UWB Tracking System Design for Free-Flyers

Abstract

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UWB Tracking System Design for Free-Flyers

Jianjun Ni* and Dickey Arndt and Phong Ngo and Chau Phan and Julia Gross
NASA Johnson Space Center, Houston, Texas, 77058

John Dusl
Lockheed Martin Corporation, Houston, Texas, 77058

This paper discusses an ultra-wideband (UWB) tracking system design effort for Mini-AERCam (Autonomous Extra-vehicular Robotic Camera), a free-flying video camera system under development at NASA Johnson Space Center for aid in surveillance around the International Space Station (ISS). UWB technology is exploited to implement the tracking system due to its properties, such as high data rate, fine time resolution, and low power spectral density. A system design using commercially available UWB products is proposed. A tracking algorithm TDOA (Time Difference of Arrival) that operates cooperatively with the UWB system is developed in this research effort. Matlab simulations show that the tracking algorithm can achieve fine tracking resolution with low noise TDOA data. Lab experiments demonstrate the UWB tracking capability with fine resolution.

I. Introduction

NASA Johnson Space Center (JSC) is developing a low-volume, low-mass, robotic free-flying camera known as Mini-AERCam (Autonomous Extra-vehicular Robotic Camera) to assist the International Space Station (ISS) operations. Mini-AERCam is designed to provide astronauts and ground control real-time video for camera views of ISS. The system will assist ISS crewmembers and ground personnel to monitor ongoing operations and perform visual inspections of exterior ISS components without requiring extravehicular activity (EVA).

Mini-AERCam builds on the success of the AERCam Sprint flight experiment on STS-87 (Figure 1) in December 1997. The AERCam Sprint system demonstrated a new capability for on-orbit collection and real-time transmission of video for Orbiter or ISS operations. This increased NASA's interest in using remotely operated free-flyers to provide camera views of the Space Shuttle and ISS from varying aspect angles and distances. However, since Sprint is not equipped with navigation sensors that provide relative position (with respect to the Orbiter or ISS) or relative attitude feedback to the operator, the only navigational aid to the operator is using the video from the free-flyer. This extremely limits the Sprint positional situational awareness around the complex ISS structure, and that for close-in operations collision cannot be prevented between Sprint and ISS. Hence, Mini- AERCam design

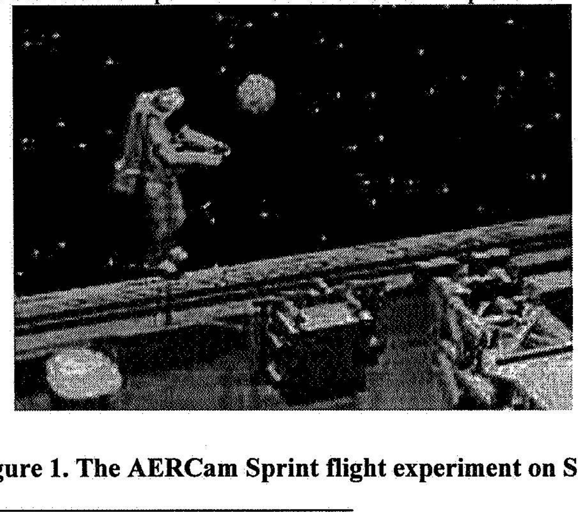

Figure 1. The AERCam Sprint flight experiment on STS-87

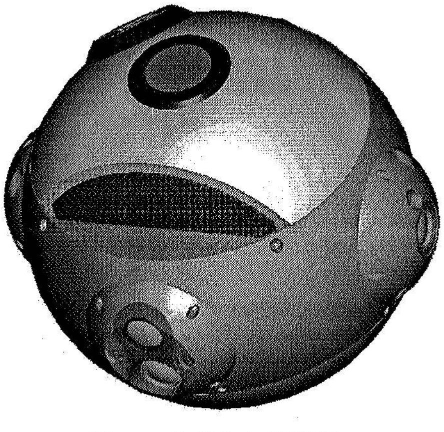

Figure 2. Mini-AERCam

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aims to add new on-board sensing and RF precise tracking capabilities.

