# Integrated Ultra-Wideband Tracking and Carbon Dioxide Sensing System Design

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## I. Introduction

A three-dimensional (3D) Ultra-Wideband (UWB) Time--of-Arrival (TOA) tracking system has been studied at NASA Johnson Space Center (JSC) to provide the tracking capability inside the International Space Station (ISS) modules for various applications. One of applications is to locate and report the location where crew experienced possible high level of carbon-dioxide ($CO_2$) and felt upset. Recent findings indicate that frequent, short-term crew exposure to elevated $CO_2$ levels combined with other physiological impacts of microgravity may lead to a number of detrimental effects, including loss of vision. To evaluate the risks associated with transient elevated $CO_2$ levels and design effective countermeasures, doctors must have access to frequent $CO_2$ measurements in the immediate vicinity of individual crew members along with simultaneous measurements of their location in the space environment. To achieve this goal, a small, low-power, wearable system that integrates an accurate $CO_2$ sensor with an ultra-wideband (UWB) radio capable of real-time location estimation and data communication is proposed. This system would be worn by crew members or mounted on a free-flyer and would automatically gather and transmit sampled sensor data tagged with real-time, high-resolution location information. Under the current proposed effort, a breadboard prototype of such a system has been developed. Although the initial effort is targeted to $CO_2$ monitoring, the concept is applicable to other types of sensors. For the initial effort, a micro-controller is leveraged to integrate a low-power $CO_2$ sensor with a commercially-available UWB radio sytem with ranging capability. In order to accurately locate those places in a multipath intensive environment like ISS modules, it requires a robust real-time location system (RTLS) which can provide the required accuracy and update rate. A 3D UWB TOA tracking system with two-way ranging has been proposed and studied. The designed system will be tested in the Wireless Habitat Testbed which simulates the ISS module environment.

This report describes the research and development effort for this prototype integrated UWB tracking and $CO_2$ sensing system. The remainder of the report is organized as follows. In Section II, the TOA tracking methodology is introduced and the 3D tracking algorithm is derived. The simulation results are discussed in Section III. In Section VI, prototype system design and field tests are discussed. Some concluding remarks and future works are presented in Section V.

## II. TOA 3D Tracking Algorithm

Many different approaches can be applied to estimate the location of a radio source including angle of arrival (AOA), time of arrival (TOA), time difference of arrival (TDOA), relative signal strength (RSS) and various hybrids of these. Studies [1] show that the average tracking error is proportional to the square of the tracking range for

TDOA, while the average tracking error is linear to the tracking range for TOA. Furthermore, the latest UWB radio PulsON 400 can achieve the ranging accuracy (bias) of 2.1 centimeters [2], which is approximately equivalent to the timing accuracy of 63 picoseconds for the TOA estimates. In this study, the TOA tracking algorithm is chosen for design to achieve the required tracking accuracy for various applications.

The 3D version of the Least Square Solution to the TOA tracking algorithm is derived as follows. Assume that there is one target radio (or tag) located at an unknown location $(x,y,z)$ in three-dimensional space and four tracking baseline radios located at positions $\{(x_1,y_1,z_1),(x_2,y_2,z_2),(x_3,y_3,z_3),(x_4,y_4,z_4)\}$, which are assumed to be known precisely. Further, assume that measurements of the flight time $\{t_1,t_2,t_3,t_4\}$ of the signal from the target radio to each of the baseline radios are available (Two-way ranging of PulsON 410 radios can estimate the flight time TOA with certain level of precision).

If the propagation velocity of the signals is given by the constant $c$, then it can be shown that the following system of linear equations is satisfied:

$$\mathbf{Gp} = \mathbf{h}$$

where

$$\mathbf{G} = \begin{bmatrix} x_2 - x_1 \; y_2 - y_1 \; \mathrm{z}_2 - z_1 \\ x_3 - x_1 \; y_3 - y_1 \; \mathrm{z}_3 - z_1 \\ x_4 - x_1 \; y_4 - y_1 \; \mathrm{z}_4 - z_1 \end{bmatrix}, \text{ p=}\begin{bmatrix} x \\ y \\ z \end{bmatrix},$$

$$\text{h=}\frac{1}{2}\begin{bmatrix} x_2{}^2 + y_2{}^2 + z_2^2 - c^2t_2^2 - (x_1{}^2 + y_1{}^2 + z_1^2 - c^2t_1^2) \\ x_3{}^2 + y_3{}^2 + z_3^2 - c^2t_3^2 - (x_1{}^2 + y_1{}^2 + z_1^2 - c^2t_1^2) \\ x_4{}^2 + y_4{}^2 + z_4^2 - c^2t_4^2 - (x_1{}^2 + y_1{}^2 + z_1^2 - c^2t_1^2) \end{bmatrix}.$$

