BareTag Tool-Tracker

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***Abstract*—Over the past 10 years, the majority of tools on a construction site have converted from wired to battery-powered. While this makes tools easy to move around, it also makes them easy to misplace and an easier target for theives. Data indicates that the construction idustry suffered nearly $1,000,000,000 in loses due to tool theft in 2016 alone [1], strongly indicating the need for a robust and effective theft mitigation system. We propose the BareTag Tool Tracker, a novel approach to tool tracking that utilizes Ultra-Wideband(UWB) and Bluetooth Low-Energy(BLE) radio in order to real-time track tools, materials, or other valuable items on a construction site. The system utilizes a series of pre-placed Anchor posts, that send UWB pings to a Tag that is connected to a tool. Each Anchor can then calculate its distance to a Tag, relaying that information to a Base station over Long Range(LoRa) radio. The base station runs the aggregated distance data through a multilateration algorithm that can calculate the Tag's location with $\pm$ 10 cm accuracy. The calculated location is then output to a local terminal, as well as uploaded to a cloud database for future reference. Altogether, the BareTag Tool-Tracker is highly accurate ($\pm$ 10 cm), low-power (1 year of battery life), and scalable (increase range by adding additional Anchors).**

I. Introduction

On constructions sites tools are constantly being misplaced causing workers to spend extra time searching and waiting before returning to their assignments. Furthermore, in recent years research has shown that theft on constructions sites has built up costs for construction companies and slowing down projects, very detrimental for small companies. Many different approaches have been taken to solve this growing issue.

A. Significance

In 2016 it was estimated that in the United States alone $1,000,000,000 worth of construction tools were stolen [1]. A survey by the Charted Institute of Building discovered that out of the 1000 construction mangers interviewed, a third responded that they had experienced theft weekly on their sites. It was estimated that each of these weekly incidents cost the business an average of $6,000, in some cases, in a single night the site had lost $100,000 worth of equipment [2]. What's worse is that this is a growing case. The FBI has reported that in 2021, theft on construction sites had outgrown theft in convenience stores [3]. Many managers have reported that these incidents have escalated to organized crime with evidence of sophisticated planning and coordinated executions. [2]. Theft on the site is not only costly to the business owners but also inconvenient for the construction workers and their managers. Due to the lack of proper tools construction workers may not continue with their assignments and managers have to keep pushing deadlines. The result of this costs the business not just in extra wages, but also extra insurance and reputation [2].

B. Context and Survey of Similar Solutions

The general problem of item tracking has had many attempted solutions and continues to be a problem of interest today. In designing our system, we extensively researched many similar solutions to examine how these solutions fall short of achieving our system's goals. Other solutions we have examined use various technology for tracking such as: AI image processing, GPS, Bluetooth, and Ultra-Wideband.

One comparable solution that utilizes image processing methods is offered by SIRIX. Their approach involves human and AI-assisted item tracking, using two types of cameras: wide-angle and thermal. These cameras are strategically placed throughout the job site and are monitored 24/7 by both human operators and AI [4]. However, this solution is highly unreliable and unsustainable due to the presence of blind spots that fall outside the cameras' field of view, leaving certain areas unprotected. Additionally, human judgments and AI decision-making can introduce further response time, potentially allowing thieves to escape with stolen items before any alert is triggered. Another concerning issue is with the way that the system is powered. Attackers, especially a criminal organization as mentioned in the problem statement could easily disable the system by cutting the power generator or energy source, rendering it inoperative, leaving the remote surveillance team with no recourse other than calling the authorities. While both SIRIX and BareTag offer 24/7 security systems, only BareTag qualifies as a true round-the-clock security measure. BareTag does not depend on human or AI intervention to ensure tools and materials are secure. Additionally, BareTag's low power consumption allows it to operate more efficiently across diverse terrains, offering higher portability and flexibility compared to the energy-intensive SIRIX system.