The Mini-AERCam target design is a spherical "nanosatellite" free-flyer 7.5 inches in diameter (Figure 2). The Mini-AERCam system consists of a Free Flyer (FF), Communication and Tracking (CAT) hardware, and an operator Control Station (CS). Many institutions and companies have been involved in the R&D for this project. A Mini-AERCam ground control system has been studied at Texas A&M University [1]. The path planning and control algorithms that direct Mini-AERCam's motions have been developed through the joint effort of Carnegie Mellon University and Texas Robotics and Automation Center [2]. NASA JSC has designed a layered control architecture that integrates all functions of Mini-AERCam [3]. The research effort in the Avionic Systems Division at JSC will focus on the communication and tracking subsystem that is designed to perform three major tasks: 1. To transmit commands from ISS to Mini-AERCam to control the robotic camera's motions (downlink). 2. To transmit real-time video from Mini-AERCam to ISS for inspections (uplink). 3. To track the Mini-AERCam's precise position for motion control. In this paper, we will focus on task 3 to discuss the tracking system design.

The ISS propagation environment is unique due to the nature of the ISS structure and multiple RF interference sources [4]. The ISS is composed of various truss segments, solar panels, thermal radiator panels, and modules for laboratories and crew accommodations. A tracking system supplemental to GPS is desirable both to improve the accuracy and to eliminate the structural blockage due to the close proximity of the ISS which could at times limit the number of GPS satellites accessible to the Mini-AERCam. Ideally, the tracking system will be a passive component of the communication system which will need to operate in a time-varying multipath environment created as the robot camera moves over the ISS structure. In addition, due to many interference sources located on the ISS, SSO, LEO satellites and ground-based transmitters, selecting a frequency for the ISS and Mini-AERCam link which will coexist with all interferers poses a major design challenge. In this research effort, we exploit UWB technology for the tracking system design to meet all of the challenges in this complicated environment.

II. UWB Technology

Ultra-wideband (UWB), also known as impulse or carrier-free radio technology, is one promising new technology. It has been utilized for decades by the military and law enforcement agencies for fine-resolution ranging, covert communications and ground-penetrating radar applications. In February 2002, the Federal Communications Commission (FCC) approved the deployment of this technology in the commercial sector under Part 15 of its regulations [5]. It is increasingly recognized that UWB technology holds great potential to provide significant benefits in many applications such as precise positioning, short-range multimedia services and high-speed mobile wireless communications.

The DARPA study panel that coined the term *ultra-wideband* in the 1990's defines it as a system with a fractional bandwidth greater than 0.25. (FCC redefined the term UWB to describe any signal with bandwidth equal to or in excess of 500 MHz or a fractional bandwidth greater than 0.2.) The basic concept of current UWB technology is to develop, transmit and receive an extremely short duration burst of RF energy – typically a few tens of picoseconds to a few nanoseconds in duration. Whereas conventional continuous sine wave radio systems operate within a relatively narrow bandwidth, UWB operates across a wide range of frequency spectrum (a few GHz) by transmitting a series of low power impulsive signals.

For the emerging technology of UWB radar and UWB wireless communications, the transmitted signal can be regarded as a uniform train of UWB pulses represented as

$$s(t) = \sum_{n=-\infty}^{+\infty} \Omega(t - nT_r) \tag{1}$$

where T_r is the pulse repetition interval, and $\Omega(t)$ is the pulse-shaping waveform which is often a Gaussian monocycle. In the time domain, the Gaussian monocycle is mathematically similar to the first derivative of Gaussian function. It has the form

$$\Omega(t) = \frac{t}{\tau} e^{-(\frac{t}{\tau})^2} \tag{2}$$

where τ is the monocycle's duration. Figure 3 shows an ideal monocycle centered at 2 GHz in both the time and frequency domains [6].

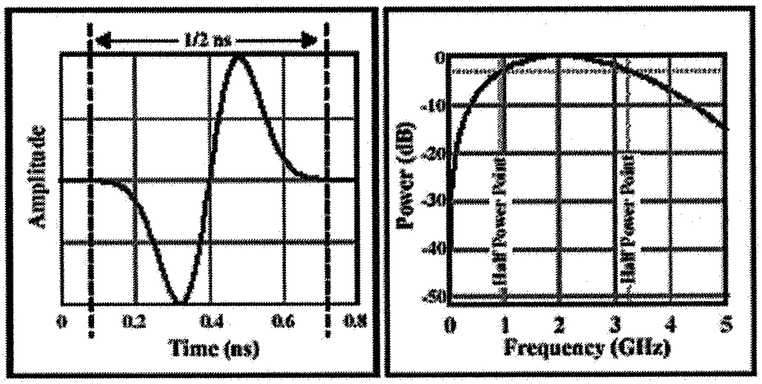

Figure 3. Gaussian monocycle in time and frequency domains. [6]

Conveying information over an impulse-like radio waveform, UWB is characterized by several uniquely attractive features:

