UWB Tracking System Design for Lunar/Mars Exploration

Jianjun Ni*, Dickey Arndt+, Phong Ngo+, Chau Phan+, Julia Gross+
*david.ni1@jsc.nasa.gov

+NASA Johnson Space Center, Houston, Texas/USA

Abstract

This paper describes a design effort for a prototype ultra-wideband (UWB) tracking system that is currently under development at NASA Johnson Space Center (JSC). The system is being studied for use in tracking of lunar/Mars rovers during early exploration missions when satellite navigation systems are not available. The UWB technology is exploited to implement the tracking system due to its properties such as high data rate, fine time resolution, low power spectral density, and multipath immunity. A two-cluster prototype design using commercially available UWB products is proposed to implement the Angle Of Arrival (AOA) tracking methodology in this research effort.

An AOA technique using the Time Difference Of Arrival (TDOA) information is utilized for location estimation in the prototype system, not only to exploit the precise time resolution possible with UWB signals, but also to eliminate the need for synchronization between the transmitter and the receiver. After the UWB radio at each cluster is used to obtain the TDOA estimates from the UWB signal sent from the target, the TDOA data is converted to AOA data to find the angle of arrival, assuming this is a far field application. Since the distance between two clusters is known, the target position is computed by a simple triangulation.

Simulations show that the average tracking error at a range of 610 meters is 2.7595 meters, less than 0.5% of the tracking range. Outdoor tests to track the SCOUT vehicle (The Science Crew Operations and Utility Testbed) near the Meteor Crater, Flagstaff, Arizona were performed on September 12-13, 2005. The tracking performance was obtained with less than 1% tracking error at ranges up to 2000 feet. No RF interference with on-board GPS, video, voice and telemetry systems was detected. Outdoor tests demonstrated the UWB tracking capability.

I. Introduction

In this paper, we discuss the design and performance of a prototype UWB tracking system that is currently under development at NASA Johnson Space Center (JSC). The system is being studied for use in tracking of lunar/Mars rovers during early exploration missions when satellite navigation systems are not available. The Science Crew Operations and Utility Testbed (SCOUT) vehicle under development at JSC provides a testbed for the utilization of the UWB tracking system in such an environment.

UWB impulse radio technology is exploited in the design and implementation of the prototype localization system due to its capacity for fine time resolution, which is on the order of picoseconds, its low power spectral density, which allows the system to coexist with other communication systems, and its resistance to multipath interference. In addition, the high data rate capability of UWB allows for the future implementation of the localization system as a passive component of a larger multimedia communication system.

A two-cluster Angel of Arrival (AOA) tracking method using Time Difference of Arrival (TDOA) information is utilized for implementation of the tracking system, not only to utilize the achievable fine time resolution of UWB signals, but also to eliminate the need for synchronization between the transmitter and the receiver. The UWB radio at each cluster is used to obtain the TDOA estimates from the UWB signal sent from the target. Assuming this is a far field application, the TDOA data can be carefully converted to AOA data to find the angle of arrival. Since the distance between two clusters is known, the target position is computed by a simple triangulation.

The performance of this prototype system in the operating range of interest has been studied numerically using Monte Carlo simulations implemented in Matlab, and experimentally by deploying and testing the prototype system in an outdoor testbed environment. The results of all performance evaluations are presented and discussed in the current paper.

The remainder of this paper is organized as follows. In Section II, an AOA tracking methodology using TDOA estimates is introduced. The AOA tracking simulation results are presented in Section III. A two-cluster prototype system design using available UWB radios is discussed in Section IV, and the outdoor experimental test is discussed in Section V. Some concluding remarks are presented in Section VI.

II. Tracking Methodology

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. For near field applications, the TDOA approach has been chosen as the tracking method since it does not require synchronization between the transmitter and receiver, but can still exploit the fine time resolution available with UWB signals [1, 2]. For far field applications, the AOA approach can be applied to estimate the location of a target since the approximation error under the far field assumption is relatively small. The AOA technique is discussed briefly below.

