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A Step Towards Automated Tool Tracking on Construction Sites: Boston Dynamics SPOT and RFID

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Tool tracking and inventory management on a construction project is often more reactive than proactive. It is not that tools are not of value, but to larger firms, a certain comfort level exists with a loss to a relatively small line item, especially when compared to the resources that may be expended to track the tool inventory. With current market construction robotics serving a number of uses, testing multiple applications of autonomous robots creates more return for end-users. This research aims to execute a proof of concept for automated tool tracking using an autonomous robot and RFID technology. The research was carried out with three types of scans namely: Human held RFID reader; Robot mounted RFID reader in manual mode; Robot mounted RFID reader in autonomous mode. A total of 39 tools were tagged using passive UHF RFID tags and the study looked at the average cycle count time it took time to read 39 tags for the three scan types and the reliability of the robot and RFID technology. Results show reliability of the autonomous robot in acquiring RFID information, including zero failures in tag identification and autonomous guidance.

Key Words: Construction Robotics, RFID tags, Autonomous Tool Tracking, Automation

Introduction

Tool loss (aka “shrink”) and inventory management represent variable line items for all construction projects. Although a certain amount of tool depreciation and/or replacement is expected with each project, loss (such as theft) and the costs associated with tracking tools on a jobsite is often an unknown. In 2005, Berg & Hinze studied the effects of theft on jobsites and noted that of 102 firms surveyed, 42 had experienced an incident of tool theft, averaging roughly $1,617 per incident. The result from their work shows that stolen tools, equipment, or materials are rarely recovered, with about a 7% recovery rate. In addition to theft, the cost associated with inventory management is typically placed on an onsite employee who has a multitude of other job requirements Goedert et al. (2009).

Today, tool tracking is still an evolving field. Many tool manufacturers have Bluetooth enabled sensors that are either integrated into the tools or can be placed on the outside of the tool. This technology works well but does have a couple of inherent issues. First, the technology is active, meaning it requires battery power that will drain over time and eventually fail. Second, these Bluetooth sensors are expensive. Depending on quantity purchased, a single external tag can cost $30 or more (Grainger, n.d).

Advancements in passive UHFRFID technology and autonomous mobility platforms has allowed research to improve tool tracking where Bluetooth technology is limited. Passive UHF does not require battery power and the cost associated with each tag runs in the cents, not dollars. With current market construction robotics serving several uses, testing multiple applications of these robots creates more return for end-users. This research explores the use of inventory management through passive UHF and autonomous robotics. The research attempts to address the following questions:

1. Are there any challenges associated with RFID scanning via manual or autonomous terrestrial robots?
2. In an experimental setting, what is the average cycle count time for the three scan types i.e., Human held RFID reader; Robot mounted RFID reader in manual mode; Robot mounted RFID reader in autonomous mode?
3. Is there any failure in capturing the Passive UHF tags for any of the three scan types?

Although the focus of the study was on small tools, the researchers believe that the findings of this proof of concept could be extrapolated to equipment and materials – recognizing that the RFID tags may need to change based on the material makeup of the tagged item.

Literature Review

There is an abundant literature that addresses Real Time Locating Systems (RTLS) technologies. Li et al., (2016) state that Radio frequency identification (RFID), Global positioning system (GPS), Ultra-wideband (UWB), Vision analysis, Wireless local area network (WLAN), Ultrasound, Infrared (IR) are some of the examples of RTLS technologies.

According to (Valero et al., 2015), tool misplacement in the workplace cause undesirable interruptions. On one hand, the workers will be looking for the proper tool on a jobsite, this being a time-consuming task. In other instances, the tool inventory will be enhanced to avoid delays. In either of the settings, there is money that is lost. However, the addition of RFID tags to the equipment can be a useful strategy to optimize the budget.

Lu et al., (2011) also backs that RFID technology can be applied to locating machines and tools; with its strengths of wavelength, and contactless. Goodrum et al., (2006) developed a tool tracking and inventory system which is also capable of storing operation and maintenance (O&M) data using commercially available active radio frequency identification (RFID) tags. The study demonstrated that active RFID can be used to inventory small tools and store pertinent O&M data on the tools in construction environments

Although RFID is neither the most accurate nor the most conveniently deployed RTLS, its application in the construction industry has been researched intensively (Li et al., 2016); 36 out of 90 (total studies selected for RTLS) positioning studies talk about RFID applications in Construction Industry. Li et al., (2016) cites (Ko, 2010; Montaser & Moselhi, 2014) to suggest that the accuracy of RFID can be improved by using different locating techniques and algorithms. For example, Montaser and

Moselhi (2014) compare accuracy by two locating techniques, triangulation, and proximity, while Ko (2010) compares the accuracy of the different algorithms being used.