In the presence of TOA measurement errors, the target radio location can be estimated using the standard least square solution

$$\begin{aligned} \hat{\mathbf{p}} &= \arg\min(\mathbf{G}\hat{\mathbf{p}} - \mathbf{h})^T(\mathbf{G}\hat{\mathbf{p}} - \mathbf{h}) \\ &= (\mathbf{G}^T\mathbf{G})^{-1}\mathbf{G}^T\mathbf{h}. \end{aligned}$$

## III. Tracking Simulations

In order to analyze the tracking error behavior and gain some insight regarding achievable tracking accuracy, several Monte Carlo simulations were performed using a few tracking baselines (consists of four radios) configured in the Wireless Habitat Testbed (WHT) (see Figure 1). Within WHT, an rectangular cuboid with dimension 18 feet (L) x 6 feet (D) x 6 feet (H) is defined as the available tracking space where about 931 test points are set one foot apart (see Figure 2). The standard deviation of TOA estimates 100 picoseconds is used in these simulations.

Figure 1. Wireless Habitat Testbed

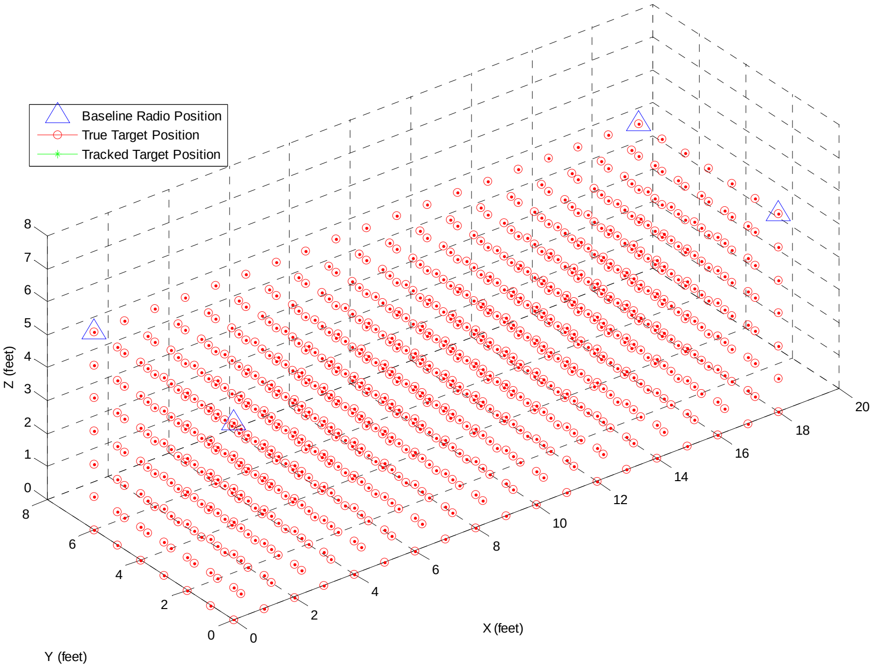

Figure 2. UWB TOA 3D Tracking Space inside WHT

Four different tracking baselines are evaluated with simulation. For installation feasibility and blockage concern, these four baselines are chosen for evaluation:

Configuration #1 “Top Rectangle” [R1=(0’,0’,6’), R2=(0’,6’,6’), R3=(18’,6’,6’), R4=(18’,0’,6’)];
Configuration #2 “Depth-Tilted Rectangle” [R1=(0’,0’,0’), R2=(0’,6’,0’), R3=(18’,6’,6’), R4=(18’,0’,6’)];
Configuration #3 “Length-Tilted Rectangle” [R1=(0’,0’,0’), R2=(0’,6’,6’), R3=(18’,6’,0’), R4=(18’,0’,6’)];
Configuration #4 “Twisted Rectangle” [R1=(0’,0’,0’), R2=(0’,6’,6’), R3=(18’,6’,6’), R4=(18’,0’,0’)].