- Low-power carrier-free ultra-wide bandwidth signal transmissions
- Low impact on other RF systems due to its extremely low power spectral densities
- Immunity to interference from narrow band RF systems due to its ultra-wide bandwidth
- Multipath immunity to fading due to ample multipath diversity (RAKE receiver)
- Capable of precise positioning due to fine time resolution
- Capable of high data rate, multi-channel performance
- Low-complexity low-power baseband transceivers without intermediate frequency stage

The rapid technological advances have made it possible to implement cost-effective UWB radar and UWB communication and tracking systems. Furthermore, array beamforming and space–time processing techniques promise further advancement in the operational capabilities of UWB technology to achieve long-range coverage, high capacity, and interference-free quality of reception [7]. Hence, UWB technology is chosen to implement the communications and tracking system for Mini-AERCam in this research effort.

III. System Design

The communications and tracking system for Mini-AERCam supports the operation of ISS by providing real-time video from Mini-AERCam. The commands for motion control based on the tracing information of Mini-AERCam are sent (or relayed) from ISS. The functional block diagram shown in Figure 4 includes two parts: the ISS assembly and the Mini-AERCam assembly.

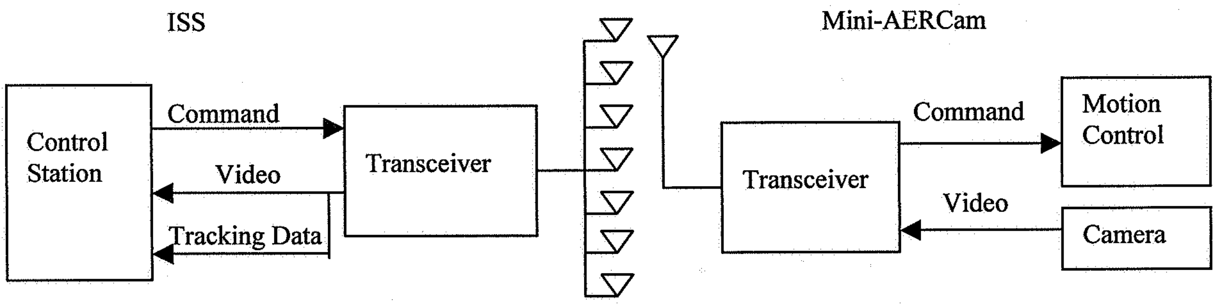

Figure 4. Block diagram of the communications and tracking system for Mini-AERCam

To date, there are a few principal UWB chipset manufacturers including Time Domain Corporation [8] and XtremeSpectrum, Inc. [9] offering commercially available products. In this research effort, we have investigated their chipsets and decided to exploit products from Time Domain Corporation to design the communication and tracking systems for Mini-AERCam.

Time Domain's PulsON 200 Ultra Wideband (UWB) Evaluation Kit (EVK) allows product developers to examine the performance, capabilities and properties of ultra wideband technology. The EVKs can be configured for testing or as elements of an application demonstration. The EVK has the following key features:

- PRF (Pulse Repetition Frequency): 9.6 MHz
- 8 data rates: 75 kbps, 150 kbps, 300 kbps, 600 kbps, 1.2 Mbps, 2.4 Mbps, 4.8 Mbps, 9.6 Mbps
- Center Frequency (radiated): approximately 4.7 GHz
- Bandwidth (10 dB radiated): 3.2 GHz
- Co-exists with all US-based wireless systems (including GPS)
- Superior multipath immunity as a result of UWB-physics
- Fine resolution tracking
- FCC Compliant - FCC 15.517, 15.209
- Diamond Dipole Antenna
- StrongARM TM Microprocessor for Embedded Applications Development

The PulsON 200 EVK includes 2 complete software modules designed to provide performance-based information and to allow users to build custom applications. The Performance Analysis Tool (PAT) is a software module that can be used to perform Propagation Studies, Data Rate Studies, Performance/QoS Analyses, Ambient Noise Analyses, and Link Budget Analyses. Statistical Tools include Throughput, Eb/Neff, BER, Total Packets sent, Dropped Packets, Acquisition Statistics, FEC, and Nulling. The module Host API allows users to host applications without extensive interaction with the embedded UWB Kernel and without a full VxWorks ® development environment. With the functional calls, users can create their own UWB packets, send and receive information, gather performance statistics, execute built-in tests, and calibrate the radio. These capabilities form the core UWB Kernel abstractions that are needed when interacting with the EVK radios.

The potential advantages of a UWB system for this application including: high-speed video transmission, multipath resistance, ease of interoperability with other RF systems and precision tracking characteristics together with the availability of commercial UWB products, makes this technology a good choice for implementation of the Mini-AERCam communication and tracking system. NASA JSC has purchased three EVKs (6 UWB radios) and one UWB Signal Generator for developing UWB applications on space communications and tracking.

