Low Cost Real Time Location Tracking with Ultra-Wideband

Anthony Ambrose[1] Celal Savur[2] Ferat Sahin[3]
Department of Electrical and Microelectronic Engineering
Rochester Institute of Technology
Rochester, NY, 14623, USA
{axa6841[1], cs1323[2], feseee[3]}@rit.edu

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***Abstract*—An emerging technology for indoor localization is ultra wide-band, also known as UWB. UWB has been making waves as a system that can be both secure and function as an "indoor GPS". The proliferation of UWB is underway and soon it will be as ubiquitous as Bluetooth or Wi-Fi. With this in mind, the benchmarking of the DWM3000EVB module in an Ultra Wide-band Real Time Locating System is the goal of this research. The UWB RTLS created is a three anchor - one tag system that can calculate position just under 100 Hz and has an average accuracy of 5 centimeters.**

***Index Terms*—Ultra wide-band, UWB, Real Time Location System, RTLS, human robot collaboration, indoor position tracking, DWM3000EVB, DW3000, Qorvo**

I. Introduction

Ultra-wideband (UWB) is not new and has been around for decades, but UWB technology is only recently being commercially developed. In 2014, Decawave released the DW1000 UWB chip which was a game changer in the UWB market at the time. However, time has passed and a lot of new UWB standards have come into place, such as the FiRa Consortium specifications and IEEE standards. In early 2021, the DW3000 family of UWB transceivers was released, promising interoperability with Apple's U1 chips. All this activity around UWB hints at a future where it becomes as ubiquitous as Bluetooth. Currently, commercial off the shelf UWB RTLS components use the now outdated DW1000 series chips and are generally expensive.

This research is a simple example of how UWB can be used in a system of systems capacity. The lower-level system of UWB nodes communicate and provide time of flight (TOF) measurements to the higher level system, which is the localization algorithm. The algorithm could also make use of sensor fusion to combine the UWB data with other localization data. An example would be the DW3000 UWB nodes being used in a UWB and LiDAR network that monitors the users position to create a safe indoor human robot collaborative workspace. The concept of a "real time locating system" is valuable because it allows for the user's position in the local frame to be known, as opposed to simply warning the machine when the user is near. Some RTLS methods such as LIDAR end up being prohibitively expensive, while others such as a Bluetooth RTLS using RSSI is not accurate enough to work well.

Contributions of this research are listed below:

- A cheap solution object tracking system
- Created a UWB RTLS with 5 centimeter accuracy in high coverage zones
- The evaluation of that UWB RTLS against a millimeter accurate system
- Research with the Qorvo's DWM3000EVB module

This paper is organized as follows: section II is the background literature, such as the current usages of UWB. Section III covers the research methodology: the hardware used, algorithm description, and evaluation criteria for the UWB RTLS. Section IV covers the experiment and all the necessary details to understand the results. Section VI is the results, figures, and analysis of the system.

II. Literature Review and Background

The background literature is split between: the UWB research field, the various UWB communication schemes, the background on the hardware used in this research, and research in the human robot collaboration field.

A. UWB Research

The invention of GPS was one of the biggest technological advancements of the last 50 years. However, GPS is not really usable indoors due to the walls and ceilings attenuating the GNSS signal. This created a need for indoor localization systems and UWB was a perfect candidate to fill that position. The particular module typically used for UWB research is the DW1000 chip, which has a measured accuracy range between 10-20 centimeters [4]. Further research on the DW1000's accuracy showed that the measurement channels would occasionally become unstable, impacting the accuracy of the entire system. However, these unstable channels can be detected using their PSD and thus the detected unstable channels can be ignored to maintain high accuracy [8].

An example UWB network is a two anchor and one tag system that can measure velocity changes between a robot and human, in order to maintain distance between the two [3]. UWB shows the most promise as part of a robust sensor fusion algorithm and researchers have found success in fusing both IMU and UWB positioning data with an Extended Kalman Filter [9]. Kalman filtering can also be used with solely UWB data to reduce error in LOS/NLOS conditions. Researchers found that a Kalman filtered and linearized system

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can significantly reduce the Root Means Squared Error and Circular Error Probable in LOS/NLOS/multipath conditions [14].