The simulation results show that Configuration #1, #2 and #3 are not appropriate tracking baseline choices since all four radios being on the same plane in these configurations causes the singularity problem of matrix G in the TOA Least Square Solution tracking algorithm described in Section II. Configuration #4 “Twisted Rectangle” has radios installed in different planes within tracking space so that there is no singularity problem associated with this configuration. The simulation results for Configuration #4 are shown in Figure 3 and Figure 4. For this configuration, the average tracking error is 0.2392 feet with a standard deviation 0.1373 feet.

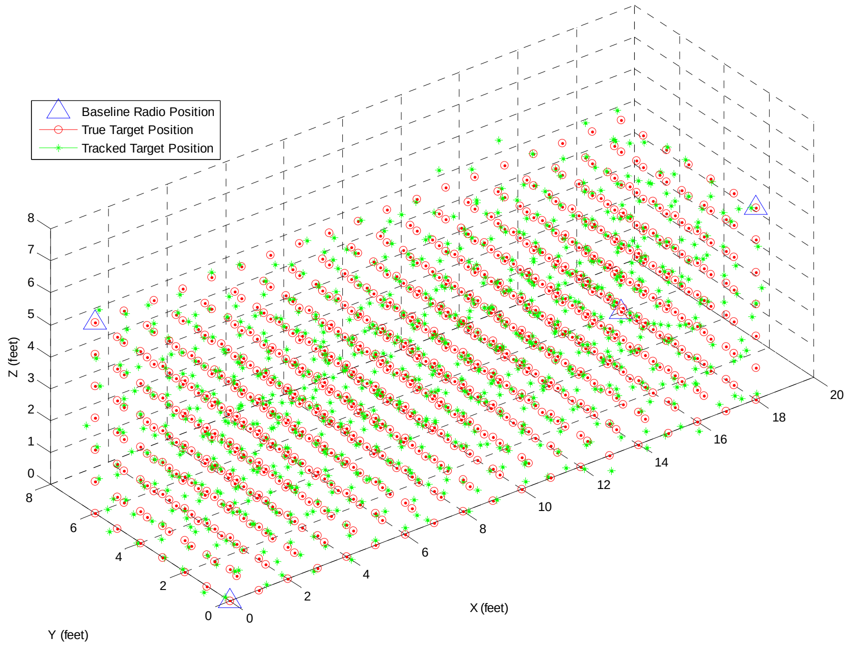

Figure 3. Tracking Simulation Results for Configuration “Twisted Rectangle”

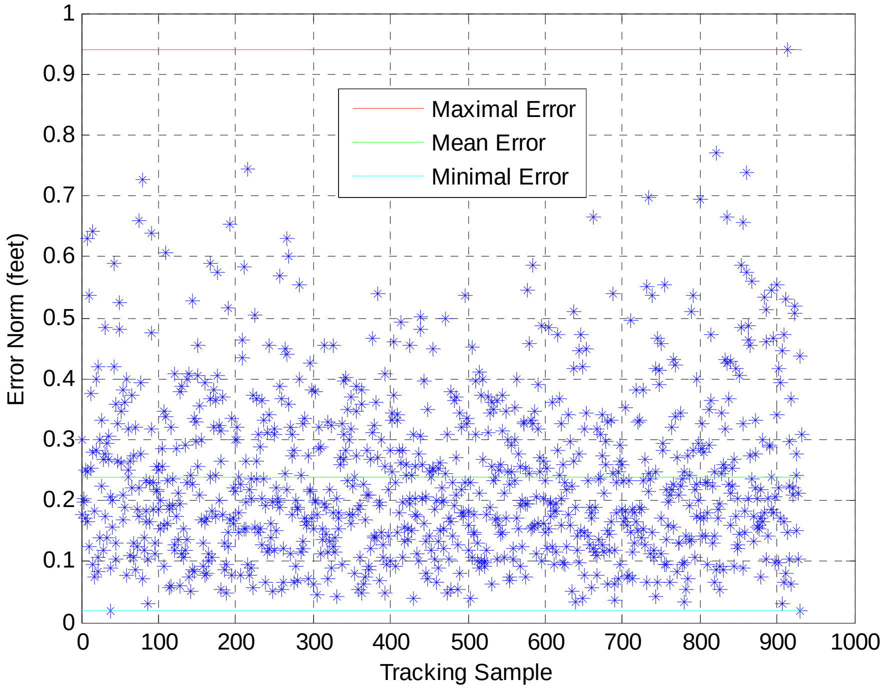

Figure 4. Tracking Error Analysis for Configuration “Twisted Rectangle”