IV. Tracking Algorithm

To make Mini-AERCam's coordinated maneuvers feasible, an accurate, robust, and self-contained tracking system that is small, low power, and low cost is required. Compared to GPS receivers, which can offer range resolution on the order of one meter, UWB radio can achieve sub-centimeter range resolution much faster and with less effort [6]. The experiment in [10] shows UWB systems can provide ranging measurement accurate to the centimeter level over distances of kilometers, using only milliwatts of power from an omni-directional transceiver no bigger than a pager. In this research effort, the tracking subsystem will be designed to provide the precise positioning required for Mini-AERCam motion control.

Many technologies have been applied to locating the source of radio signals, such as angle of arrival (AOA), time difference of arrival (TDOA) and relative signal strength (RSS). The extremely high fidelity of the UWB timing circuitry permits very high accuracy of propagation time measurements while transmitting data. This fine time resolution feature of UWB motivates us to apply a TDOA approach for tracking system design.

The distance between the transmitter and the receiver is directly proportional to the propagation time since electromagnetic waves travel with constant velocity in free space. The TDOA approach determines the possible position of the transmitter by examining the difference in time at which the same signal arrives at multiple receivers. Each TDOA measurement determines that the transmitter must lie on a hyperboloid with constant range difference between the two receivers. At least three receivers are needed for a 2D location estimate, and four receivers for a 3D location estimation. The intersection of hyperboloids provides the location of the transmitter.

The most common method of locating the transmitter is solving TDOA equations. Suppose there are N receivers measuring the time of arrival (TOA) of pilot signals from the transmitter in a 2D case. The TOA estimates of the signal from receiver i and j are denoted t_i and t_j respectively. A range difference measurement r_k can be calculated from the TDOA measurement

$$r_k = c(t_i - t_j) = d_i - d_j = f_k(x, y) \tag{3}$$

where d_i and d_j are the distances from the transmitter to receivers i and j and c is the speed of light. Since the positions of all the receivers are known, this equation is a function $f_k(x, y)$ only of the unknown coordinate position of the transmitter (x, y). The number of independent equations K is equal to $N-1$.

Generally, the transmitter location is determined by finding a least-square (LS) solution to linearized versions of the TDOA equations [11]. The conventional method for linearization uses Taylor series expansion, which is given by

$$f_k(x,y) = f_k(x_0,y_0) + \frac{\partial f_k}{\partial x}(x-x_0) + \frac{\partial f_k}{\partial y}(y-y_0) \tag{4}$$

where the partial derivation are evaluated at the *a priori* estimate for the transmitter position (x_0, y_0). This estimate is normally a previous solution for the transmitter's position.

These equations can then be expressed in a matrix equation $\mathbf{A}\mathbf{p}_T = \mathbf{b}$, where

$$\mathbf{A} = \begin{bmatrix} \frac{\partial f_1}{\partial x} & \frac{\partial f_1}{\partial y} \\ \vdots & \vdots \\ \frac{\partial f_K}{\partial x} & \frac{\partial f_K}{\partial y} \end{bmatrix} \quad \mathbf{p}_T = \begin{bmatrix} (x-x_0) \\ (y-y_0) \end{bmatrix} \quad \mathbf{b} = \begin{bmatrix} r_1 - f_1(x_0,y_0) \\ \vdots \\ r_K - f_K(x_0,y_0) \end{bmatrix} \tag{5}$$

The least squares solution to this matrix equation is the estimated position of the transmitter given by

$$\hat{\mathbf{p}}_T = (\mathbf{A}^T\mathbf{A})^{-1}\mathbf{A}^T\mathbf{b} \tag{6}$$

The Taylor series LS algorithm is simple and easy to implement. However, we find that it has two major drawbacks. First, it requires a proper guess close to the initial position. This may cause problems in practice. For instance, once the signal is lost, then the communication link is reestablished after a while, the proper initial guess of the moving transmitter is not easy to obtain. Second, it suffers from a convergence problem since the convergence of this iterative method is not guaranteed.

A two-stage weighted LS algorithm [12] can eliminate the initialization and convergence problems. This method linearizes the TDOA equations by adding a dummy variable. The original non-linear TDOA equations are transformed into a set of linear equations with an extra variable which requires one more receiver or sensor. At the first stage, the weighted linear LS solution gives an initial position result. At the second stage, use the known relationship between the receiver coordinates and the dummy variable to refine the first solution. The final solution will take the sign from the first stage and the absolute value from the second stage. Since this algorithm can achieve the Cramer-Rao lower bound for Gaussian TDOA noise at moderate noise level, which means it is an optimal estimator, it will be exploited to find the position estimate for the free-flyer in this research effort.

