, a cloud-based solution could be used to integrate the quadruped robot's control for remote navigation through the construction site with 360 live-stream videos of the construction status, as well as a real-time AR solution to visualize and compare the as-built status with as-planned BIM geometry (Halder, Afsari, Serdakowski, & DeVito, 2021). By optimizing task execution and reducing downtime, these robots can contribute to cost savings and project timeline efficiencies (Afsari et al., 2022). Moreover, their role in enhancing safety can lead to reduced insurance and compensation costs through the attenuation and or total aversion of human involvement in the execution of precarious activities, further underscoring the economic rationale behind their adoption (Brosque & Fischer, 2022b).

The inculcation of quadruped robots in task execution on construction sites is not entirely unprecedented. The technology has been explored in the sectors of site inspection, automating the entire procedure, and uploading data collected to be reconciled with a BIM 3D model (Halder et al., 2022). In addition, this study posits that quadruped robots can serve as mobile inventory suppliers and first aid agents, thereby addressing critical logistical and safety challenges within construction environments. By assessing the material-carrying capabilities of the quadruped robot, its locomotive ability could be utilized to efficiently transport components, medical supplies, and handheld tools between processing stations. This research hence aspires to delineate and expand the scope of the applicability of quadruped robots within the construction and facilities management environments beyond the known inspections and image-capturing related activities.

The importance of the positive impact of robotic integration in the construction sector cannot be undermined; its improvement in both quality and safety is significantly monumental. In a study by Brosque and Fischer (2022a) assessing the efficiency of ten robots in different construction sites across the globe, results indicated a 90% reduction in time expended in the execution of repetitive tasks and 72% in hazardous tasks. Ergo, these indicators translate directly into the extent of the prospective augmentation in the safety and quality metrics this research can attain in optimizing construction site activities. Furthermore, this research proposes strategic approaches leveraging quadruped robots to enhance safety practices, thereby significantly contributing to the construction industry's body of knowledge. The anticipated benefits extend beyond safety and efficiency improvements, suggesting a paradigm shift in construction operations management. This study explores the integration of quadruped robots into construction operations to serve as a mobile inventory supplier and first aid agent. This aim will be accomplished through answering the following research questions:

i. RQ1: What is the material-carrying capacity of quadruped robots, and how efficiently can they transport items?
ii. RQ2: Does the quadruped robot's auto-walk feature enhance operational efficiency and reduce time consumption for material transportation tasks compared to manual operation?
iii. RQ3: What strategic approaches can be proposed to optimize the use of quadruped robots to enhance safety practices in the construction environment?

The methodology encompasses the meticulous design and additive construction of a carrier appositely aligned with the quadruped robot's weight-hauling capabilities and the programming of its software with information about charted paths connecting locations of interest in a controlled environment mimicking a construction site. This research aims to assess the feasibility and benefits of such integration and contribute valuable strategies and insights to the construction industry, paving the way for widespread adoption and innovation.

2. Experimentation Process

To address the research question regarding the material-carrying capacity of quadruped robots and their efficiency in transporting components between different locations in a construction setting, the study conducted a series of experiments at the Advanced Manufacturing and Pilot Facility (AMPF) at Georgia Tech (Georgia Tech, 2024). The AMPF's manufacturing laboratory provided a safe environment for initial experimentation and assess quadruped robots and their efficiency in transporting materials. The manufacturing setting serves as a proxy for construction site conditions. It allowed the team to evaluate whether quadruped robots can effectively transport materials in a manufacturing setting and familiarize themselves with the transportation process using such robots. Boston Dynamic's SPOT robot (Boston Dynamics, 2023) was used in the research.