Sun et. al, (2013) proposes the following applications of RFID in construction industry namely: i. Construction Time and Schedule Management; ii. Construction Quality Management; iii. Construction Supply Chain Management; iv. Construction Safety Management; v. Construction Document Management; vi. Construction Waste Management

In addition to the above, Table 1 summarizes some of the key studies relevant to application of RFID technology within the context of Construction Engineering and Management from before 2010.

Table 1

Notable Secondary Literature in the domain of RFID and Construction Engineering and Management [adopted from (Lu et al., 2011)]

Citation	**Remarks**
Jang and Skibniewski (2009)	Development of a system for tracking construction assets by combining radio and ultrasound signals.
Goodrum (2006)	Employed the technology for tool tracking on construction job sites.
Dziadak et al. (2009)	Using RFID, developed a model for three-dimensional position of underground assets.
Domdouzis et al. (2007)	Exploratory study on utilizing RFID in the construction industry for tracking of pipe and other valued items, and an in-situ inspection.
Tzeng et al. (2008)	Investigated the effect of RFID and interior finishing materials on RFID system recognition.
Yin et al. (2009)	Established a precast production management system using RFID technology
Wang (2008)	Carried an exploratory study to use RFID technology to improve construction quality inspection and management.
Chin et al. (2008)	Combined RFID and 4D CAD to logistics and progress management using an information system approach.

Methodology

The aim of this exploratory study was to execute and present a proof of concept that involves testing passive UHF with the aid of an autonomous, terrestrial robot for inventory management through an operational experiment carried out at Robins and Morton Construction Field Laboratory, Auburn University. The test was carried out to verify a proposed conceptual mechanism of integrating autonomous robot and a RFID scanner mounted on the robot. The equipment used are “off-the-shelf” and available to the public.

Autonomous Robot

The autonomous robot used in this study is a Boston Dynamics SPOT. SPOT was selected for this research for two reasons; the robots capabilities and the availability of the robot to the researchers. During the experiment, the robot was carrying 4 payloads – A pan/tilt/zoom camera as a mount, a Zebra RFD8500 handheld RFID reader, and a Velodyne LiDAR scanner and SPOTCore processor to improve the autonomous vision of the robot during the autonomous walk. Figure 1 presents the payload layout during the experiment.

Figure 1. RFID Reader Mounted on top of SPOT

RFID

There are several hundred options for inlays for passive UHF RFID inlays. Performance of a passive UHF RFID system is determined by the RFID reader, the transmit and receive antenna attached to the reader, any environmental factors between the reader antenna and the RFID inlay, and the type of material the RFID inlay is attached to. For the purposes of this research, a combination RFID reader/antenna unit was used, which we will refer to collectively as the "reader".

The RFID reader was a Zebra RFD8500. There were a variety of tools to be tagged. Because the tools are manufactured with various combinations of rubber, plastic, metal, and other materials, it was challenging to find a consistent tagging location across all tool types to apply the inlay. In a full deployment, specially cased RFID inlays can be selected to offset the effects of the different material types. However, for feasibility testing and use case validation we selected a general-purpose inlay.

The Avery Dennison Dogbone R6 is a midsize inlay with generally even performance across various types of materials. The product data sheet is attached which illustrates theoretical read range across a variety of material types. In testing through various projects at the Auburn RFID Lab, the Dogbone is generally considered a solid first choice option for testing tagged items with a variety of unspecified material types and configurations.

In full deployment, it is likely possible that smaller inlays may be used as well. It is recommended to select a tagging location across all tool types in which the inlay can be applied to a consistent material type, and to use a ruggedized inlay, encased in plastic or rubber material, to protect the inlay from damage, and to offset the inlay from the tool for improved performance.
For the purposes of this testing, the Dogbone R6 inlays scanned on all products tagged in each testing scenario.

The Experiment

The research looked at three scan types, using 10 scans for each type:

a) Human held RFID reader
b) Robot mounted RFID reader in manual mode
c) Robot mounted RFID reader in autonomous mode

As shown in Figure 2, the tools are stored in an 8'W x 40' L x 8' H Conex. The tagged tools within the Conex are located on the floor and wall mounted in a space roughly 6.5' H x 16' L. A total of 39 tools were tagged.

Figure 2. Tagged Tools in Conex

The experiment was designed in a manner to first establish a control study (Human held RFID reader) and then compared with that of the SPOT's performance in two modes i.e., Guided and Autonomous. Time taken to register all 39 tags was chosen as the performance metric while also verifying that all 39 tags were read properly, and the robot did not have any issue with the autonomous actions.

Data Collection

Each scan type began from the same point, roughly 15 feet from the threshold of the Conex box where the tools are stored. The cycle count time clock was started once the human researcher took their first step towards the Conex with the reader activated. For the robot, the cycle count time was started when the robot took its first step in manual mode or when the user pushed "play" to active the autonomous mode. This distinction is important, as the autonomous robot often has a delay in its first steps (~3 seconds) while it downloads the guidance and data packages from the handheld where that information is stored.