B. UWB Network Schemes

The most used UWB networking scheme is Time Difference of Arrival (TDOA). This consists of a system of time synchronized anchors. The distance between a tag and anchor is determined through the signal's TOF [12]. The main advantages of TDOA are the scalability and the low energy consumption, as it can be scaled to thousands of moving tags provided the anchors have enough zone coverage. However, TDOA has the major disadvantage of having to set up the infrastructure in the area, which typically involves precisely surveyed anchor locations and daisy chained ethernet cables to achieve time synchronization across the anchor network. TDOA is best used in a large warehouse environment where moving vehicles or boxes need to be tracked by an overall network.

Two Way Ranging (TWR) is another UWB network scheme where there is bidirectional communication between the tag and each of the anchors. As a result, this system is not nearly as scalable as TDOA, only capable of supporting tens of tags instead of thousands, yet there is higher precision and positional stability in a TWR communication system. Since the anchors do not need to be time synchronized in this communication protocol, the infrastructure costs are much lower. The time resolution can be further improved by using round trip TOF with heterogeneous clocks, which generates a finer time resolution than synchronized clocks [11] [12]. TWR is best used for localization of robots or autonomous vehicles. There are also some niche UWB communication methods, such as angle of arrival (AoA), phase difference of arrival (PDOA), and inverse TDOA. AoA allows for the tag position to be calculated based on the direction of the incoming signal relative to the anchor. However, for this the anchor needs two time synchronized antennas. PDOA is similar to TDOA in the scalability and level of infrastructure needed. It differs in that instead of calculating distance from the tag to each anchor, it obtains the angle of the tag signal relative to each anchor and thus is able to get the tag position [15].

A particular disadvantage of device to device communication using UWB is the impact that no line of sight (NLOS) environments can have on the ranging measurements. It was found that NLOS situations can drastically reduce accuracy, especially for two way ranging communication methods using UWB [5] [7]. Research has shown that combining TDOA/TWR/AOA methods can improve positioning accuracy in NLOS environments, where it would otherwise be subject to multipath error [10].

C. DWM3000EVB

The DW1000 ultra-wideband chip, produced by Decawave in 2014, was one of the first UWB chips available and as such, is used in most UWB applications. However, the DW1000 does not meet the current IEEE UWB standards. Qorvo, formerly known as Decawave, has recently released their second generation of UWB chips — the DW3000 family of transceivers. The DW3000 is IEEE 802.15.4a and IEEE 802.15.4z BPRF mode compliant, as well as "fully alligned with FiRa™, PHY, MAC, and certification development". Along with IEEE and FiRa standards, the DW3000 family is also interoperable with the Apple U1 chip. This opens up a whole new world of robotics capabilities with respect to UWB; since iPhones are prolific and have access to a lot of data, such as GPS location or motion data.

The DW3000 supports UWB channel 5, 6.5 GHz; and channel 9, 8 GHz. The chip has a ceramic UWB antenna soldered on, so no third party external antenna is required. The performance can likely be improved with a better antenna; however, the DW3000 does not come with a way to swap the antenna out. The ceramic antenna has an operational range of about 120 °. The DW3000 has a nominal positioning accuracy of 10 cm. It is capable of both Two Way Ranging (TWR) and Time Difference of Arrival (TDoA) RTLS schemes. Most importantly, it is much more cost efficient relative to the UWB chips of the past. In clear LOS conditions, the stated range is 90 meters and the stated accuracy is 10 centimeters.

The DWM3000EVB is a development module offered by Qorvo, built off the DW3110 IC. The DWM3000EVB brings the supply rails, GPIO pins, and SPI communication pins off the DW3110 in an Arduino Uno Shield form factor. Due to this it can be used with an Arduino Uno or with any other microcontroller with SPI. The DWM3000EVB also comes with an SDK, to be used with either the nRF52840-DK or the NUCLEO-F429ZI development boards. The DWM3000EVB could be used with other boards, such as a Teensy or an Arduino itself; however, this would require a custom driver to be written interfacing the SPI communication between the two targets.