Another comparable solution we evaluated is a commercial system called GoCodes, which specifically addresses the issue of tool tracking. This system employs continuous GPS tracking to monitor valuable equipment within a geofence, helping businesses prevent the loss or theft of tools. While it offers effective on-site tracking, off-site tracking relies on individuals scanning QR codes placed on the tools. If a user scans the

QR code, the item's location outside of the geofence can be updated [5]. However, this approach has a significant flaw — no tool thief would voluntarily scan the QR code, and they could easily remove the codes from the tools, eliminating any trace of the theft. Although GoCodes provides a workable solution, it has several drawbacks that our system aims to overcome. For one, GPS tracking is power-intensive, often requiring frequent battery replacements for the trackers. Additionally, GPS tracking needs an unobstructed line-of-sight to function efficiently, which can be compromised in dynamic construction environments. Furthermore, our system is designed to operate in very rural construction areas where satellite connectivity may be limited. Unlike GPS, which requires a strong satellite connection for accurate tracking, ultra-wideband (UWB) technology, which our system uses, does not rely on satellites, making it more reliable in such environments.

A common solution and a more reliable approach is using the Apple AirTags. In the Apple AirTags, there are BLE modules that help it communicate with other iPhones to create the Find My network. Additionally, it has UWB modules that allow the user to get a more accurate location of where the tag is once the AirTag is close enough to the user's iPhone [6]. This creates a well-rounded system to let users get a general idea of where their items are with a battery life of up to a year. The difference between the BareTag and the AirTag is that the BareTag is used for accurately tracking high-value items within the set UWB perimeter. BareTag emphasizes the use of the UWB module so construction workers can easily find their tools, along with an additional BLE module for the Find My Network feature outside of the set perimeter. Unlike Airtag, our system aims to not only track and retrieve items but also to accurately and reliability track tools to optimize efficiency.

The final solution takes a similar approach to BareTag. Pozyx tracks items indoors by installing UWB anchors throughout the building, which communicate with UWB tags. These anchors are height-adjustable and plugged into walls. Once configured and registered in the system, items can be geofenced, and the collected data can be used to optimize workflow and labor efficiency [7]. While Pozyx offers an effective indoor tracking solution, it is less efficient in outdoor environments. In locations like construction sites, where power availability may be limited, anchor placement becomes a significant challenge. Additionally, even though Pozyx's UWB tags are advertised to have a battery life of over five years, they are bulky and lack a low-power option. In contrast, BareTag's anchors come with pre-installed communication systems and built-in batteries, making the system more portable and scalable. Furthermore, BareTag's tags feature a built-in accelerometer with an automatic sleep function to maximize power efficiency. This not only extends battery life but also reduces the frequency of battery replacements, saving time and resources. In summary, BareTag's anchors do not rely on external power sources, and the tags are equipped with a low-power solution, making them more suitable for outdoor and construction site use compared to Pozyx's solution.

C. Societal Impacts

Our system can positively benefit all of society. As a tool tracking system made for construction workers, they are the most obvious group of people who benefit from this system. With construction workers being the primary users of our system, many of our design choices will be made specifically for the system to be easily used by the average construction worker. We want to create a user-interface that helps construction workers track their tools without having to do any additional work of their own. While this will greatly help construction workers find their tools and not have to worry about their tools being stolen, it benefits owners of construction firms even more. With accurate tool tracking, they can ensure their workers are working as efficiently as possible and not wasting their time looking around sites for tools. Owners of construction companies are also the ones responsible for supplying their workers with the tools needed to complete jobs. We want our system to reduce these costs for construction firm owners by reducing the loss and theft of their very expensive tools. Preventing theft and increasing the efficiency of workers can help a construction firm look more professional and hireable by employers that need construction work done. Our system aims to help construction teams work quicker to efficiently finish jobs which will increase the number of jobs they can take. Because our system increases construction efficiency, anyone benefiting from the construction of literally anything can benefit from it as well. The only people that will be hurt by our system are thieves that will be caught stealing expensive tools by our system.

D. Goals, Specifications and Testing Plan

The BareTag Tool Tracker will implement the following goals, 1. Real-time tracking within a specified zone, 2. Precise accuracy for tracking within the zone, 3. Low Power, 4. Reliability outside the zone, 5. Scalability.

The specifications listed in Table 1 demonstrate the goals that our project aims to achieve by the time that we have a finalized product.

II. DESIGN

This section describes the system design including design alternatives, design justifications, and hardware and software block diagrams.