Human held RFID reader

The first scan was carried out by two of the researchers using a RFID Scanner and a stopwatch. The cycle count time was started as soon as the Human held scanner started moving towards the Conex and stopped as soon as all 39 tags were recorded. This was repeated 10 times.

Robot mounted RFID reader in Manual Mode

As shown in Figure 1, the RFID reader was placed atop the robot's PTZ camera in order to elevate it. The manual mode scan was carried out by a team comprising of three researchers – a timekeeper, a researcher watching the tag counts, and a robot pilot. The cycle count time was started as soon as the robot started moving towards the Conex and stopped as soon as all 39 tags were recorded. This was repeated 10 times.

Robot mounted RFID reader in autonomous mode

The final scan type was carried out by utilizing the autonomous mobility function of SPOT i.e., Robot mounted RFID reader in autonomous mode. The robot was trained to walk the same route as the human and manual robot. The cycle count time clock was started as soon as the robot pilot activated the autonomous mode. This was repeated 10 times.

Results

Q1: Are there any challenges associated with RFID scanning via manual or autonomous terrestrial robots?

The research did not encounter any issues with the robot in manual or autonomous mode. As a proof of concept, the research yielded strong results; however, the number of robot-based runs (20 in total), the controlled/lab-based setting (i.e. no obstructions or variability), and the short distances all played a role in the reliability of the robot. Future research will continue to add complexity to the robot's abilities in manual and autonomous mode.

Q2: In an experimental setting, what is the average cycle count time for the three scan types i.e., Human held RFID reader; Robot mounted RFID reader in manual mode; Robot mounted RFID reader in autonomous mode?

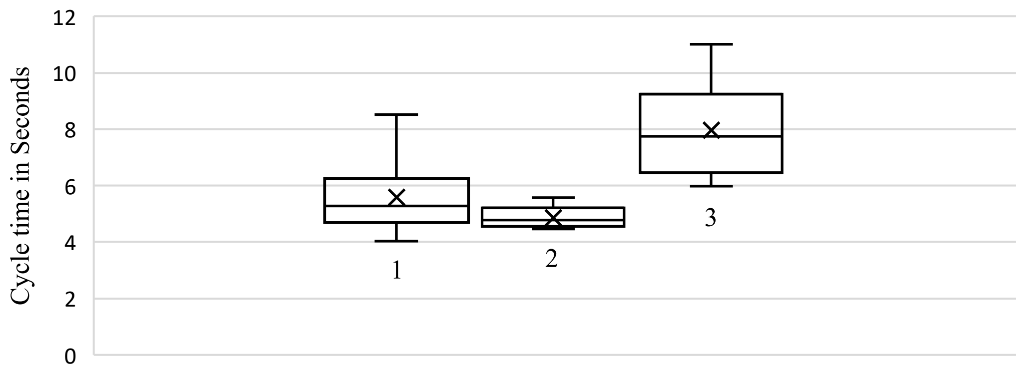
The analysis results are presented in three forms namely: i. Box-Whisker plot to visualize the variation in recorded data for all three types of scans respectively; ii. Descriptive analysis for the cycle count time data gathered, iii. Trend analysis for the cycle count times for the total of 10 runs conducted for each of three scans respectively. Table 2 summarizes the descriptive statistics for the 10 test runs that were conducted for each of three scan types.

Table 2

Descriptive Statistics for each of the three scanning strategies in Cycle Count Time

Run Number	**Human held RFID reader (sec)**	**Robot mounted RFID reader in manual mode (sec)**	**Robot mounted RFID reader in autonomous mode (sec)**
Run 1	6.49	5.16	7.57
Run 2	6.18	5.38	6.54
Run 3	4.04	4.69	7.67
Run 4	6.03	4.47	8.24
Run 5	4.76	4.87	5.97
Run 6	4.47	4.56	7.84
Run 7	4.83	4.54	9.17
Run 8	5.74	5.58	11.00
Run 9	4.83	4.56	6.2
Run 10	8.51	4.88	9.46
Mean	**5.59**	**4.87**	**7.97**
Min	4.04	4.47	5.97
Max	8.51	5.58	11.00
SD	**1.31**	**0.39**	**1.58**

To point out the key result of the experiment, the second scan type i.e., Robot mounted RFID reader in manual mode was the quickest on average (Mean Cycle Time: 4.87 seconds) and with relatively lesser deviation in performance (SD: 0.39 seconds).



