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Toward Autonomous Construction Material Inventory Management using a Boston Dynamics SPOT and Ultra-High Frequency (UHF) Passive RFID

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Construction materials account for a significant percentage of the resources on a construction site and plays a vital role in the success of the project. By utilizing an experimental methodology, the goal of this research was to execute a proof of concept for autonomous inventory management of construction materials using Ultra-High Frequency passive RFID and a terrestrial autonomous robot. An experiment was administered to identify the reliability (tags read vs. tags placed) of the proposed system in a dynamic environment in autonomous mode. According to the results, the robot was largely able to navigate around and between smaller objects versus larger obstacles. Using Bootstrap simulation, the successful read rate (percent) was found to be [67,88] [LL, UL] at a 95 percent confidence interval. Based on the results, using a Boston Dynamics SPOT with UHF Passive RFID to control building material inventories could be a viable route with additional research. Future research will improve material management through RFID, computer vision, and Bayes Filters for localization.

Key Words: Ultra-High Frequency passive RFID, Construction Robotics, Tracking, Automation

Introduction

Inventory management plays a vital role during the construction phase of a project (Cai et al., 2014). An accurate and up-to-date inventory of the materials and equipment on site allows for a project management team to ensure deliveries are made on time, invoices are correct, and stored materials can be billed to pay applications. Ideally, this creates an environment that promotes efficient workflows and high productivity. The construction environment, however, is complex and in a constant state of change throughout the entirety of a project's life cycle. These conditions make it difficult to keep an up-to-date inventory of all the materials located on a project site without dedicating significant resources to tracking and documentation (Cai et al., 2014). On most projects, construction materials are kept in an outdoor material storage area known as a laydown yard before being installed in the structure. Assuming the project is big enough to justify it, the standard practice for tracking material inventory within a laydown yard is to divide the area into a grid and assign alphanumeric identifiers to each section (Song et al., 2015). Smaller projects use lay-down yards with less concern as to how the material is organized, which can lead to mismanagement of availability and maneuverability. Regardless of size, inventory databases must be manually updated as materials are brought into or removed from storage for any reason, whether it be removed for installation, purchased, and brought into the laydown yard, or even moved to a new location within the storage area. This process depends on the careful examination of tracking logs, invoices, and visual confirmation of the materials themselves. Due to this heavy human involvement and dependency on the experience level of the person responsible for the inventory, this manual method tends to be *"inconsistent, time-consuming, labor-intensive, and error-prone"* (Afsari et al., 2021, p.1). Autonomous technology is emergent in the construction industry and can address many of the limitations and inefficiencies found in today's manual processes (Afsari et al., 2021; Melenbrink et al., 2020).

Autonomous technology deployed on a construction site is meant to minimize the source of human error and provide a frequently updated stream of data that requires little to no human intervention. This research will add to the growing knowledge of autonomous technologies in construction by studying the read rate of inventory management of construction materials using passive RFID and a terrestrial autonomous robot by assessing the application of a Boston Dynamics SPOT equipped with a custom-built Hexagon RFID payload. The research was undertaken to investigate the ability of the robot to autonomously traverse a dynamic environment and identify the potential effects of the routing around objects on the RFID payload's ability to read tags successfully.

Literature Review

Standard Practices for Laydown Yards

The traditional method of gathering information about on-site construction materials is comprehensive manual inspection - which is time-consuming, labor-intensive, and prone to human mistakes (Song et al., 2015). The laydown yard is typically divided into a grid, and an alphanumeric location code identifies each grid section. To identify the location of a material item, the grid location code, and the material item identification code are manually recorded after receiving and then are later fed into the central database. This procedure is repeated if an item is relocated while stored in the laydown yard to record its most recent location. When it comes time for field installation, the laydown yard team will search the database for the item's identity and position codes. The object in the grid location is then manually searched for and retrieved by the crew. The material flow network shown in Figure 1 is proposed by (Song et al., 2015).