The variance of the position estimate is related to the variance of the time estimate. Tracking requires that the direct path portion of the UWB signal be located and its arrival time inserted into the tracking algorithm. Hence, the accuracy of the TDOA estimates is very critical for the position tracking. The conventional approach to estimate TDOA is to compute the cross-correlation of a signal arriving at different receivers. The TDOA estimate is taken as the delay that maximizes the cross-correlation function. A potentially much more accurate alternative for TDOA estimates in a UWB system relies on higher-order moments rather than cross-correlation [13]. To complete the tracking algorithm, the sequence of TDOA estimates is passed to a Kalman filter to update the current estimate of position.

V. Matlab Simulation

In order to analyze the tracking resolution, several Matlab simulations are implemented using the two-stage weighted LS algorithm. The receiver coordinates are assumed precisely known. TDOA estimates are noisy and the noise is assumed with an independent identical Guassian distribution. Through the theoretical analysis, it is known that the tracking error is a function of two variables: variance of TDOA data and mean of TDOA data. First, a 2D orbit tracking simulation is implemented to analyze the factor of TDOA variance. The simulation setting is as follows:

- Receivers' configuration: four receivers are evenly located on a circle with radius of 5 meters.
- Transmitter trajectory: transmitter moves on the orbit with radius of 100 meters
- Noise level: three different standard deviation of TDOA noise (std=0.01, 0.001, 0.001)

The simulation results corresponding to different noise levels are shown in Figure 5, Figure 6 and Figure 7.

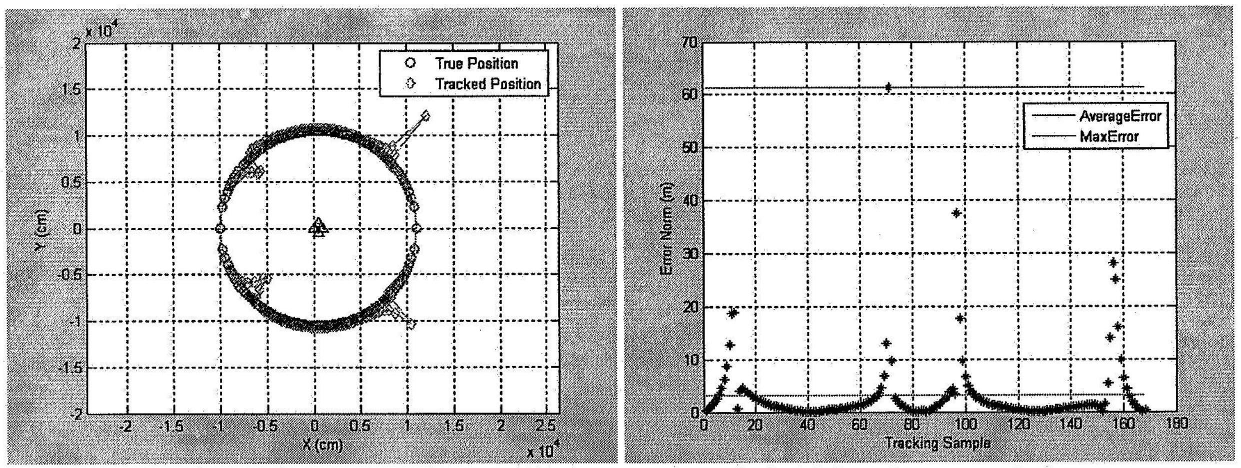

Figure 5. Orbit tracking with TDOA noise level (std=0.01) and error analysis.