D. nRF52840-DK

The nRF52840-DK is a development board for RF applications, such as Bluetooth/BLE, NFC, and Zigbee. It has a connected SEGGER J-Link debugger to speed development processes. The nRF52840-DK is compatible with Arduino Uno Revision 3 form factors, which allows the DWM3000EVB to plug right in without any issue. As an additional bonus, the nRF52840-DK is able to be powered by an external supply from 1.7V to 5.0V and Li-Po batteries, making it a good candidate for a UWB anchor or tag. For this research, each anchor nRF52840-DK was powered through USB from the wall outlet and the tag was powered via laptop.

E. Human Robot Collaboration

Human robot collaboration, or HRC, can be broken up into three parts — awareness, intelligence, and compliance. Awareness is about the quantity and quality of information inputs to the HRC system. An example of this would be ring of 2D LiDAR sensors [6] giving distance measurements from the robot to the operator. This does not necessarily have to be physical though, as an accurate "digital twin" also improves robot awareness. Intelligence is the robot using its "awareness" in order to make decisions in accordance with its objective. Compliance is the feedback loop between human and robot, the collaborative part of HRC. The delineation is between robot-to-human communication and human-to-robot. The former has many options, from relaying information visually through a display or auditorily via robotic beeps. The latter is either explicit or implicit human feedback, by either commands or physiological signal feedback [1] [13].

A prevalent feature in human safety is speed and separation monitoring (SSM) [2]. This outlines all the necessary inputs for a safe environment — the speed of both the human and the robot and the distance separating the two. The more resolution the robot has on the speed of the human's movement, the better it can work around the human without collision or a decrease in productivity. Ideally, the safety zone becomes an extension of the robot itself [2] as seen in Figure 1.

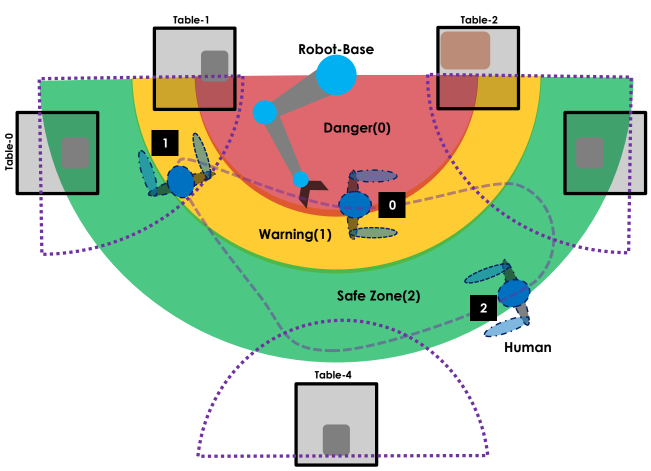


Fig. 1: HRC Safe Zone

In conclusion, this research is aim to use UWB sensor to have chapter alternative to expensive motion capture system. Then based on application requirement the proposed approach can be used in HRC application or any indoor applications. Next, we will explain how multiple UWB are used, and real-time position is estimated.

III. Methodology

This section details the specific RTLS setup and the communication protocol between the UWB nodes. Explanations of the algorithms used in this research are included, as well as the criteria being used to evaluate the UWB RTLS.

A. Real Time Locating System

The DWM3000EVB - nRF52840-DK combination will be used to create a Real Time Locating System (RTLS). The tag has two-way communication lines with each of the anchors and there are three anchors mounted on tripods. The anchors are the initiators and are constantly sending out a signal, waiting for a response. The tag is the responder and waits for an incoming signal before responding with a pre-configured message. Once the initiator receives that message, it calculates the distance between itself and the responder, and sends out a final message. With that final message, the responder calculates the distance on its end and ends the communication. In this TWR scheme, both the anchor and tag side have ranging information which could be used to make the RTLS more robust, versatile, or unique to the use case. The back and forth messages also contain device ID information for both parties, so the ranging data can be identified per anchor.