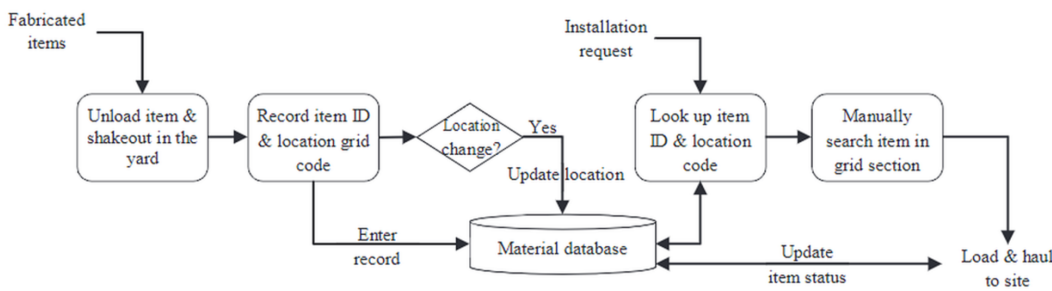

Figure 1. Flowchart of standard manual practice in laydown yard procedures (Song et al., 2015).

RFID Inventory Management in Construction

Using RFID technology to track materials and equipment on site is proven to enhance construction operations and assist in meeting these demands (Ren et al., 2011). Increased knowledge of material location and inventory provided by the application of RFID can reduce costs associated with any time that would otherwise be wasted while in search of materials and tools as well as the cost associated with misplaced inventory (Valero and Adán, 2016). Research has also shown that the application of RFID technology can significantly increase the efficiency of logistics processes since the data gathered can be used to automate and better manage a project's supply chain (Popova et al., 2021). The use case for construction is to remove the need for manually inspecting inventory and even make some key logistics processes automatic (Valero and Adán, 2016).

Autonomous Inventory Management in Construction

Construction personnel on construction sites typically rely on insights from people's observations to coordinate on-site resources, even though accurate and complete location information is vital for tracking resources and the success of the construction project (Kim and Haas, 2000; Torrent and Caldas, 2009). This method requires a lot of manual labor and time, and when the resources are managed over a lengthy period, it is also susceptible to possible human mistakes (Jaselskis and El-Misalami, 2003; Sacks et al., 2003; Thomas and Ellis, 2017). Workers are frequently hindered when they are looking for the supplies they need for ongoing tasks (Rojas and Aramvareekul, 2003; Caldas et al., 2006). Additionally, the management process is made more difficult by the fact that building resources' deliveries are made in bulk and usually not in sequential order (Soltani et al., 2013). Won et al. (2020) draw the conclusion that these problems have underlined the need for automated resource tracking. The loss of materials and other items at the site is one of the problems that many contractors deal with (Bansal et al., 2022; Sole et al., 2013).

Earlier research has shown the advantages of using auto-identification and localization technology to automate the tracking of onsite materials (Schneider and Grau, 2022; Caldas et al., 2006; Grau et al., 2009; Ren et al., 2011). The automatic identification and subsequent location of materials, as well as the easy integration and sharing of material status data, are two distinct aspects of the automatic tracking of materials. The advantages of technology-enabled onsite materials tracking over human onsite materials management have been documented in several case studies and field tests (Caldas et al., 2006; Ergen et al., 2007; Grau et al., 2009; Lu et al., 2011; Song et al., 2006). By automating onsite materials management and enabling just-in-time delivery using auto-identification technology, project resources (time, personnel, paperwork) are used more efficiently, which boosts craft labor and construction productivity (Caldas et al., 2006; Grau et al., 2009; Jaselskis and El-Misalami 2003). In addition, cost, safety, time, and quality gains have been noted (Caldas et al., 2006; Lu et al., 2011). Researchers at Auburn University used a Boston Dynamics SPOT with a Zebra RFD8500 to study the use of autonomous robots and RFID in tracking construction site tool inventory. The study, conducted inside a Conex, showed the system reliably completed all 20 cycles without missing any tags (Wetzel et al., 2022b).