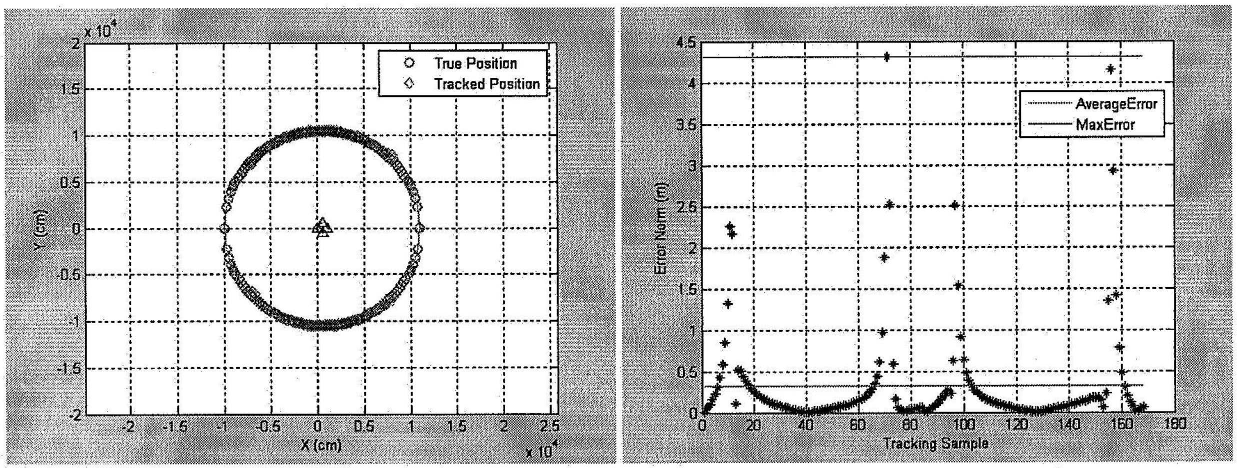

Figure 6. Orbit tracking with TDOA noise level (std=0.001) and error analysis.

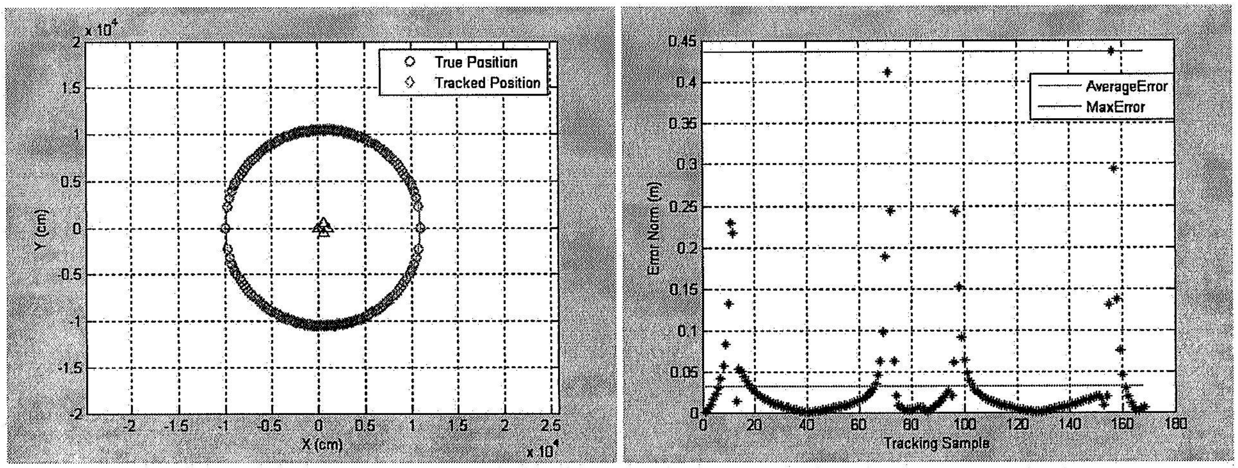

Figure 7. Orbit tracking with TDOA noise level (std=0.0001) and error analysis.

The tracking error is defined as the error norm which is the Euclidean distance between the true position and the tracked position. The results are summarized in Table 1.

Standard Deviation of TDOA (ns)	Maximum Error (m)	Average Error (m)
0.01	61.3271	3.1372
0.001	4.3110	0.3172
0.0001	0.4366	0.0317

Table 1. Error Analysis of orbit tracking with different TDOA noise levels.

From the above results, we come to a conclusion that the tracking error is linear to the standard deviation of TDOA data. Therefore, in order to improve the tracking resolution, we have to increase the accuracy of TDOA estimates.

If the physical conditions (often due to hardware limitation) can not provide picosecond level accuracy of TDOA data, is there any way we can go to improve the tracking resolution? A similar simulation is implemented with the only change being in the receiver configuration. Instead of putting four receivers evenly on a circle with radius of 5 meters, one reference receiver is put at the origin and other three receivers are put evenly on the circle. The simulation results corresponding to the noise level (std=0.01) are shown in Figure 8.