For blockage concern, Configuration #1 “Top Rectangle” is preferable than Configuration #4 “Twisted Rectangle”. In order to avoid the singularity problem of Configuration #1, a modified configuration “Slightly-Twisted Top Rectangle” [R1=(0’,0’,5’), R2=(0’,6’,6’), R3=(18’,6’,5’), R4=(18’,0’,6’)] is proposed and evaluated. The simulation results [see Figure 5 and Figure 6] show that the average tracking error is 0.9183 feet with a standard deviation 0.6927 feet.

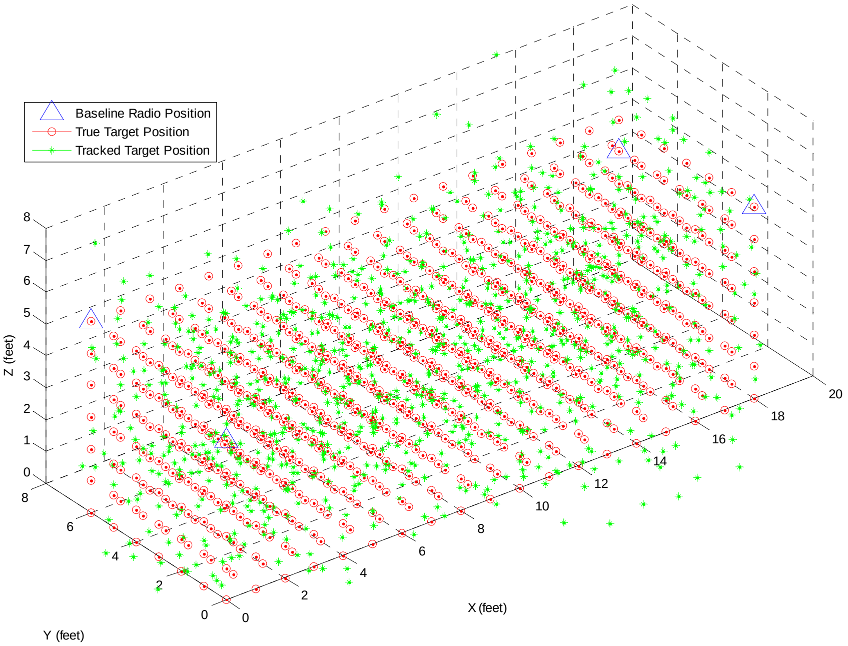

Figure 5. Tracking Simulation Results for Configuration "Slightly-Twisted Top Rectangle"

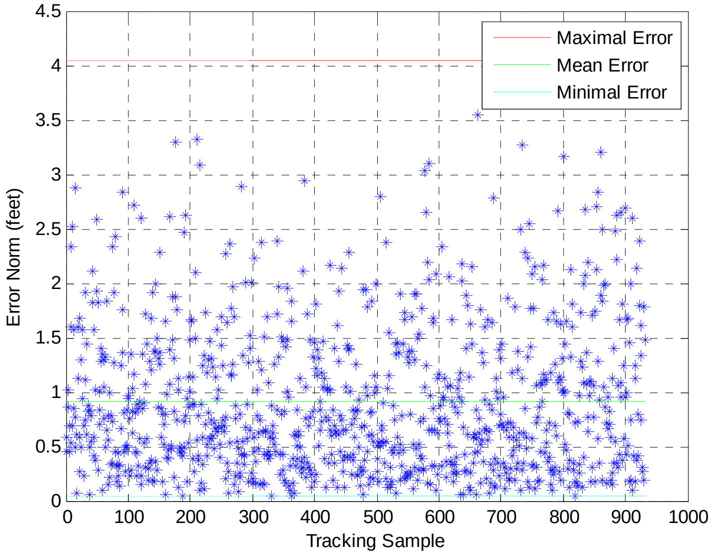

Figure 6. Tracking Error Analysis for Configuration "Slightly-Twisted Top Rectangle"

It is known that the TOA tracking error is proportional to the standard deviation (STD) of TOA estimates in 2D tracking described in [3]. The current PulsON 410 radios can provide the STD of TOA estimates at level of 61 picoseconds. With further hardware improvement and advanced signal processing techniques, it is believed that the STD of TOA estimates can be reduced to the level of 10 picoseconds. Therefore, performance evaluation is also conducted with 10 picoseconds of TOA estimates STD for

Configuration “Twisted Rectangle”. The simulation results [see Figure 7 and Figure 8] show that the average tracking error is 0.0239 feet with a standard deviation 0.0137 feet. The result shows that the statement that the TOA tracking error is proportional to the standard deviation (STD) of TOA estimates is also true for 3D tracking.