A. Overview

At a high level, the BareTag Tool Tracker utilizes Ultra-Wideband (UWB) and Bluetooth Low Energy (BLE) radio in order to real-time track an item's location on a construction site. The technology at the core of our design is UWB radio. UWB radio is a form of radio communication that utilizes pulses of radio energy at specifically timed intervals in order to transmit information. This protocol is not ideal for data communication, but is very accurate in performing distance

TABLE I
DESIGN GOALS AND TESTING PLAN

Specification	Testing Plan
The system will track an item's geo-coordinates with a reliability of 95% within a specified 100 m x 100 m zone.	Ping the Tag at randomized coordinates within the Sustainable Engineering construction site.
The system will have less than 50 cm precision for tracking within the specified zone.	Compare Tag's measured location to its actual location within a predefined grid.
The system will operate 24/7 for 1 year without replacing the batteries.	Measure the power consumption of the system in multiple modes.
Ensure that the Tag can be tracked via the Find My network outside of the UWB zone.	Confirm tracking accuracy in scenarios with different saturations of Find My devices by comparing with AirTags in the same location.
Should easily be scalable to increase the range of the UWB perimeter by adding more Anchors at desired locations.	Demonstrate that a Tag's trackable range in the UWB zone increases when adding a new Anchor.

ranging. With two UWB transceivers, one configured as the controller (Anchor) and the other configured as the responder (Tag), the Anchor can range it's distance to the Tag via UWB pings. The Anchor begins by sending a ping with the desired Tag's ID encoded, the Tag will almost immediately send back a response ping, the Anchor can then use the time between when it sent its ping to when it received the Tag's ping, in order to calculate the distance between the two transceivers.

$$d = \frac{\frac{ToF}{2}}{c}$$

Where d is distance between the Anchor and Tag, ToF is time of flight, and c is the speed of light.

With distance measurements between 3 Anchors and 1 Tag, we can preform a trilateration algorithm in order to calculate the Tag's location within our site.

The equations for the three circles (Anchor to Tag distance):

$$(x - x_1)^2 + (y - y_1)^2 = r_1^2$$
$$(x - x_2)^2 + (y - y_2)^2 = r_2^2$$
$$(x - x_3)^2 + (y - y_3)^2 = r_3^2$$

Where r_i is the distance from an Anchor to a Tag, (x_i, y_i) are the cordinates for each Anchor on a 2D x, y plane, and (x, y) are the coordinates for the Tag we are trying to locate. Next we subtract the second equation from the first:

$$(-2x_1+2x_2)x+(-2y_1+2y_2)y = r_1^2-r_2^2-x_1^2+x_2^2-y_1^2+y_2^2$$

Likewise, subtract the third equation from the second:

$$(-2x_2+2x_3)x+(-2y_2+2y_3)y = r_2^2-r_3^2-x_2^2+x_3^2-y_2^2+y_3^2$$

Re-writing these two equations using A, B, C, D, E, and F:

$$Ax + By = C$$
$$Dx + Ey = F$$

Finally, the Tag's (x, y) coordinates are:

$$x = \frac{CE - FB}{EA - BD}$$
$$y = \frac{CD - AF}{BD - AE}$$

Once the Tag's location has been calculated via our trilateration algorithm, the Tag's location will be output to a local terminal, as well as uploaded to a cloud database. Outputting to a local terminal allows us to have the system function without the need for an internet connection, something that may not be available on rural construction sites. If internet is available, we can upload location to cloud database. With location data stored remotely, any user with internet access can get their Tag's current location, or past location.

Aditionally, as one of our main goals is to prevent theft, when a Tag leaves the designated construction site, a notification will be sent to the user, letting them know that one of their Tag's has left the site. To continue to track the Tag once it leaves the construction site, we will turn off the Tag's UWB radio, and turn on the Tag's BLE radio. Using BLE advertisements, the Tag will be able to communicate with nearby devices that are using the Apple Find My protocol. The Find My protocol allows BLE devices to be tracked with around 10 meter accuracy when in loactions saturated with Apple devices. With this tracking outside of the construction site, users can not only keep track of their tools on a construction site, but also track down stolen tools outside of the construction site. To help integrate our Tags into the Find My network, we will be using the open source project, openhaystack.

Openhaystack, is an open source project originating from TU Darmstadt, that utilizes Find My's open API, as well as a collection of reverse engineering and security analysis work to allow generic BLE devices to be tracked via Apple's Find My network.

Altogether, the BareTag Tool Tracker utilizes UWB and BLE in order to real time track the location of Tags on and off a construction site. The design combines existing solutions for item tracking with UWB as well as the robust and expansive Find My network to prevent tool theft and increase construction site efficiency.