The first step of the experiment was illustrating the manufacturing facility in 2D and 3D representation to determine where the quadruped robot would operate. Then, the 2D drawings were used to plan the pathways for the robot to maneuver, and the 3D drawings were used to prepare the positions for the placement of fiducials markers. These drawings serve as the foundation for identifying critical areas and pathways where materials need to be transported by the robot. By creating a design path, the robot is programmed to navigate the predefined route, leveraging the information provided by the fiducial markers along the way. Strategic placement of fiducial markers within the facility is essential, as these markers serve as reference points for the robot's navigation system. Thus, accurately depicting the facility layout and fiducial marker placement is crucial for effective path planning and navigation. Once the facility layout and fiducial marker placement are established, a customized path is designed for the robot within the manufacturing laboratory. The described process is meant as an opportunity to learn the advantages and limitations of the proposed application. It is recognized that construction sites are dynamic and that using predefined paths presents challenges. However, the lessons learned will be used to determine the approach to use in dynamic environments once the team determines the viability of the methodology.

One of the quadruped robot's standout features is its autonomous 'Autowalk' capability (Fig. 1(b)). This advanced navigation system, powered by onboard sensors and cameras, allows the robot to navigate its surroundings easily. It can detect stationary obstacles and strategically placed 'Fiducial markers', reference points for accurate positioning and precise navigation. One of the steps of “Autowalk” involves integrating fiducial markers as the primary navigation tool for the robot. As shown in Fig. 1(a), the fiducial codes enable the robot to interpret and respond to the necessary markers strategically placed within the environment. The Auto walk feature is usually programmed through the robot's remote control. However, more advanced use can be done through a Python script that will connect directly to the robot’s API or through the “SPOT CORE” Computer payload, which can be added to the robot. For the scope of this research, we only utilized the remote controller.

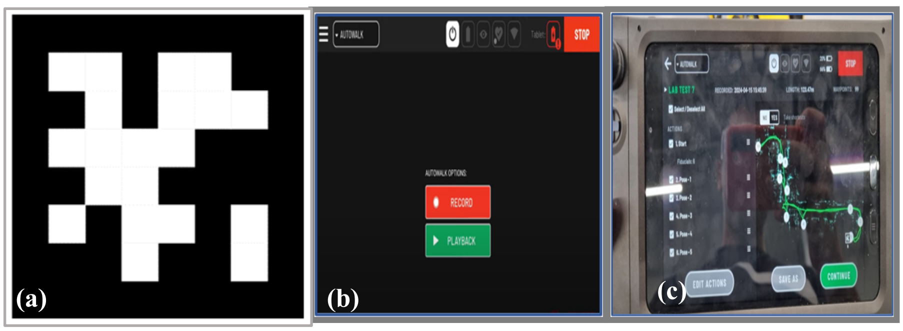

Fig. 1(a-c). Fiducial Marker, Auto-walk and Record; and Path overview.

Next, a module was developed to be placed on the back of the robot to enhance its capacity for material carrying. This module, a crucial part of our research, consists of two systems. Firstly, a scale system for material carrying transports manufactured machine parts from one manufacturing machine to another. Secondly, A Structural system will hold up the scale system and allow for opportunities to add extra payload or scale up the structure to connect to other robots, increasing the overall payload capacity. Fig. 2 is the overview of the experimental procedure.