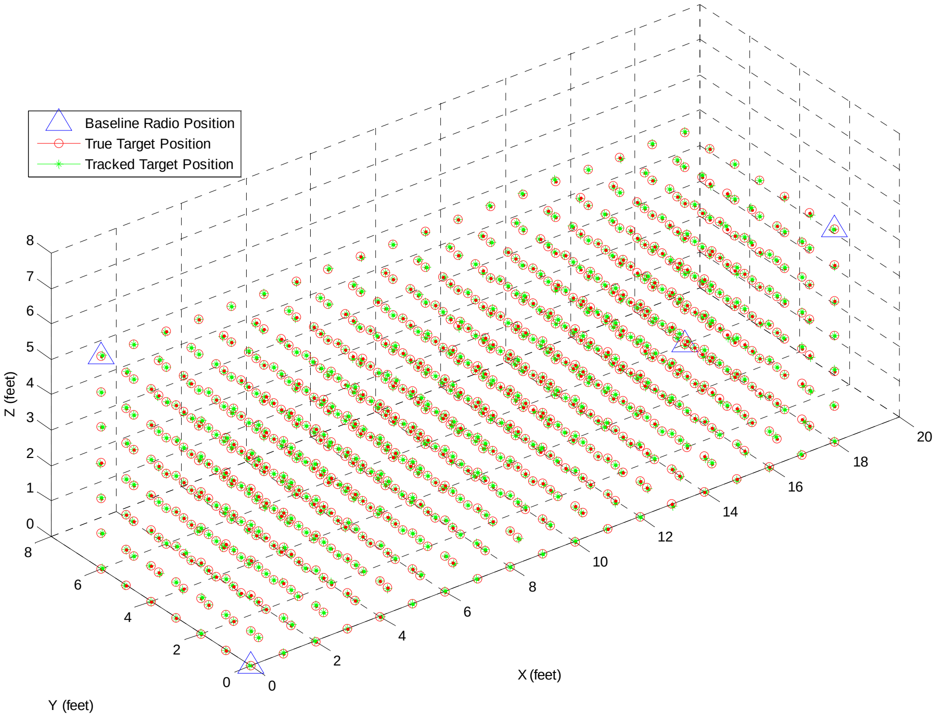

Figure 7. Tracking Simulation Results for Configuration “Twisted Rectangle” with 10 ps TOA_STD