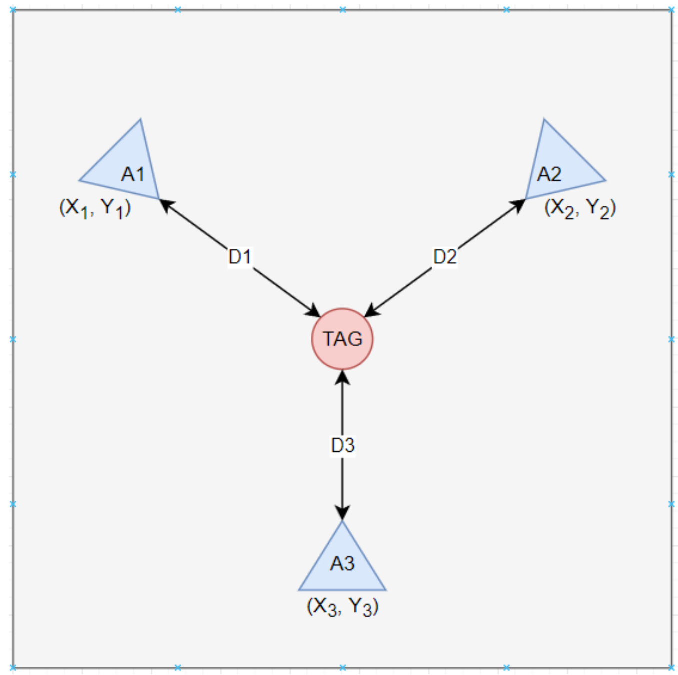


Fig. 2: General RTLS Setup

The general RTLS organization of anchors and tags is shown in Figure 2, with anchors: A1, A2, and A3 and their respective distances: D1, D2, and D3. The anchors must be surveyed beforehand in order to get their (x, y) coordinates as precise as possible. It is important to note that this UWB RTLS only works in 2D space, but it could be modified with additional anchors to work in 3D space as well.

B. Algorithms

The algorithm 1 is one where trilateration only occurs after new ranging measurements come in for each anchor. The tag does not sequence communication with anchors by default, which is what the "flag" variable is for. The tag could communicate with A1 three times before talking to A2. The "flag" allows the algorithm to sequence communication to ensure that new ranging measurements come in for each anchor within a specified time frame.

Once data for all three is received, the trilateration function is called, with the formulation shown. The speed of each anchor transmission is 100 Hz so the final position calculation speed is 33 Hz. The trilateration algorithm assumes the

Algorithm 1 General Code Flow

```
Flag ← 1
New_measurement ← Most Recent Measurement
New_anchorID ← Anchor ID
while 1 do
    if New_anchorID = A1 and Flag = 1 then
        D1 ← New_measurement
        Flag = 2
    else if New_anchorID = A2 and Flag = 2 then
        D2 ← New_measurement
        Flag = 3
    else if New_anchorID = A3 and Flag = 3 then
        D3 ← New_measurement
        Flag = 1
        trilateration()
    end if
end while
```

Algorithm 2 Trilateration

$$A = -2 \times X_1 + 2 * X_2 \quad (1)$$

$$B = -2 \times Y_1 + 2 * Y_2 \quad (2)$$

$$C = D_1^2 - D_2^2 - X_1^2 + X_2^2 - Y_1^2 + Y_2^2 \quad (3)$$

$$D = -2 \times X_2 + 2 * X_3 \quad (4)$$

$$E = -2 \times Y_2 + 2 * Y_3 \quad (5)$$

$$F = D_2^2 - D_3^2 - X_2^2 + X_3^2 - Y_2^2 + Y_3^2 \quad (6)$$

$$X_{sol} = \frac{(C \times E) - (F \times B)}{(E \times A) - (B \times D)} \quad (7)$$

$$Y_{sol} = \frac{(C \times D) - (F \times A)}{(B \times D) - (E \times A)} \quad (8)$$

positions of each anchor is known and is precisely input into the code. It calculates everything in centimeters - as such, the output solution (X_sol, Y_sol) is also in centimeters. The overall algorithm could be changed so that it trilaterates after any new measurements come in. This small difference would allow for a higher refresh rate of 100 Hz on the position calculation if more data points is advantageous to the use case.