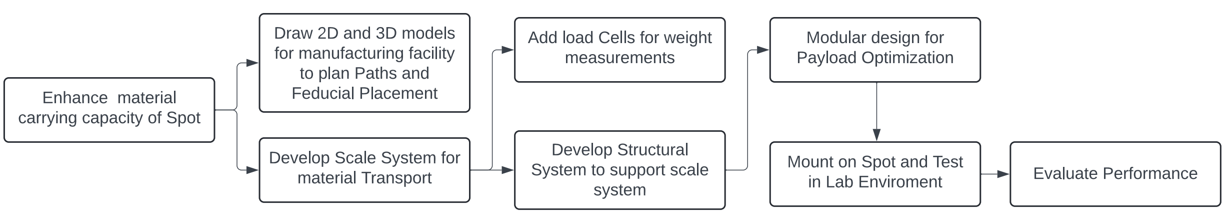

Fig. 2. Methodology Flow chart

2.1 Scale System

As shown in Figure 3, The scale system will be placed at the center on top of the quadruped robot to maintain the center of gravity. Its dimensions are 332 by 160 by 50 millimeters, allowing it ample space to take the most machine parts per transport cycle securely. This scale system comprises four parts (Fig. 3). The first is the frame that holds all the parts together. It has filleted edges and a rectangular shape, with a concave webbed supporting structure in the middle. This supporting structure acts as a base on which all the load cells sit, and the weighing plate goes on top. The surface of the plate is designed with a soft, silicon-like material that will allow easy placement of materials and avoid damage to the base plate. The material's texture will ensure a firm grip on the machine parts, allowing the parts to be at angles and easily lifted by the robotic arm at each manufacturing device. The weighing load cells are placed centrally under the base plate to allow for even weight distribution and easy central monitoring. However, as the robot walks, it vibrates, so this simple assembly will allow for quick recalibration of the load cells. The surrounding frame structure is further bolted to the truss structure below it to strengthen it and stop sway.

Like the open-source system developed by Olalekan Ogunbiyi et al. (2023), the scale will utilize a load cell to measure the force of the materials placed on the base plate. The force will distort the electrical currents passing through the load cell, and these distortion signals are fed into the analog-to-digital converter (ADC). The ADC converts the signals into digital data that can be analyzed regularly by the robot operators to ensure that the system is working correctly or sends an alert if the recommended weight is exceeded.

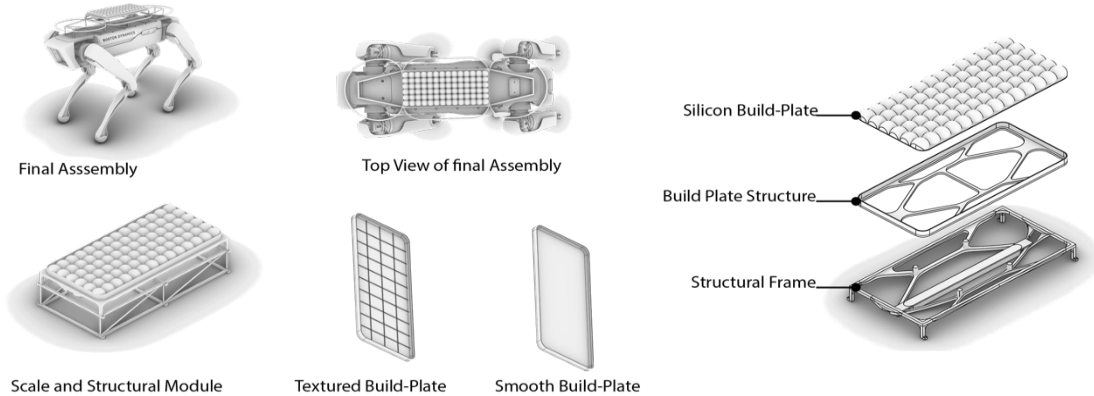

Fig 3. The Scale System Component

2.2 Structure system

This structure holds a scale system using a lightweight steel truss structural system for maximum load-carrying capacity (Valerio De Biagi, 2016). This system provides perpendicular members to which other systems can attach. The truss is divided into three modules, with the second module carrying the scale (Fig. 4). This configuration allows different modules for different payloads or scale modules. If all the load-carrying capacity of the robot is required, two modules could be removed, and only the scale system module could be utilized to ensure maximum efficiency. This modular design allows for opportunities for a "kits of parts" type of fabrication where parts of the structure can be fabricated on-site and do not require any extra fabrication technologies. A lightweight structural shield is placed around the structure and the system to act as a roll cage to prevent accidental clashes. Material handling is part of the focus of the paper. As such, multiple modules can be aggregated across multiple robots for a fleet carrying more weight than just one robot (Fig 4).