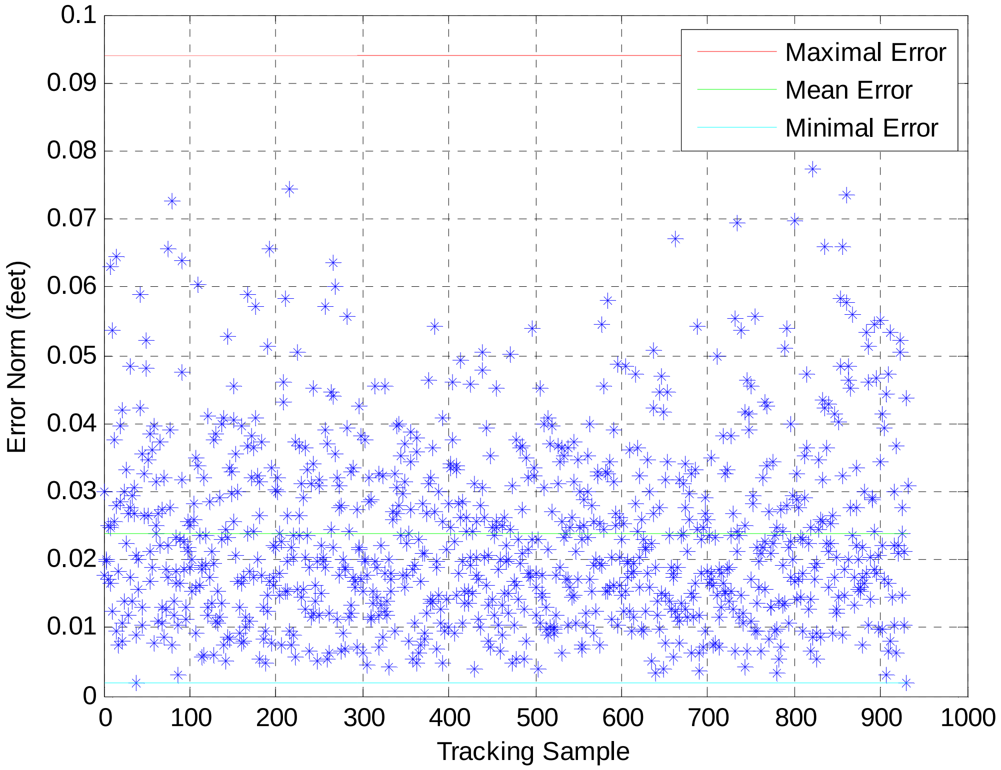

Figure 8. Tracking Error Analysis for Configuration “Twisted Rectangle” with 10 ps TOA_STD

## IV. System Design and Field Test

### A. System Design

A prototype system was designed using the UWB radios PulsON 410 Ranging and Communication Module (RCM) from Time Domain Corporation. The UWB impulse radio (UWB-IR) technology is exploited in the design and implementation of the prototype location and tracking system due to its capacity for fine time resolution, low power spectral density, resistance to multipath interference. A key element of the system design philosophy was to avoid introduction of system components or structure that would in any way degrade the fine time resolution of the UWB signal since it is critical for precise tracking. In keeping with this goal, a system configuration shown in Figure 9 is adopted. Four UWB radios are chosen as the fixed anchors as the tracking baseline, among them one is chosen as the master anchor which is connected to a control PC. As for the target unit (see Figure 10), a microcontroller (MSP430 from TI) connecting a UWB radio and a $CO_2$ sensor provids the local host process capability. The control PC configurates the system and runs the TOA tracking algorithm. Once the target unit receives a data request from the master anchor, the microcontroller will command the target UWB radio to range to four anchor radios and obtain a $CO_2$ measurement from the $CO_2$ sensor. Then four range measurement and one $CO_2$ meassurement will be put into a data packet and sent to the master anchor. The control PC will run the 3D TOA tracking algorithm to compute the target location. Both target loccation data and data will be displayed in the a graphical user interface (GUI).

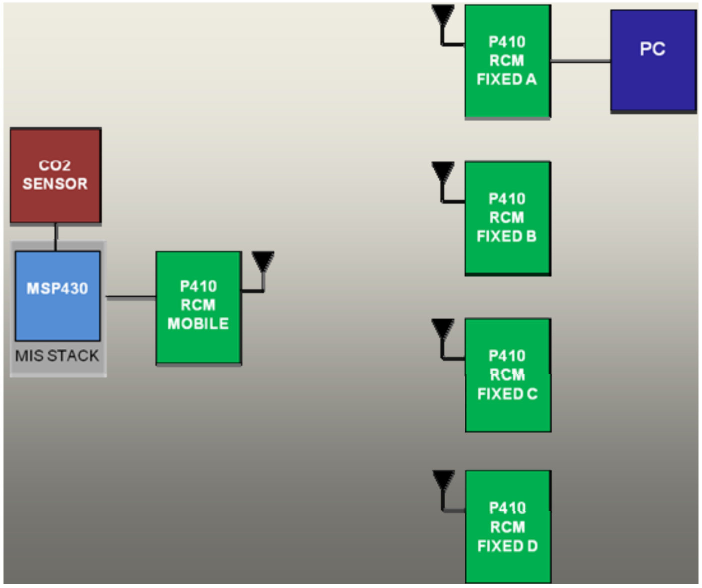

Figure 9. Configuration of Integrated UWB Tracking and CO2 Sensing System

Figure 10. Prototype of Target Unit

## B. Field Test

A field test of the integrated UWB Tracking and CO2 Sensing System was conducted in the rotunda area in Building 29 of JSC. The tracking baseline consisting of four anchor radios is set up as shown coordinates: Radio 101 (-48’9.5”, 8’, 19’10.75”), Radio 103 (28’9.5”, 4’, 19”8.5”), Radio 104 (0, 0, 5.75”) and Radio 105 (-12’, 52’, 6.25”). Radio 104 is designated as the master anchor which is connected to a laptop. The target unit with Radio 106 is mounted on a robot. First, a trajectory run test was conducted with the target speed of 5 miles/hour and the tracking update rate of 5 Hz. The tracked target trajectory in X_Y plane is shown in Figure 11.