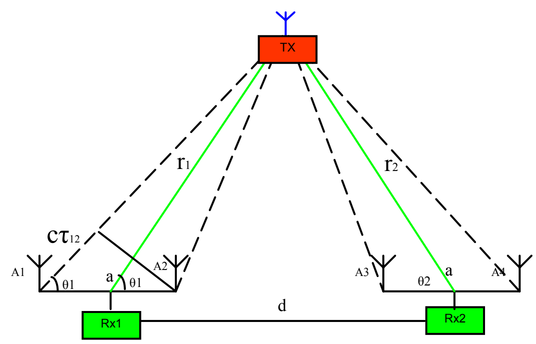

Fig. 1 AOA Localization in 2-D Space

A two dimensional AOA tracking case is illustrated in Figure 1. Two receivers are used to locate the transmitter in this 2-D space by a simple triangulation. Two receivers' positions (Rx1(0,0), Rx2(d,0)) are assumed known. If the angle of arrival from the target to each receiver (i.e. θ_1 and θ_2) can be estimated, the transmitter's position can be computed using the Law of Sine as follows,

$$\left[\frac{d\cos\theta_1\sin\theta_2}{\sin(180^0-(\theta_1+\theta_2))}, \frac{d\sin\theta_1\sin\theta_2}{\sin(180^0-(\theta_1+\theta_2))}\right]$$

.

* This research was performed while the author held a National Research Council Research Associateship Award at NASA Johnson Space Center.

In order to find the AOA information (θ_1 and θ_2), two antennas spaced by distance *a* are connected with each receiver. Since the UWB signal has fine time resolution, the TDOA information (τ_{12} and τ_{43}) has been measured and carefully converted to the AOA information as follows.
Since electromagnetic waves travel with constant velocity *c* in free space, the distance between the transmitter and the receiver's antenna is directly proportional to the propagation time of the signal. Under the far field assumption (**r₁**, **r₂** >> *a*),

$$c\tau_{12} \approx a \cos\theta_1$$

$$\theta_1 \approx \mathrm{arcCos}\,(c\tau_{12}/a);$$

Similarly,

$$c\tau_{43} \approx a \cos\theta_2$$

$$\theta_2 \approx \mathrm{arcCos}\,(c\tau_{43}/a).$$

The method to measure the TDOA information (τ_{12} and τ_{43}) will be discussed in details in Section IV.

III. Simulation Results

In order to analyze the tracking error behavior and gain some insight regarding achievable tracking resolution, several Matlab simulations were performed using the AOA tracking method described in Section II. The results of two of these simulations are discussed below.

A. Tracking error with perfect TDOA estimates

In order to transform TDOA estimates to AOA data, a far field assumption (r_1, r_2 >> d so that the lines from the target to two antennas at each receiver are approximately parallel) is made. A 2-D tracking simulation is presented to illustrate the impact of this far field assumption on tracking performance. The simulation setup is as follows:

- Baseline configuration: two receivers are 50 meters apart (d=50m) and two antennas at each receiver are 15 meters apart (a=15m).
- Transmitter trajectory: the transmitter moves in a semi-circular orbit (from 0 degree to 180 degree) with a radius of 610 meters (r_1=610m).
- TDOA noise level: the TDOA estimates are assumed perfect.

The simulated tracking error due to the parallel approximation is plotted in Figure 2. The simulation result shows that the tracking error due to approximation has a W shape pattern. In general, this approximation error is relatively small with the average about 0.05 meters. The tracking error at certain trajectory range (angle of target from 30 degree to 150 degree) is below the average error.

B. Tracking error with noisy TDOA estimates

A similar simulation with noisy TDOA estimates (standard derivation 10 picoseconds) is conducted and the error analysis (from 30 degree to 150 degree) is illustrated in Figure 3. The simulation shows that the tracking error is random and the average tracking error at range of 610 meters is 2.7595 meters, less than 0.5% of the tracking range.