B. Tag

The Tag refers to the trackable device that will be attached to the tools on a worksite. The goal is for the Tags to be less than $31.9mm^2$, which is of a similar size to the Apple Airtag. The thickness of the Tags is aimed to be under $16mm$, with the primary contributor to this size being the pouch cell $290mAh$ Lithium Polymer battery. The peak current draw of the Tag is $45mA$ and is out of the range that a coin cell could support, which led to the decision to use a LiPo that fits within our area size goals at 25 mm x 28 mm. We are aiming for a one year battery life.

The primary part of the Tag is the Qorvo DWM3001C. This module is driven by the nRF52833 MCU which includes

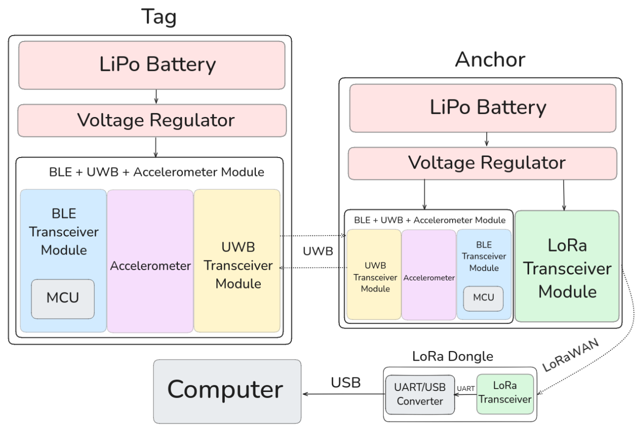

Fig. 1. Full system hardware block diagram

BLE functioality. The DWM3001C also includes, UWB and accelerometer modules. The UWB functionality is driven by the DWM3110, which has an integrated PCB antenna. BLE is provided by the nRF52833. This MCU is built on an ARM Cortex M4 and operates at $2.4GHz$. This MCU is programmable over SWD and thus requires a corresponding interface to be added to the PCBs. The accelerometer is the LIS12DH, and is used to wake up the module upon motion detection. The module will set the interrupt pin on the DWM3001C high when there is motion detected. Otherwise, the Tag is in a low power mode and is not receiving UWB pings. Therefore, before the tag goes to sleep the location needs to be checked to determine the last known resting location. The Tag has the BLE radio turned off until it exits the UWB area, at which point an interrupt pin turns it on to integrate the Tag into the Apple Find My network. At this point, the UWB module turns off to conserve power. The accelerometer still regulates the power mode of the Tag depending on motion to conserve power. This device draws a lot of concepts from ECE 523 and ECE 304, both of which have a heavy focus on minimizing power consumption via software and component selection. The TPS79933 voltage regulator has an output of $3.3V$ when the input voltage is over $3.475V$. This component is used in both the Tags and Anchors as both devices operate on a $3.7V$ battery with all modules operating at a $3.3V$ ideal voltage.

C. Anchor

There needs to exist at least 3 anchors for the coordinates of a Tag to be transmitted to the Host Device, which are calculated through multilateration. The Anchors use the same Qorvo DWM3001C modules as on the Tags as all of the submodules have a use case here too. The Anchors use UWB to ping the Tag and determine its location within the area defined by the proximity of the other anchors. They process this data using the nRF52833 MCU and send it to a host device over LoRaWAN for coordinate computation. The RYLR998 LoRa module in the Anchors operates within the operating range of LoRaWAN: $902.3MHz$ to $914.9MHz$. This module communicates with the MCU via UART. The use of these LoRa modules means that the Host Device does not need to be on the site of the construction due to the kilometers of range that LoRa supports. We will build the LoRaWAN protocol on top of LoRa using the nRF52833 MCUs and Host Device. The use of the nRF52833 means that we can take advantage of the BLE it provides and use it for a variety of functions. The GPS coordinates of the Anchors must be known in order to get the real-world position of the Tags, and we can achieve this through a mobile app that will communicate with the Anchors over Bluetooth. This operation will occur during the setup and positioning of the Anchors. We can also use BLE to communicate with an Anchor to alert that a Tag in BLE mode has been returned within range of the Anchors. These features result in more power consumption than the Tags, so a 2.2Ah Lithium Ion battery is used. This is possible due to less size constraints for the Anchors than of the Tag. The Anchors are not constrained by size, and therefore we do not have any strict specifications for its dimensions. As stated before, the TPS79933 voltage regulator outputs 3.3V, which is the ideal operating voltage for the DWM3001C and LoRa module.