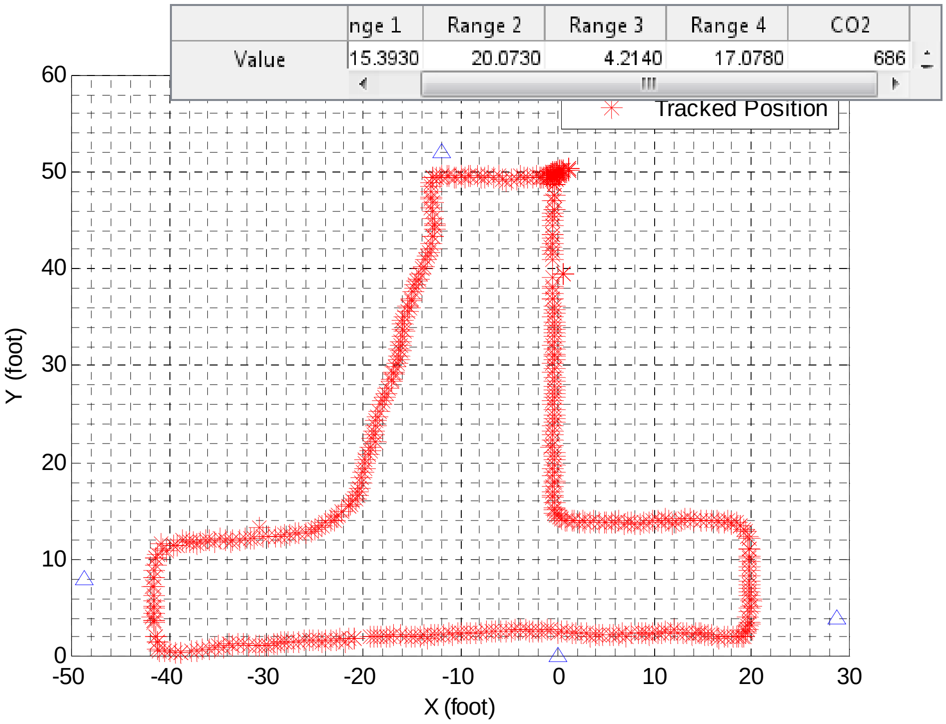

Figure 11 Tracking Trajectory of the Target

After that, a tracking accuracy test was conducted at five arbitrary locations of the target with three different heights. The test data of target height at 2.5625 feet, 4.4167 feet and 6.1875 feet are shown in the Table 1, Table 2 and Table 3. At each test point, one hundred runs are conducted to generate the test statistics. Table 4 summarizes the statistics of all test data from 1500 test runs. The test data shows that with a tracking update rate 5 Hz, sub-inch tracking accuracy on X and Y was achieved while average tracking error less than four inches on Z was observed due to shorter Z-dimension span. For all test runs, the CO2 measurement from the target location was reported and displayed at the control PC with an update of 5 Hz.

## Table 1. Statistics of Test Data (z=2.5625 feet)

| Target Position (foot) | | | Tracked Position (foot) | | | Bias (foot) | | | Standard Deviation (foot) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| x | y | z | x | y | z | x | y | z | x | y | z |
| 0 | 14 | 2.5625 | -0.0452 | 14.0346 | 2.7680 | 0.0452 | 0.0346 | 0.2055 | 0.0631 | 0.0663 | 0.1472 |
| -8 | 38 | 2.5625 | -8.0394 | 37.9153 | 2.6532 | 0.0394 | 0.0847 | 0.0907 | 0.0701 | 0.0737 | 0.1951 |
| -16 | 30 | 2.5625 | -16.0383 | 29.9854 | 2.6812 | 0.0383 | 0.0146 | 0.1187 | 0.0697 | 0.0744 | 0.2337 |
| -16 | 12 | 2.5625 | -15.9962 | 12.1353 | 2.9072 | 0.0038 | 0.1353 | 0.3447 | 0.0749 | 0.0793 | 0.1822 |
| -10 | 26 | 2.5625 | -9.9930 | 26.0337 | 3.0386 | 0.0070 | 0.0337 | 0.4761 | 0.0596 | 0.1002 | 0.2344 |