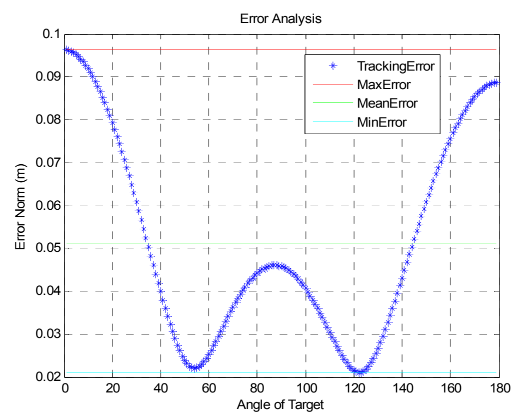

Fig. 2 Tracking error with perfect TDOA estimates

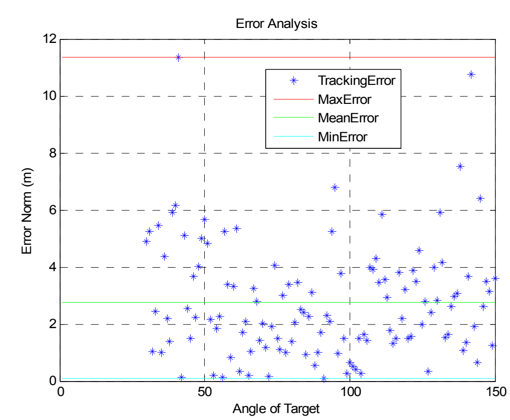

Fig. 3 Tracking error with noisy TDOA estimates

* This research was performed while the author held a National Research Council Research Associateship Award at NASA Johnson Space Center.

IV. System Design

We have designed and implemented a two-cluster prototype of the UWB AOA tracking system and conducted some experiments to test the UWB tracking capability using the TDOA estimates at JSC. In this section, some issues including design philosophy, key hardware and TDOA estimates will be discussed.

A. Design Philosophy

The extremely high fidelity of the UWB timing circuitry permits very precise measurements of propagation time while transmitting data. 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, the AOA technique using TDOA estimates was adopted for tracking in order to avoid the degradation in time resolution introduced by synchronization errors between the transmitter and receiver. A two-cluster prototype system was designed, which connects two antennas through a power combiner to one UWB receiver at each cluster, using low-loss, phase aligned interconnect cables with precisely calibrated delays. In this way, two delayed versions of the received UWB pulse are obtained at each receiver within a scanning window. Since the cable delays are known precisely, it is straightforward to measure the TDOA estimates between the two antennas at each receiver. The TDOA data are fed into the AOA algorithm described in Section II and the transmitter position is computed and displayed in the tracking window.

B. Key Hardware

Time Domain Corporation UWB radios were chosen for this design effort. The Time Domain PulsON 200 UWB Evaluation Kit (EVK) allows product developers to examine the performance, capabilities and properties of UWB technology. The EVK radios can be configured for testing or as elements of an application demonstration. The EVK has the following key features [3]:

- PRF (Pulse Repetition Frequency): 9.6 MHz
- 8 data rates: 75 kbps, 150 kbps, …, 4.8 Mbps, 9.6 Mbps
- Center Frequency (radiated): approximately 4.7 GHz
- Bandwidth (10 dB radiated): 3.2 GHz
- EIRP: -11.5 dBm
- 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 EVK radios can provide ten picosecond time resolution by using appropriate data extraction algorithms.

C. Cross-Correlation plus Peak Detection (CCPD) method

To estimate the time delay between pulses, a method called Cross-Correlation plus Peak Detection (CCPD) has been introduced. Cable delays were chosen such that the two delayed versions of the signal from different antennas at each receiver fit within a scanning window 100 nanoseconds in duration. A peak detector is first used to detect the direct-path arrival of each signal and separate it from later multipath arrivals. Cross correlation between the two direct-path arrivals is then employed to estimate the precise time delay between the signals. The maximum cross-correlation coefficient between any two of the arriving signals gives the optimal (maximum-likelihood) estimate of the time delay between the two.

A reference tag is used to calibrate the system to obtain the cable delays. Before operating the tracking system, a transmitter is placed at a known position to act as a reference tag, and the cable delays are computed based on the multiple arrivals from the reference transmitter position. Once the cable delays are known, the CCPD finds the time delays between signals. The TDOA estimates can be obtained at the accuracy of ten picoseconds. The TDOA data are fed into the AOA algorithm coded in Matlab and the transmitter position is calculated as the output and displayed in the tracking window.

* This research was performed while the author held a National Research Council Research Associateship Award at NASA Johnson Space Center.

V. Outdoor Test

Outdoor tests have been conducted to test the UWB tracking capability with extended range in an open environment. Due to the conservative FCC limit on the UWB emission power (-41.3dBm/MHz), the transmitting range is limited. In order to increase the tracking range, four high gain horn antennas are used as receiving antennas and a low noise amplifiers (LNA) is added at the receiving side after each receiving antenna.