Placing the scale system directly on the back of the robot presents challenges, such as space constraints and the dead load of the scale system exerting pressure on the robot's surface. The truss design addresses these challenges by elevating the scale, increasing available space, and accommodating a larger surface area. Consequently, the increased volume leads to a higher load on the robot. However, the truss enhances the robot's load-bearing capacity by redistributing compression and tension loads.

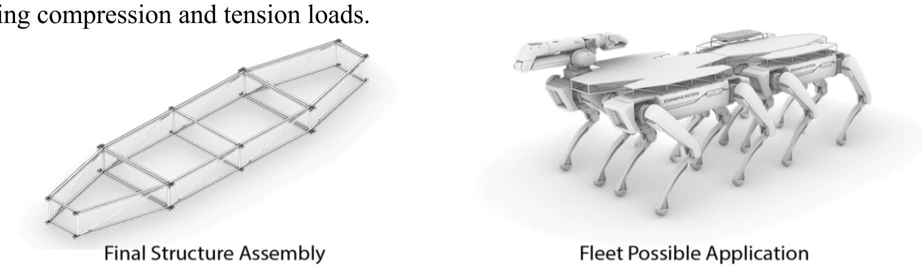

Fig. 4. The Structure System

3. Results

3.1 RQ1: What is the material-carrying capacity of quadruped robots, and how efficiently can they transport items?

The primary objective of this research is to enhance the material-carrying capacities of the Boston Dynamic Quadruped robot for the construction environment. The robot has 12 degrees of freedom (DOF), where 4 DOFs are at the hip for sway in the X and Z directions, while 8 DOFs are at the knee for vertical movements in the Y direction and horizontal movements in the X+Z directions. The hip axis is restricted to a +45-degree angle, and the knee can move up to +90 degrees. This innovative design allows it to adjust its leg configurations dynamically for optimal movements across rugged terrain with a maximum speed of 1.6 m/s and carry a maximum weight of 25lb.

For the controlled environment experiments, a prototype of the carrying system was constructed from readily available materials (Fig 4A). The experimental simulation involved planning a path for the robot using fiducial markers and the automated navigation system (Autowalk). The robot was programmed to visit different robotic workstations to deliver or collect base plates or tools. The recorded path guided the robot's navigation through the manufacturing laboratory, with each cycle taking approximately 5 minutes to complete. The robot successfully navigated the path, carrying a 25lb payload within the manufacturer's specified maximum payload capacity of 30lb. The steps for achieving quadruped robot transportation included Autowalk and recording, driving the robot to recognize fiducial markers (Fig 1(a)), initiating and saving the recorded path (Fig 1(b).), initializing Autowalk, adding poses, and navigating between stations (Fig 5) for repetitive transportation tasks. During the experiment, the robot successfully transported 25lb of base plates from one location to another, demonstrating its capability within the manufacturing laboratory setting. The quadruped robot’s efficiency was evaluated based on its ability to navigate a pre-recorded path through various robotic workstations, delivering and collecting items. The robot completed the circuit in 5 minutes and could repeat the path until it manually stopped. This indicates high efficiency in repetitive tasks within a controlled environment. The experiment demonstrated that quadruped robots can effectively transport materials in manufacturing. The results suggest that quadruped robots have a promising role in automated material transport within construction settings. Their ability to carry significant weights and navigate autonomously through pre-determined paths could reduce manual labor and increase efficiency.

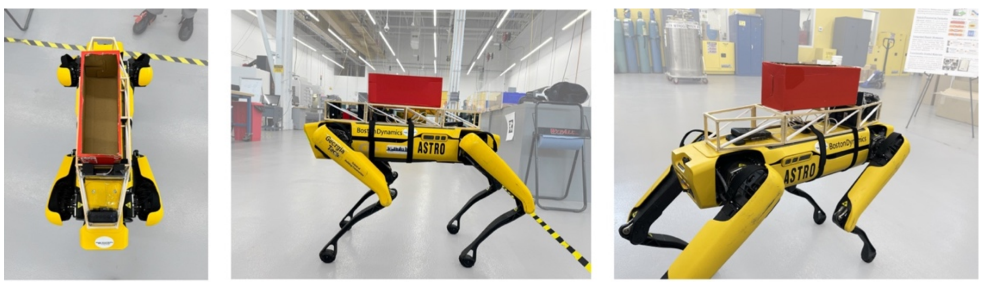

Fig. 4A. Final Simulated Assembly

3.2 RQ2: Does the quadruped robot's auto-walk feature enhance operational efficiency and reduce time consumption for material transportation tasks compared to manual operation?