## Table 2. Statistics of Test Data (z= 4.4167 feet)

| Target Position (foot) | | | Tracked Position (foot) | | | Bias (foot) | | | Standard Deviation (foot) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| x | y | z | x | y | z | x | y | z | x | y | z |
| 0 | 14 | 4.4167 | -0.0442 | 13.8792 | 4.4189 | 0.0442 | 0.1208 | 0.0023 | 0.0632 | 0.0775 | 0.1253 |
| -8 | 38 | 4.4167 | -8.0323 | 38.1975 | 4.8574 | 0.0323 | 0.1975 | 0.4407 | 0.0606 | 0.0798 | 0.2142 |
| -16 | 30 | 4.4167 | -16.0283 | 30.1112 | 4.8651 | 0.0283 | 0.1112 | 0.4485 | 0.0616 | 0.0683 | 0.1922 |
| -16 | 12 | 4.4167 | -15.9730 | 11.9976 | 4.8457 | 0.0270 | 0.0024 | 0.4290 | 0.0713 | 0.1064 | 0.1573 |
| -10 | 26 | 4.4167 | -10.0313 | 25.9989 | 4.8650 | 0.0313 | 0.0011 | 0.4483 | 0.0706 | 0.0871 | 0.2243 |

## Table 3. Statistics of Test Data (z= 6.1875 feet)

| Target Position (foot) | | | Tracked Position (foot) | | | Bias (foot) | | | Standard Deviation (foot) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| x | y | z | x | y | z | x | y | z | x | y | z |
| 0 | 14 | 6.1875 | -0.0440 | 13.9857 | 6.4021 | 0.0440 | 0.0143 | 0.2146 | 0.0588 | 0.0867 | 0.1509 |
| -8 | 38 | 6.1875 | -8.0560 | 38.0724 | 6.6731 | 0.0560 | 0.0724 | 0.4856 | 0.0787 | 0.1025 | 0.2434 |
| -16 | 30 | 6.1875 | -16.0216 | 30.1908 | 6.7165 | 0.0216 | 0.1908 | 0.5290 | 0.0653 | 0.0592 | 0.1929 |
| -16 | 12 | 6.1875 | -15.9958 | 11.8310 | 6.3318 | 0.0042 | 0.1690 | 0.1443 | 0.0568 | 0.0934 | 0.1564 |
| -10 | 26 | 6.1875 | -10.0140 | 26.0515 | 6.6048 | 0.0140 | 0.0515 | 0.4173 | 0.0606 | 0.1234 | 0.3028 |

**Table 4. Statistics of All Test Data (1500 test runs)**

| Bias (foot) | | | Standard Deviation (foot) | | |
|---|---|---|---|---|---|
| x | y | z | x | y | z |
| 0.0291 | 0.0823 | 0.3197 | 0.0660 | 0.0868 | 0.2019 |

## V. Conclusion

A prototype of the integrated UWB tracking and CO2 sensing system has been designed, implemented, tested, and proven feasible for providing the real-time and location-aware wireless CO2 sensor measurements. UWB technology has been exploited to implement the tracking system due to its properties such as fine time resolution and low power spectral density. The TOA tracking method has been employed to fully utilize the accurate ranging capability of the UWB signal. Simulations show that the desired fine tracking resolution can be achieved for any size of proximity tracking with chosen system configuration “Twisted Rectangle” if the extension of the baseline radius in 3D is feasible. Filed tests demonstrate that this UWB tracking system can track the moving target in real time and an inch-level tracking accuracy can be achieved with an update rate of 5 Hz. It demonstrated that an environment data such as CO2 level can be wirelessly measured and automatically tagged with both time and location information. Future work includes testing the system in a multipath intensive environment like the Wireless Habitat Testbed, and integrating with other type of wireless sensors to monitor more environmental parameters such as temperature, humidity and radiation.

## References

[1]. R. Barton, et al; “Performance Capabilities of Long-Range UWB-IR TDOA Localization Systems”, EURASIP Journal on Advances in Signal Processing, Volume 2008, Article ID 236791, 17 pages.
[2]. “Data Sheet of PulsON 410 RCM”, Time Domain Corporation, March 2013.
[3]. J. Ni; “Performance Evaluation on the Least Square Solution to the Ultra-Wideband Time-Of-Arrival Tracking”, 2011.