Scope and Limitations

The research scope is a laboratory-based, experimental study. The research took place at the Robins & Morton Construction Field Lab on the campus of Auburn University. The experiments were carried out via Boston Dynamics SPOT with software v3.1 and the prototype version of a proprietary RFID technology provided by Hexagon PPM. For a full comprehension of the findings, it is crucial to appreciate the inherent limitations of the methodology and scope of the research study. The research intentionally used a single-pass research methodology for this study. Single pass in this research means the robot only walked by the tags once in each run and did not backtrack. By evaluating a single pass, the research focused on the read rate at the most efficient mode but recognized the read rate would like to be improved by a multi-pass approach. Second, a general, all-purpose RFID tag was the main subject of the research. Therefore, rather than concentrating on a particular use case or material-specific tag, the results primarily reflect a wide range of applications. The variety of RFID tags created for specific materials or purposes may have unique qualities and performance efficiencies that this study has not yet examined.

Experimental Design

The experiment simulated an outdoor material laydown yard like that found on a construction site. In this experiment, the research looked to identify reliability. Reliability is defined as the robot successfully traversing the environment without fail or human intervention and the RFID Payload successfully reading all tags placed along the robot route on a single pass. Tags were placed at various elevations to replicate the variety found in a field environment. Ten runs of this experiment were performed with the same environmental conditions that were present during the training route, and ten runs were performed after introducing obstacles to the trained path of the robot for a total of 20 runs. This allowed for the identification of potential effects that a dynamic environment might have on the Boston Dynamics SPOT's ability to autonomously traverse a construction environment in a way that ensures successful readings of all placed tags. The data logs gathered during each run of this experiment were analyzed along with the environmental conditions surrounding the tag to calculate the success rate of the reader in collecting tag IDs, as well as providing helpful information regarding environmental factors that may affect the ability of the payload to read a tag successfully.

The field lab was subdivided into zones (Figure 2), and RFID tags were placed together at various elevations throughout the course. Zone 2 tested the greatest height range; right-side tags were 2 feet below the surface level of the robot, while left-side tags were 10 feet above. Zones 2 and 3 were separated by steel shipping containers containing 25 tags to differentiate data.

As a base marker, an April Tag marked the beginning and end of each run. During the training run, the Boston Dynamics SPOT robot was manually steered about five feet from each tagline. After completion of the training run, the RFID payload was turned on and wirelessly connected to a laptop to record all read tags during each run. The RFID payload uses a terminal emulator (PuTTY) to wireless send the tag reads to a user interface in real-time. The robot traveled the predetermined route with the active payload, gathering RFID tag IDs. The experiment was run ten times under training run site conditions and ten more times with obstacles placed in the robot's path. Readings were logged and exported as *.txt files after the experiment, then loaded into an Excel spreadsheet for processing and noting any missed tags and probable in situ factors impacting readability.