This research question evaluates the time and efficiency of using the auto-walk vs. manual operation to complete tasks. The robot scans the fiducial initially, and then the operator must manually control it to record the path and set the duration for postures of the tasks. After the recording, the data about the path and postures are stored in the controller memory. The path is then automatically optimized to ensure smooth movement of the robot. Upon scanning the fiducials again, the auto-walk feature is activated, allowing the robot to replicate the previously recorded actions more efficiently. The challenge noted during the simulation was that since the auto walk feature was a recording, the robot could not detect that it had parts before moving to the next point. It only uses the initial preprogrammed time in the initial recording. Thus, it could move to the next point without any parts.

As shown in Fig. 5, The recorded path starts from Location 1 (Start point) to Location 6 (Endpoint). The path was approximately 147 meters, with six stops at different machines. At each machine, there was a posture of an average time of 10 seconds. The robot starts from Location 1 (start point), which is the TRAK VMC12si (Vertical Machining Centre) with a robotic arm, to Location 2 (manufacturing lab), where the material was loaded in the scale. The material was carried from location 2 to location 3 (Okuma android, a CNC machine with a robotic arm). From location 3, the material was carried to location 4 (wire EDM cutting machine). From location 4, the material was carried to location 5 (tensile stress testing machine). This represents the entire process and path for transporting parts across the multiple machines in the manufacturing lab.

The total time spent on manual operation of the spot was 4 minutes 23 seconds. In comparison, the total time spent operating the auto walk was 3 minutes 33 seconds. This suggests that the auto walk is more efficient and can optimize speed and accuracy for navigating predefined paths. The robot finds an alternate route whenever there is an obstruction on the path. If that fails, it goes back to the original point.

There are notable differences between the two modes in the posture setup times. Generally, the posture setup times for the manual setups were higher than the auto walk setup times. For example, in position three, the manual posture setup took 18 seconds to get right, while in auto walk, it took only 13 seconds to get in the position. There is a 6-second difference. This difference indicates that the manual controls are generally slower and less precise due to the human element required to operate the robot. The distance traveled between Location 1 and Location 2 is 57.6 meters.

However, the time required to cover the distance is different; for manual, it is one minute and four seconds, while for auto walk, it is fifty-five seconds. So, there is a difference of nine seconds. Thus, the difference indicates the auto-walk optimizes the path and speed.