C. Evaluation Criteria

The UWB RTLS will be evaluated against the OptiTrack Motion Capture system currently implemented in the Century Mold Collaborative Robotics (CMCR) Lab at RIT. The OptiTrack system, referred to as Mocap through this paper, has 12 cameras set up around the room and has one millimeter accuracy through the use of rigid body detection. The rigid body tag is placed on the back of the UWB tag, so the path as measured by Mocap is accurate to within a few millimeters of the tag's actual position in 3D space. The UWB RTLS works in 2D space so the Z-axis data from the Mocap is left unused.

IV. Experiment

The DWM3000EVB is mounted onto the nRF52840-DK, which is then mounted onto a tripod using a 3D-printed housing. The housing also allows for the anchors to be stuck onto the walls after prototype testing is complete. There were three anchors in total, mounted as close to the corners as possible for maximum area coverage in the room. They could not be mounted directly onto the walls because the Mocap system was used to survey the anchor locations and it does not work well on wall-mounted objects.

The general experiment consists of the user holding the UWB tag in their right hand, which also has the Mocap rigid body tag attached, and walking around the room. As the user walks, the Mocap system collects millimeter accurate positional data at a rate of 120 Hz. Meanwhile the UWB RTLS does the same at just under 100 Hz, as the data is coming in parallel from each transmitter but the receiver is limited to sequential processing. Finally, the positional data of both tags are aggregated and plotted to have a visual representation of the path as measured by both systems.

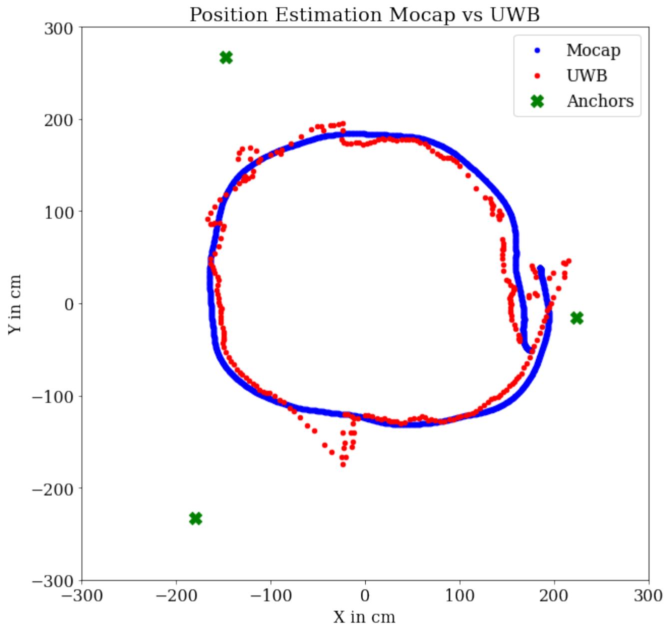
V. Results

Each of the anchor positions was measured with the Mocap system, down to the millimeter. Once set up and measured, none of the anchor tripods were moved. The overall calculation speed of the program was about 33 Hz, since each anchor was communicating at 100 Hz and the algorithm waits for 1 new measurement per anchor before trilaterating. The following paths were tested: a large circle, a small circle, a large square, and a small square. There was enough discrete data points to apply a rolling average to smooth the UWB tracking, so a rolling average of 33 was applied to the aggregated calculations. This smooths the visualization considerably, but a low rolling average of 5 is useful in order to see specific spots of error along the path.