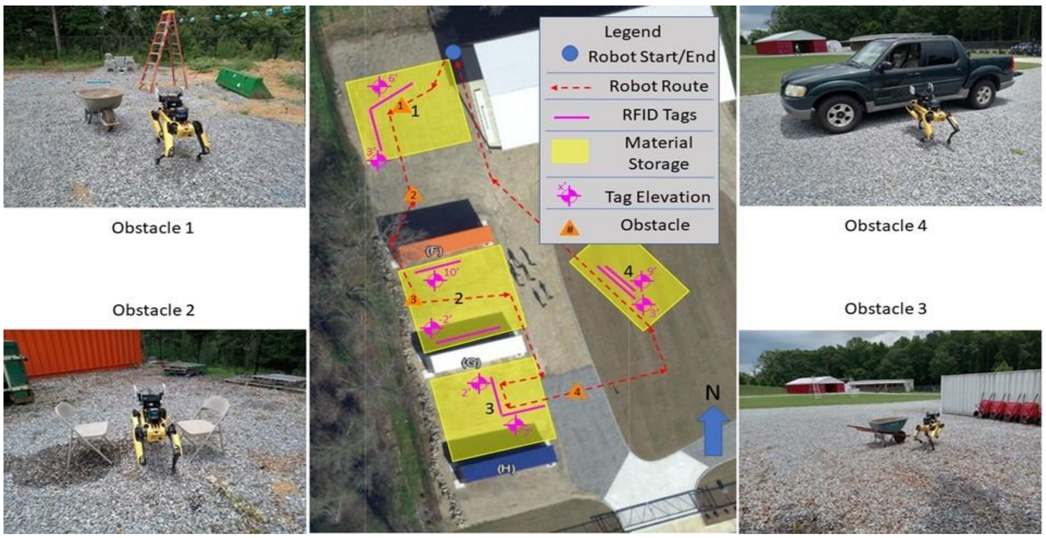

Figure 2. Experiment Layout

Bootstrap Resampling

The experiments utilized Bootstrap resampling to extrapolate the data to 500,000 runs. When a relatively limited amount of experimental data is available, the bootstrap method can be advantageous in obtaining a computer-generated upper limit (UL) and lower limit (LL) by resampling to a specified confidence interval (Alborzi et al., 2008). The Bootstrap technique is a robust statistical tool employed to estimate the distribution of a statistic (the mean successful read rate was used in this case) by repeatedly sampling with replacement from the original data. For this research, a 95% confidence interval was used. Resampling creates datasets by randomly using data from a source dataset (success read percentages) and replacing it, with each iteration producing a fresh Bootstrap sample consisting of 10 data points. Mean success read percentages are then determined from these new datasets, and the distribution of this statistic is used to assess the uncertainty of the original dataset. According to Brad Efron (1992), the originator of the bootstrap method, "the bootstrap does with the computer what the experimenter would do in actuality if it was possible if he or she would repeat the experiment." For this research, Bootstrap was run in "RStudio" version 2022.12.0 build 353. Through the analysis of these simulated samples, the research was able to acquire valuable knowledge about the variability and dependability of the original 20 test findings. This provided a thorough comprehension of the statistical properties of the experiment, such as the confidence intervals.

Results and Analysis

The routing for the robot was aimed to simulate a real-world construction site and to also follow guidance formulated using data from previous research (Wetzel et al., 2022a; Wetzel et al., 2022b.) The robot was routed through the course 10 times with the same environmental conditions as the training route, then 10 more times with obstacles placed in its path to test the robot's ability to adapt to a dynamic construction environment. The successful scan rate was determined for each run by analyzing the log of tags read compared to the total number of tags placed. A total of 100 tags were located along the course, 25 in each of the 4 zones. Table 1 presents the data gathered during each run of the ten simulated laydown yard runs without and with path obstructions. The average read for each of the ten runs was 76%. Tags were consistently missed in the low side of Zone 2 where tags were 10 feet above the robot on its left side and 2 feet below the robot on the right side, creating the most complex read scenario for the robot. All tags located in Zones 3 and 4 were believed to be easily scannable by the payload, however, many of the runs resulted in a poor read rate. Possible explanations are a drop in power to the payload or a steady wind that rotated the tags. These explanations are conjectures, and additional tests are needed to identify the inconsistencies.

Based on ten test runs and 500,000 Bootstrap replications at 95% CI, the success rate for the laydown yard experiment without obstructions lies between 64.50% and 85.90%. Table 1 displays data gathered during each run of the simulated laydown yard experiment without and with path obstructions. Column A contains the data for the without-path obstructions case, and Column B contains the data for the with-path obstructions case. In the experiment set up where there were path obstructions, the payload was able to achieve a 78% successful read rate during this test. Whereas without path obstructions, the successful read rate was determined to be 76% respectively.

Table 1

Laydown yard experiment results (A=without path obstructions and B=with path obstructions)

Run #	Successful Read Rate		Zone 1		Zone 2		Zone 3		Zone 4	
	A	B	A	B	A	B	A	B	A	B
1	37%	90%	25	25	12	15	00	25	00	25
2	88%	90%	25	25	13	15	25	25	25	25
3	88%	66%	25	25	13	16	25	25	25	00
4	62%	91%	25	25	14	16	23	25	00	25
5	89%	92%	25	25	14	17	25	25	25	25
6	89%	67%	25	25	14	17	25	25	25	00
7	60%	91%	25	25	14	16	21	25	00	25
8	89%	68%	25	25	14	15	25	25	25	03
9	89%	89%	25	25	14	14	25	25	25	25
10	64%	36%	25	25	14	11	25	00	00	00
Avg	**76%**	**78%**								

A = without path obstructions; B = with path obstructions

Similar to the runs without the obstructions, tags were consistently missed in the low side of Zone 2. Run 10 missed all tags located in Zone 3 and Zone 4. During runs 3, 6, and 10, the robot did not successfully navigate to Zone 4. The truck located between Zones 3 and 4 caused issues in the robot's ability to travel between the two zones. Upon failing to find a path around the truck, the robot returned to the start fiducial using the path taken through Zones 1, 2, and 3. On 3 separate runs, the robot contacted the handles of at least one of the wheelbarrows placed in its path. This did not impact the data but would be an issue on an active construction site.