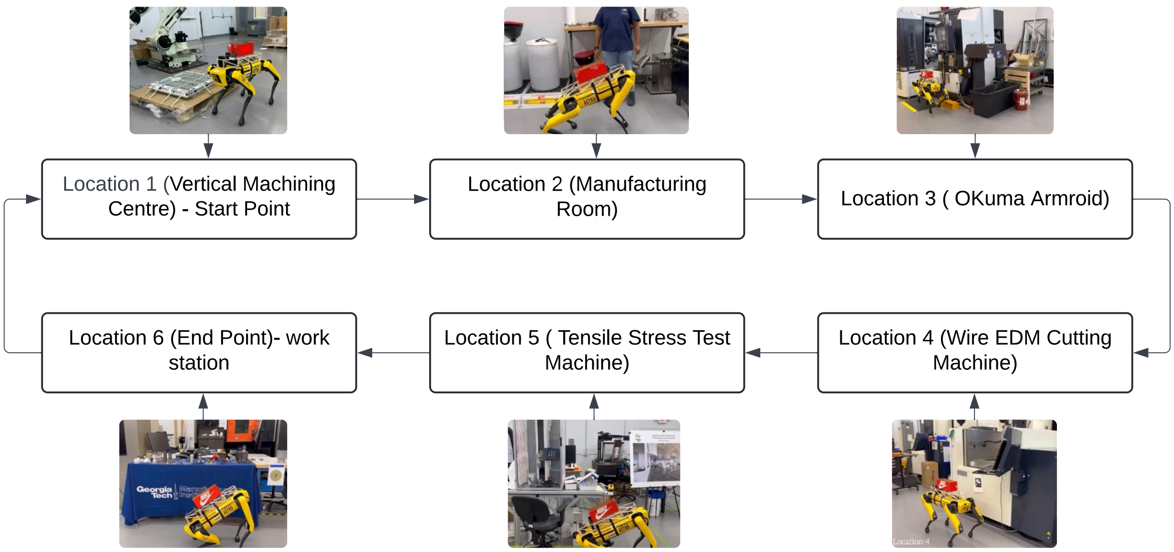

Fig. 5. Quadruped robot navigating between different robotic work stations

3.3 RQ3: What strategic approaches can be proposed to optimize the use of quadruped robots to enhance safety practices in the construction environment?

Quadruped robots can move components between different workstations or storage areas efficiently due to the payload capacity, which could be suitable for moving small building materials. On construction projects, this improves workflow efficiency, reduces the need for human labor, and eliminates the risk of accidents due to heavy lifting. The development of quadruped robots, particularly the Spot model, combined with the ability to utilize fiducial markers for designing path trajectories, offers a promising tool for creating 24/7 delivery systems within construction sites. The laboratory experiment performed for this research has demonstrated that path creation using fiducial markers presents a straightforward and readily implementable solution for improving on-site logistics. As an illustrative example, the model in Fig. 6 represents the laboratory practice scenario adapted to a construction site. The concept involves establishing a network of paths connecting the construction storage area with key points throughout the building under construction. Based on pre-programmed requests, the quadruped robot would navigate these paths to retrieve tools or materials from storage and deliver them to designated drop zones within the building. Each drop zone would be linked to specific paths and corresponding fiducial markers.

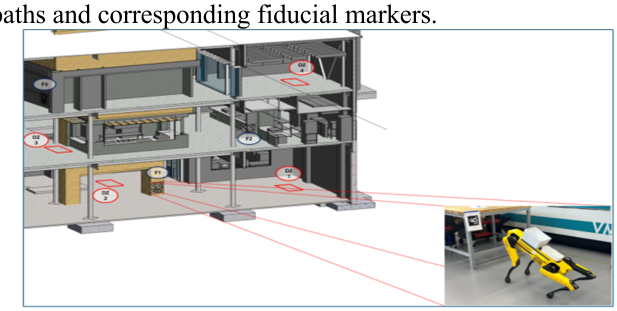

Fig. 6. Proposed illustrative example of quadruped robot applicability in a facility environment *(F: Fiducial; DZ: Drop Zone)*

4. Discussion

The findings from the experiment assessing the material-transporting capability of quadruped robots in the construction industry showed that these robots could effectively transport materials within a controlled manufacturing environment. Equipped with a scale system carrying module, the quadruped robot successfully navigated pre-planned paths and transported a 25lb payload within the manufacturing laboratory. The robot executed tasks with accuracy and reliability by utilizing fiducial markers and onboard sensors for guidance. This discovery is significant as it indicates that quadruped robots are capable of transporting small building materials on construction sites, potentially reducing the need for labor and improving efficiency by autonomously transporting loads (Afsari et al., 2021). Similarly, these results align with studies suggesting that robotic solutions can greatly enhance efficiency by optimizing task performance (Halder et al., 2022).