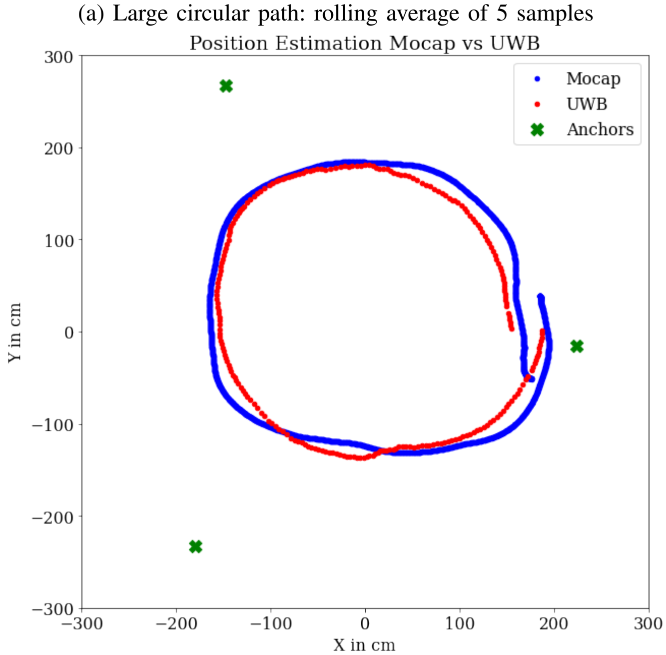
Figures 3a and 3b show the large circular path with rolling averages of 5 and 33 respectively. The former shows the positioning error at the bottom of the path in much greater clarity. In the room, this was when the user was walking away from anchor 3 - ”A3” - so the the tag had a hard time getting a signal back from A3. Since the algorithm will wait for a new measurement from each anchor before calculating position, this halts position calculation as one as one single anchor has yet to respond. The max error is 251 millimeters in the large circular path.

The small circular path is shown in Figure 4, rolling average of 33. This UWB path tracks much better with the Optitrack path, likely due to the smaller path being more within the anchor coverage zone. The max error in this path was 74 millimeters.

The square paths are shown in Figures 5 and 6. The large square had a maximum error of 243 millimeters, while the small square had a maximum error of 344 millimeters. Once again, the most points of error are seen directly to the right of A3. A3 is angled towards the center of the room, so this