In September 2005, a joint tracking test was conducted with the SCOUT vehicle at the Meteor Crater in Arizona. The two-cluster UWB AOA tracking system baseline has the following setup (Figure 4): two receivers are 50 meters apart and two horn antennas at each receiver are 15 meters apart. One UWB radio was integrated with the SCOUT vehicle as the transmitter (Figure 5).

Fig. 4 Tracking System Baseline Setup

Fig. 5 Tracking Target – SCOUT Vehicle

The objective of the test was to:

1. Test the real time tracking of a moving target.
2. Test the interference with other communication systems on vehicle

The SCOUT vehicle was running at normal speed (7 miles /hour) in the tracking area. Figure 6 shows the tracking accuracy compared to the differential GPS, with less than 1% error at ranges up to 610 meters (2000 feet). A SCOUT running trajectory recorded in Figure 7 demonstrates the real-time tracking capability of the system. The tracking update rate for the trajectory was approximately 5 Hz. No RF interference was observed between the UWB tracking system and other on-board SCOUT systems (such as GPS, video, voice and telemetry).

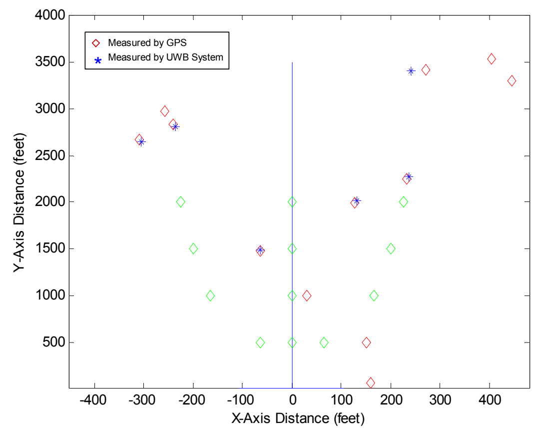

Fig. 6 Accuracy Comparison: GPS vs. UWB System

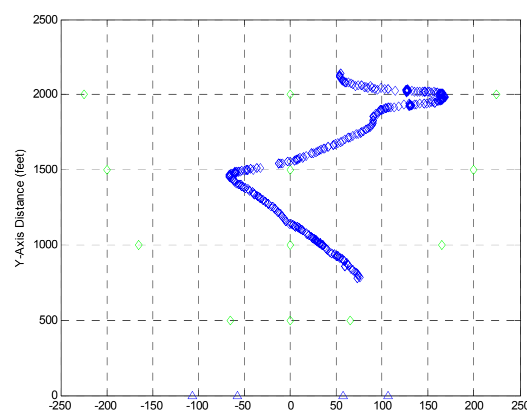

Fig. 7 Trajectory: UWB System tracking SCOUT

* This research was performed while the author held a National Research Council Research Associateship Award at NASA Johnson Space Center.

VI. Conclusion

A prototype UWB tracking system has been designed, implemented, tested, and proven feasible for space applications. UWB technology has been exploited to implement the tracking system due to its properties such as high data rate, fine time resolution and low power spectral density. The AOA tracking method using TDOA information has been employed to avoid synchronization problems between the transmitter and the receiver. A two-cluster system with high gain horn antennas has been implemented to increase the tracking range. Simulations demonstrate that the approximation error due to the far field assumption for the AOA algorithm is relatively small and the tracking scheme can achieve the desired fine tracking resolution. Outdoor tests have been conducted jointly with the SCOUT vehicle to test the tracking capability for a moving target. These tests demonstrate that the UWB tracking system can co-exist with other RF communication systems, and that a tracking resolution less than 1% of the range can be achieved.

References

[1] Jianjun Ni, Dickey Arndt, etc.; "UWB Tracking System Design for Free-Flyers", AIAA Space 2004 Conference and Exposition, September 28-30, 2004.

[2] Jianjun Ni, Richard Barton; "Design and Performance Analysis of a UWB Tracking System for Space Applications", IEEE/ACES International Conference on Wireless Communications and Applied Computational Electromagnetics, April 3-7, 2005

[3] Time Domain Corporation, "PulsON Technology Overview", http://www.timedomain.com/Files/downloads/techpapers/PulsONOverview7_01.pdf

* This research was performed while the author held a National Research Council Research Associateship Award at NASA Johnson Space Center.