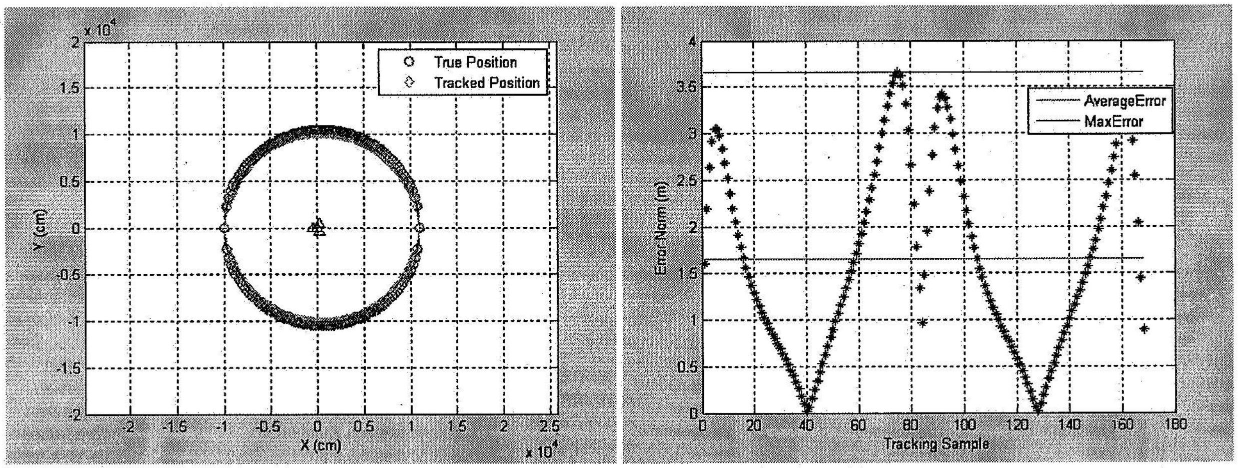

Figure 8. Orbit tracking with centered receiver configuration and TDOA noise level (std=0.01).

With this different receiver configuration, we find that the maximum error is 3.6535 meters and the average error is 1.6602 meters at the TDOA noise level std=0.01. To compare to the simulation results in Figure 5, we find that this configuration only change improves not only the average error, but also the maximum error and makes the tracking system more robust. Given a receiver configuration region and a tracking area, the optimum configuration exists. This is an interesting research topic for future work.

VI. Laboratory Experiment

A preliminary laboratory experiment is designed to test the UWB tracking capability using the TDOA estimates in a general lab environment at JSC. Since the two-stage weighted LS algorithm is chosen as the TDOA tracking algorithm, four receivers are needed to locate the position of the transmitter in a 2D space. In order to avoid the complicated synchronization problem among four receivers, we design a scheme to connect four antennas to one receiver using low-loss cables with various delays. The experiment set-up as follows: (Figure 9)

- EVK Radio: two Time Domain PulsOn 200 EVK radios #206 and #209, Radio #206 is set as transmitter and Radio #209 is set as receiver.
- Antenna: four antennas mounted on tripods with known positions are connected with the receiver and the transmitter antenna is also mounted on a tripod for flexibility of moving around.
- PC: Dell Latitude laptop running Time Domain Performance Analysis Tool (PAT) and EVKRangeDemo.
- Hub: two radios are connected to the PC through standard Ethernet cables just for radio configuration