The second objective sought to determine whether the auto-walk feature of quadruped robots enhances efficiency and decreases time consumption compared to manual operation. The experiment results indicated that the auto-walk function significantly reduced the time required for material transportation tasks. Specifically, the total duration the robot spent for auto-walk was 3 minutes and 33 seconds compared to 4 minutes and 23 seconds for manual control. This enhancement in efficiency highlights the potential of the auto-walk feature to improve speed and accuracy when following predetermined routes (Boston Dynamics, 2023; Li et al., 2023). This demonstrates the practical advantage of autonomous navigation in reducing time consumption and increasing precision for repetitive tasks, which is crucial in dynamic construction environments. Additionally, the ability to find alternate routes in case of obstructions further enhances the robot's reliability and operational robustness in dynamic and unpredictable construction environments.

The third goal focused on proposing strategies to enhance the use of quadruped robots for promoting safety measures at construction sites. The study outlined tactics such as using quadruped robots to transport components between workstations or storage areas, which can significantly reduce risks linked with heavy lifting. This network can be dynamically updated based on construction progress and specific project requirements. For example, the quadruped robot would navigate predefined paths to retrieve tools or materials from storage and deliver them to designated drop zones within the building. Each drop zone would be linked to specific paths and corresponding fiducial markers. This approach presents a promising solution for improving on-site logistics and creating 24/7 delivery systems within construction sites. Automating this process with quadruped robots can enhance productivity, allowing human workers to focus on more complex tasks. By leveraging the carrying capacity and self-navigation capabilities of these robots, construction sites can establish efficient delivery systems that reduce human involvement in tasks (Halder et al., 2021).

However, the research also underscored challenges that must be addressed to fully harness the potential of quadruped robots in construction. These challenges include load capacity of the robots beyond 25lbs, battery lifespan constraints, and difficulties in recognizing moving obstacles and small objects. Future research should focus on adapting these findings to more dynamic and complex construction environments. By addressing these challenges, we can fully leverage the safety and efficiency benefits of quadruped robots in the construction industry.

5. Conclusions

The research presented in this study offers a comprehensive examination of the capabilities and potential applications of quadruped robots in construction and facilities management. The experiments' findings at the Advanced Manufacturing and Pilot Facility (AMPF) provide valuable insights into these robots' material-carrying capacity and efficiency in a controlled environment, a proxy for construction site conditions. Regarding the material-carrying capacity, the experiments demonstrated that quadruped robots, exemplified by the Boston Dynamics Spot model, can transport weights with a demonstrated capacity of up to 25lb. This capacity, coupled with the robots' ability to navigate autonomously through pre-determined paths, holds promise for enhancing material transport and logistics within construction settings. The development of lightweight and durable payloads, such as the scale system and truss structure, further optimizes the payload capacity of these robots. The study successfully demonstrated a quadruped robot transporting a 25lb payload through a pre-recorded path in the manufacturing laboratory.

Efficiency in material transport was evaluated based on the robots' ability to navigate predetermined paths efficiently and complete repetitive tasks within a controlled environment. The experiments showed that quadruped robots can effectively navigate various workstations and efficiently deliver or collect items. This efficiency, combined with the robots' ability to operate 24/7 and adapt to changing conditions, suggests their potential to streamline workflows, reduce manual labor, and enhance overall productivity in construction projects. Lastly, the research suggests that quadruped robots have the potential to revolutionize material transport in construction and manufacturing environments. Quadruped robot’s design and features, mainly the auto-walk function, demonstrate significant efficiency and time management improvements over manual operations. The adaptability of these robots to various tasks and environments makes them a promising addition to the field, with the potential to enhance productivity and safety in construction and facilities management. The study provides a foundation for further exploration into the practical applications of quadruped robots in industry settings.

6.0 Recommendations for Future Research Areas

The findings provide valuable insights for future research to optimize the use of quadruped robots in construction environments and enhance their efficiency in material transportation tasks. However, while insightful, the experiment at AMPF does not fully replicate the complexities of a construction site. Factors such as varying terrain, dynamic obstacles, and environmental conditions could affect the robot's performance. Therefore, it is recommended that future research include field tests in actual construction environments to validate the findings and explore the robot's capabilities further, which include; testing the robot's navigation and payload capacity on uneven and dynamically changing terrains; Investigate the integration of quadruped robots with other construction automation systems and potentially humans on site.