D. Lora Dongle

This device is a RYLR998 operating over a USB/UART connection with the Host Device. The Dongle allows the Host Device to receive the Tag location data in reference to each Anchor, which the Host Device will then perform the multilateration algorithm on. The size of this device should be similar to that of a commonly used USB hub, as to not be an inconvenience to have attached to a small host device. The dimensions will be approximately $32\ mm\ x\ 18\ mm\ x\ 8\ mm$ based on a combination of the Dongle component dimensions, which are the LoRa module and a USB/Serial converter.
The Dongle receives power over USB from the Host Device, which the serial converter will drop to $3.3V$ for the ideal operating voltage of the LoRa module.

E. Host Device

This device can be whatever system a supervisor desires to use as long as it can support a USB/Serial connection, or do so using adapters. The Host Device performs the multilateration algorithms based on the data it receives from the LoRa Dongle. The calculations get backhauled to a cloud database where the history of Tag locations can be mapped out to determine daily paths. This information is also displayed locally on a map of the desired area. The Host Device is also running the macless-haystack server, which acts as a means for tracking the Tags that have left the UWB area and are using BLE to integrate with the Apple Find My network. The Tags all have unique IDs that can be linked to tools or equipment, making it easy to parse the data and determine what items have been in what location.

References

[1] "2016 equipment theft report," 2016. [Online]. Available: https://www.ner.net/wp-content/uploads/2017/10/Annual-Theft-Report-2016.pdf. Accessed Oct. 19, 2024.

[2] "Crime in the construction industry," 2013. [Online]. Available: https://www.ciob.org/sites/default/files/. Accessed Oct. 19, 2024.
[3] "An exploratory look at thefts from construction sites," 2019. [Online]. http://ascpro0.ascweb.org/archives/cd/2019/paper/CPRT247002019.pdf. Accessed Oct. 19, 2024.
[4] "Remote Video Monitoring," SirixMonitoring, Sep. 13, 2024. [Online]. Available: https://sirixmonitoring.com/remote-video-monitoring/. Accessed Oct. 04, 2024.
[5] "Pros and Cons of Construction Equipment Tracking," Tool Tracking Software, Aug. 02, 2023. [Online]. Available: https://gocodes.com/equipment-tracking-pros-cons/. Accessed: Oct. 04, 2024.
[6] "Airtag VS GPS tracker, what is the difference ?," Beepings.com, 2021. [Online]. Available:https://beepings.com/airtag-vs-tracker/. Accessed: Oct. 04, 2024.
[7] "Pozyx UWB Tags - Accurate ultra-wideband trackers," Pozyx.io, 2024. [Online]. Available: https://www.pozyx.io/products/hardware/. Accessed: Oct. 04. 2024.

APPENDIX

A. Design Alternatives

Before settling on our current design, we considered many alternatives. In order to make our user-interface have real world terrain displayed while tracking our tags, we need to find the coordinate positions of our anchors. In order to do this, we originally considered putting GPS modules on our anchors, but decided instead on creating a mobile app that can be used to find the GPS of your phone when setting up the anchors. We decided on this in order to save money, as individual GPS modules range from \$20-\$40. We also considered purchasing a separate MCU, LoRa, and UWB module to design our anchor PCBs. We found this design too complex and instead decided on the same module as we are using in the Tags. We decided on this current design because we want the tags and anchors to have the same technology to be able to program them with the same libraries in order expedite software development. Batteries have been a prominent part of our design that we have put a lot of effort into deciding on. Because we want the Tags to be small enough to go inside of tools without manufacturers having to add room for them, we decided on very small batteries inside the tag. We also considered doing energy harvesting for the anchors to increase the battery life of them, but have decided on large batteries for the anchors because they are less size constrained compared to the Tags. In our original plan, we were going to backhaul our data to a cloud database in order for processing. After some consideration, we decided on sending the data to a self-hosted database to have increased control over the hardware, software, and configurations, which allows us to customize our database to meet our project's needs. Having our own self-hosted database can also allow us to implement our own security measures, will be less expensive, and will have greater performance optimized for our specific workload.