(a) Large circular path: rolling average of 5 samples



(b) Large circular path: rolling average of 33 samples

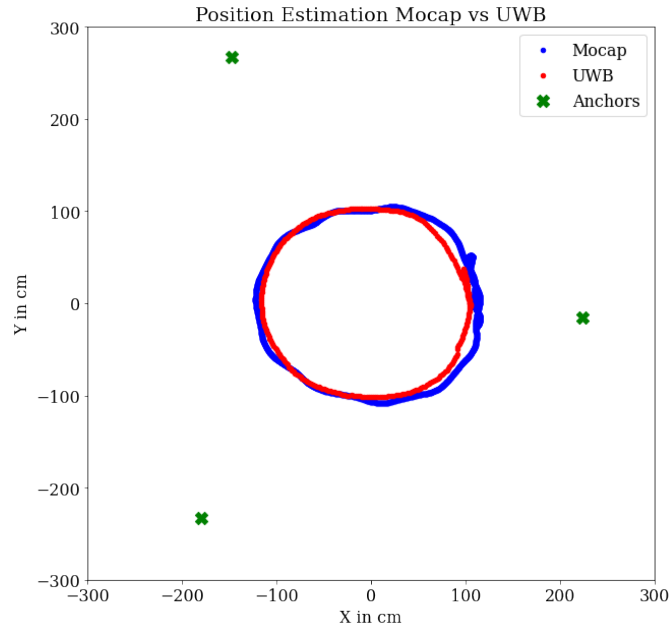


Fig. 4: Small circular path: rolling average of 33 samples

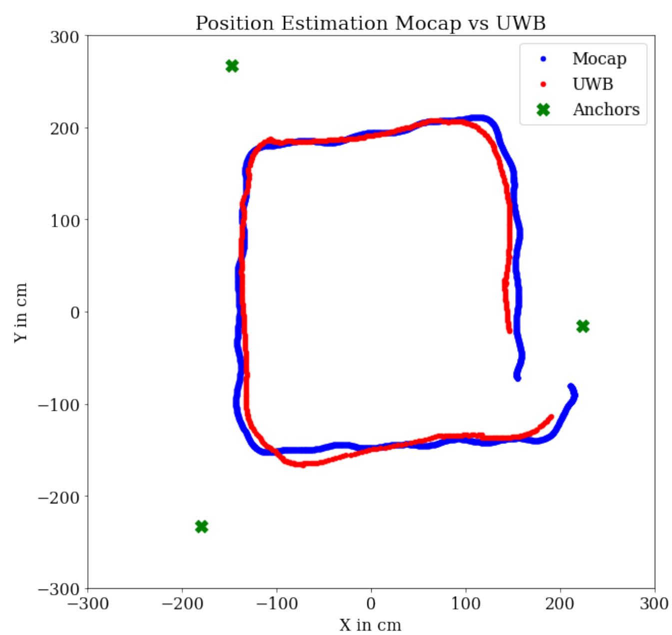


Fig. 5: Large square path: rolling average of 33 samples

area of the path is the most out of anchor coverage. The UWB RTLS performed surprisingly well on the straight paths.

VI. Conclusions

Currently, the UWB Shield has a single ceramic UWB antenna provided by Qorvo. If this was swapped out for a higher gain antenna such as the Taoglas FXUWB10, the entire system would have measurably better performance. A higher quality antenna would also allow for a better operation zone per UWB anchor. The operational zone of each anchor is also limited due to it's positioning — if they were wall-mounted then there would be greater zone coverage. They currently are a meter or two away from the walls on tripods, but a more permanent solution would be attaching the anchors to be flush with the wall and neatly route micro-USB cables up. More anchors could also be added to the system to provide more area coverage or even transition from 2D space to 3D space. In regards to price, the Mocap system cost about $15,000 while the Qorvo UWB RTLS cost $350 — Qorvo UWB being cheaper by far. The UWB RTLS also consisted of three anchors and a tag, making it extremely portable. As long as the (x, y) positions of the anchors are known, with respect to

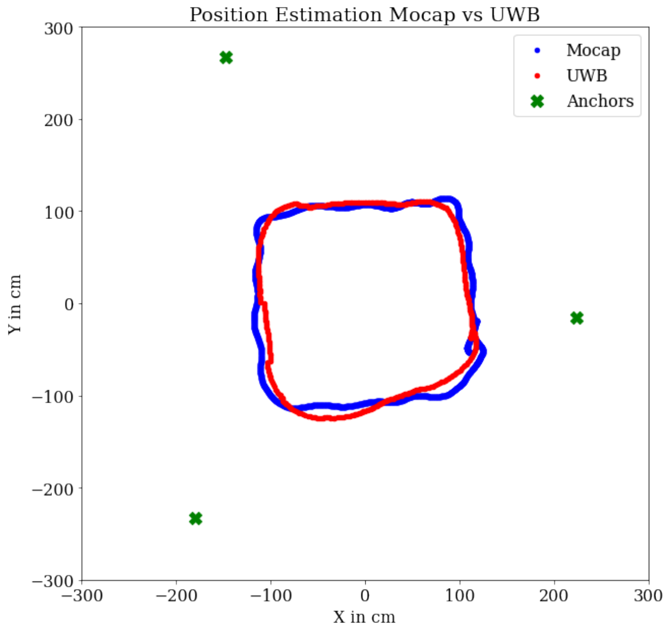


Fig. 6: Small square path: rolling average of 33 samples

the local coordinate frame, the UWB RTLS can be moved or set up anywhere. Comparatively, the 12 Mocap cameras are much more difficult to set up and even more difficult to move once set up.

Apple has also recently announced that their U1 chips are interoperable with the DWM3000EVB. Through the use of RBSManager, an iPhone app could be created that mimics the "tag" operation. Apple's U1 chip opens the door for UWB to become as ubiquitous as Bluetooth and the DWM3000EVB is an extremely strong starting place for UWB robotic development. An example use case could be a safe human-robot workspace, where the user could walk into the room and instantly be tracked by an Apple phone in their pocket or Apple watch on their wrist, alerting every robot in the environment that a human has entered the workspace.

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