1. Human Held RFID Reader 2. Robot mounted RFID (Manual Mode)
3. Robot mounted RFID (Autonomous Mode)

Figure 3: Box-Whisker Plot for Three Scanning Strategies

Observing Figure 3, the robot mounted reader in manual mode has the least amount of variation, and all the cycle count times vary to a small extent. The researchers conjecture a couple of reasons for these results:

1. A RFID Reader generally requires the user to agitate the field. Often this is done with the user "painting" the air with an up-and-down motion with the reader in their hand. While mounted on the robot, this painting motion is not possible; however, the robot does have a natural agitation that occurs while it is walking. Perhaps the gait and speed of the robot provided the agitation the reader required more efficiently than the broader painting motion the human researcher was using.
2. Although the three scan types took the same route to the tags, the human held RFID reader was likely positioned differently to begin each cycle count time. At the initiation of a cycle count, the handheld was often waist-side by the user. This is a natural and unintentional starting point, but perhaps played a role in the time for the reader to identify all the tags. On the robot, because of the mount being placed forward facing, at the initiation of the cycle count time, the handheld was already facing the tags.

The maximum variation was related to the robot mounted RFID reader in autonomous mode. This delay is a function of the data packages sent from the handheld to the robot. Upon receiving the start command, there is a small initiation sequence that the robot must perform. All time delays such as these, were included in cycle count time observations for this option. It was believed that all these intermediate steps are part and parcel of the cycle count time and therefore must be recorded.

Figure 4 further reiterates this data, showing a comparison of cycle count times graphically.

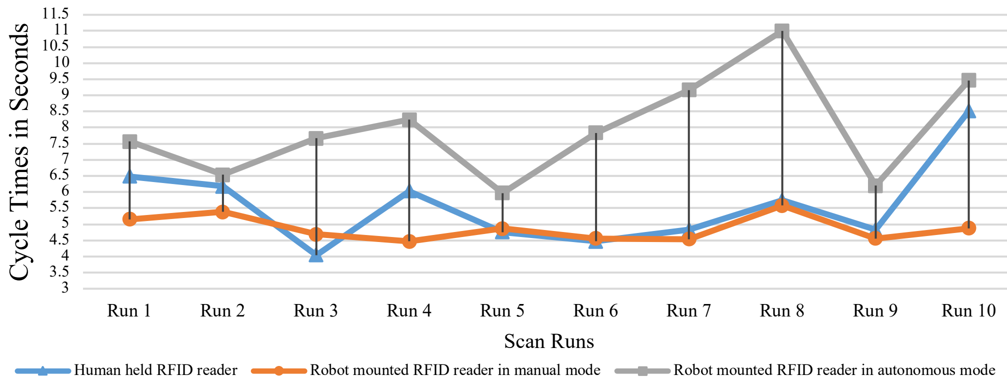


Figure 4. Relative performance of each run and scan type

Q3: Is there any failure in capturing the Passive UHF tags for any of the three scan types?

There were no UHF tag or reader failures during the experiment. In every run, all 39 tags were found within an acceptable timeframe.

Conclusions and Recommendations

At the conclusion of the proof of concept, the following conclusions and recommendations can be put forward.

Overall, terrestrial, autonomous robotics does appear to be a potential use for tool tracking. In terms of reliability, both the RFID technology and the robotics technology executed the scope of this research without fail. However, with all 30 runs in a lab-based setting, future research should look at more challenging and robust use cases. When evaluating efficiency (cycle count time), it can be concluded that on an average the 'robot mounted RFID reader in manual mode' was the quickest. It is worth mentioning that the respective cycle count times were almost certainly time dependent on the skill of the operator. Since the operator was extremely skillful, the least standard deviation is reflective of similar performance for the 10 scans that were conducted. Furthermore, after the initial few scans, the variability between the performances in 'human held RFID reader' and 'robot mounted RFID reader in manual mode' reduced considerably. Although the autonomous robot was the slowest, in practice, this number is irrelevant. In this proof of concept, the research showed the robot can be used autonomously for tool tracking. Without the need for human intervention, a slower cycle count time doesn't matter. As long as the cycle count time doesn't exceed the roughly 90-minute battery life of the robot, the productivity savings for a human; stands at 100%. It is worth noting that the costs associated with the robot and scanning equipment are significant and would certainly play a factor in the economics of a construction project. However, history has shown that often these types of technologies become cheaper as the tech improves. In addition, as more use cases are developed for both autonomous robotics and RFID on construction products, the productivity savings begin to offset the initial and lifecycle costs of these technologies.

With a successful proof of concept, the authors believe the following recommendations will pave the way for more robust autonomous tool tracking on construction sites. Future research could include:

- Variable placement settings for tagged tools, such as placing them inside a gang box or truck.

- Height limitations and the use of collaborative robotics (i.e., drones + terrestrial robots)
- Different types of RFID tags to understand the impact on performance.
- Test under on-site conditions, including muddy, rough terrain, longer distances, weather issues, variable materials, etc.

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