References

Afsari, K., Halder, S., Ensafi, M., DeVito, S., & Serdakowski, J. (2021). Fundamentals and prospects of four-legged robot application in construction progress monitoring. *EPiC Series in Built Environment*, *2*, 274-283.

Afsari, K., Halder, S., King, R., Thabet, W., Serdakowski, J., DeVito, S., Ensafi, M., & Lopez, J. (2022). Identification of indicators for effectiveness evaluation of four-legged robots in automated construction progress monitoring. Construction Research Congress 2022,

BLS. (2023). *Construction deaths due to falls, slips, and trips. The Economics Daily. Bureau of Labor Statistics, U.S. Department of Labor.*

Boston Dynamics. (2023). Spot. Bostondynamics. https://bostondynamics.com/products/spot/

Brosque, C., & Fischer, M. (2022a). A robot evaluation framework comparing on-site robots with traditional construction methods. *Construction Robotics*, *6*(2), 187-206.

Brosque, C., & Fischer, M. (2022b). Safety, quality, schedule, and cost impacts of ten construction robots. *Construction Robotics*, *6*(2), 163-186.

Company, M. (2023). Meet the Disrupters – Hyperscaling digitization in AEC. Global Infrastructure Initiative. London.

Council, N. S. (2023). Industry Incidence and Rates. Injury facts.

Dynamics, B. (2023). Dynamics spot.

Dynamics., B. (2023). Boston Dynamics. Retrieved from https://bostondynamics.com/case-studies/foster-partners/.

Dynamics., B. (2023). Partners have used the quadruped robot in several projects to take as-built scans to compare against the design models as the site was evolving.

Georgia Tech. (2024). Welcome to AMPF | Advanced Manufacturing Pilot Facility. Ampf.research.gatech.edu. https://ampf.research.gatech.edu/

Halder, S., Afsari, K., Serdakowski, J., & DeVito, S. (2021). A methodology for BIM-enabled automated reality capture in construction inspection with quadruped robots. ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction,

Halder, S., Afsari, K., Serdakowski, J., DeVito, S., Ensafi, M., & Thabet, W. (2022). Real-time and remote construction progress monitoring with a quadruped robot using augmented reality. *Buildings*, *12*(11), 2027.

Halder, S., Afsari, K., Serdakowski, J., DeVito, S., & King, R. (2021). Accuracy estimation for autonomous navigation of a quadruped robot in construction progress monitoring. In *Computing in Civil Engineering 2021* (pp. 1092-1100).

Halder, S., Rita, K., & Afsari, K. Challenges of Human-Robot Partnership in Future Construction Inspection and Monitoring with a Quadruped Assistant Robot. Construction Research Congress 2024,

Li, Y., Jiang, L., Xu, P., Xing, B., Liu, Y., & Yan, T. (2023). Research on Adaptive Control Method of Quadruped Robot's Load. https://doi.org/10.1109/icetci57876.2023.10176990

OSHA. (2018). *Commonly used statistics | occupational safety and health administration.* .

Olalekan Ogunbiyi, Oloruntoba Christopher Mohammed, & Lambe Mutalub Adesina. (2023). Development of an Automated Estimating Electronic Weighing Scale. ABUAD Journal of Engineering Research and Development (AJERD), 6(1), 59–66. [https://doi.org/10.53982/ajerd.2023.0601.08-j]

Rowell, J., Zhang, L., & Fallon, M. . (2024). LiSTA: Geometric Object-Based Change Detection in Cluttered Environments. . https://doi.org/arXiv preprint arXiv:2403.02175.

Valerio De Biagi. (2016). Structural behavior of a metallic truss under progressive damage. International Journal of Solids and Structures, 82, 56–64. [https://doi.org/10.1016/j.ijsolstr.2015.12.016]