With the ten test runs and 500,000 bootstrap replications, it can be reported with 95% confidence that the successful read rate for laydown yard experiment results with path obstructions is within LL= 66.60%, UL=88%. Comparing the results between the tests performed without path obstructions to those with path obstructions shows that a higher successful read rate was achieved during the tests run with path obstructions at 95% CI [LL=66.60%, UL=88%] VS [LL=64.50%, UL=85.90%] despite the robot not completing the course on three separate occasions. This is likely due to the low tags in Zone 2 being read in the runs performed with path obstructions, pushing the robot closer to these tags when navigating around the wheelbarrow placed in that area. In other words, the obstruction changed the routing of the robot enough to impact the distance and angle of the RF signal in relation to the tags. On 30% of the runs performed with path obstructions, SPOT failed at the truck located between Zones 3 and 4, causing the robot to cancel the route. In addition to the large object interference, in 30% of the runs performed with path obstructions, the robot contacted the handles of the wheelbarrows placed in its path in Zone 3. This indicates that there is a lower limit to the size of objects that the robot can reliably detect and navigate around as well.

Since construction sites are such dynamic environments, changing drastically almost every day, the robot would certainly encounter objects of varying sizes blocking its path. To potentially negate the severity of these changing conditions, it is recommended that the robot regularly be taken on training routes so that the amount of change seen in its path is reduced. Additionally, the route can be strategically planned to go through areas that are less likely to accumulate obstructions.

Conclusions and Future Research

The results of this research study show that the concept of a terrestrial autonomous inventory of construction materials is possible. SPOT is capable of autonomously navigating spaces, but Boston Dynamics still strongly recommends that a human supervisor accompany the robot on its autonomous missions. During the experiment, the robot had trouble navigating around both very small and very large objects in a few of the runs. As iterations to SPOT’s Autowalk come through in updates from Boston Dynamics and improvements to the robot’s vision system, future autonomous missions will likely have differing results. This could lead to advancements in the autonomous features of a Boston Dynamics SPOT that would result in a mobility platform robust and adaptable enough to reliably complete missions planned on an active construction site.

The Hexagon RFID Inventory payload has the capability to scan tags at the heights of typical materials found stored on construction sites. The antennae can be oriented at different angles, allowing for versatility and adaptability to many different site conditions. While the data gathered on the payload’s range was sufficient to perform the experiment, more investigation should be performed on the geometry of the scan area emitted by the payload. This would lead to a better understanding of the distance at which the payload can successfully read tags and allow for more in-depth guidance on how to route the robot's pass materials to ensure successful reads. Where the payload struggled to read tags particularly in Zone 2, where the tags were at -2 feet, the researchers believe that this issue could easily be engineered out with any number of options. First, route the robot to maximize tag reads. For example, multiple passes and strategic routing based on the elevation of the tags. Second, an additional set of antennae is positioned at angles. This would maximize the chance of capturing data that is placed high or low. And finally, being more strategic with tag placement, keeping tags at specific elevations and facing the payload.

This research investigated the novel utilization of autonomous quadrupedal terrestrial robots in the domain of construction inventory management. This notion, although well-known in other industries, represents a pioneering approach in this construction. The uniqueness of this study lies in two aspects: firstly, it is an endeavor in utilizing advanced robots to handle construction materials, an area that is relied on human supervision. Secondly, for a construction site that is by nature dynamic, constantly changing, and evolving. This experiment is the first step towards advanced and autonomous inventory management on construction sites using quadruped robots.

Future research will continue to evaluate autonomous inventory management using SPOT and the RFID Payload. As this research served as a proof of concept for autonomous locomotion and an RFID payload, future work by the research team will focus more on the development side. Research is underway to superimpose the quadruped robot with the functionality of supervised machine learning YOLO (You Only Look Once) object detection and Bayesian Filter localization for autonomous identification.

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