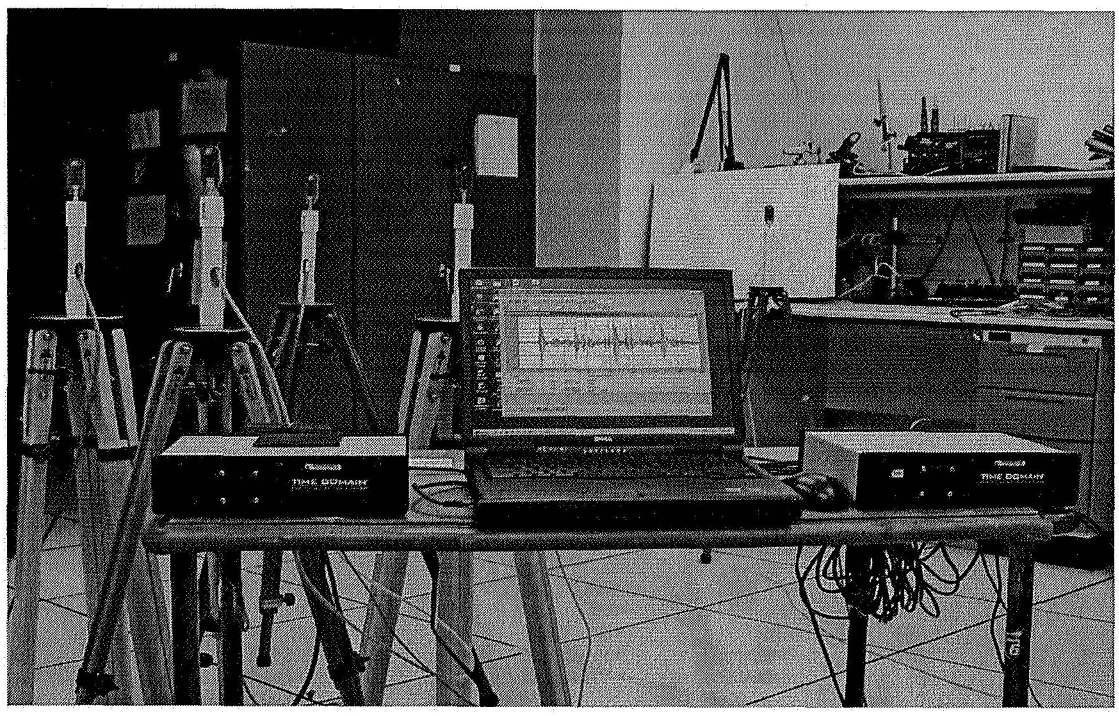

Figure 9. **UWB TDOA Tracking Experiment Set-up.**

The Pulse Repetition Frequency (PRF) of EVK radio is 9.6 MHz, that is, it transmits a pulse every 104 nanoseconds. By experiments, we found that the multipath spread in this lab sitting is normally less than 20 nanoseconds. Therefore, if we delay a received pulse by 20 nanoseconds, then the delayed version of the signal will not be corrupted by the multipath spread. Thus, we can scan 4 delayed versions of the received signal from four antennas at receiver within a scanning window less than 100 nanosecond. Since the delays of the cables are known, it is straightforward to measure the TDOA estimates from four antennas. Figure 10 shows four delayed versions of one received pulse with some multipath components in a 60 nanoseconds scanning window.

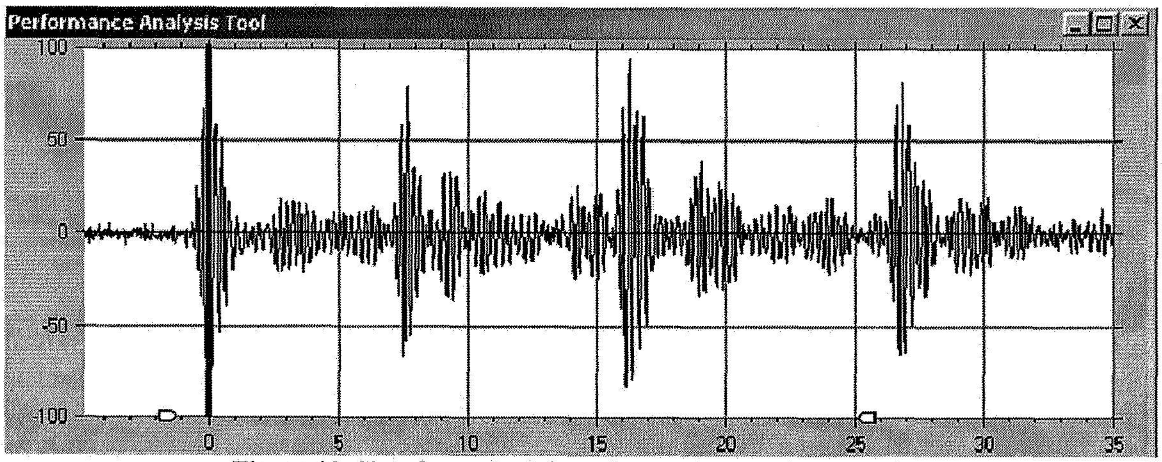

Figure 10. Signals received from four antennas at one receiver.

The TDOA estimates can be obtained from the above scan at the accuracy of hundred picoseconds. The TDOA data are feed into the two-stage weighted LS algorithm coded in Matlab and the transmitter position is calculated as the output. A reference tag is also used to calibrate the system before it operates. In this 15 feet-by-15 feet lab environment, a tracking resolution less than one feet is achieved.

VII. Conclusion

A UWB tracking system is designed for a free-flyer Mini-AERCam. UWB technology is exploited to implement the tracking system due to its properties such as high data rate, fine time resolution and low power spectral density. A two-stage weighted least-square TDOA algorithm is utilized to obtain the free-flyer's position. Matlab simulations show that the tracking algorithm can achieve the fine tracking resolution with low noise TDOA estimates. The preliminary lab experiment provides a proof of concept of the tracking feasibility of the UWB technology. Enhanced TDOA estimation method and optimal antenna configuration will be investigated to improve the resolution. The 2D tracking capability will be extended to 3D space.

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