UWB Tracking System Design with TDOA Algorithm for Space Applications

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Abstract—An ultra-wideband (UWB) tracking system design effort is underway for a free-flying video camera system to aid in inspection around the International Space Station and the Space Shuttle. This system can also be applied to tracking for Lunar/Mars rovers in early exploration phases where satellite navigation systems (such as GPS) are not available. The SCOUT vehicle under development at JSC provides a testbed for the utilization of the UWB tracking system in such an environment. UWB technology is exploited to implement the tracking system with its properties, such as high data rate, fine time resolution, low power spectral density, and multipath immunity. A system design using commercially available UWB products has been implemented. A tracking algorithm, TDOA (Time Difference of Arrival), has been investigated. The performance analysis provides guidance to improve system design. Simulations show that the TDOA algorithm can achieve fine resolution with low noise data. Outdoor tests demonstrate the feasibility of UWB tracking.


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ULTRA-WIDEBAND (UWB), also known as impulse or carrier-free radio technology, is one promising new technology. In February, 2002, the Federal Communications Commission (FCC) approved the deployment of this technology in the commercial sector under Part 15 of its regulations.[1] 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.[2] Hence, UWB technology is employed to implement the communications and tracking system design for space applications in this research effort.[3]

One such application is for a robotic free-flying camera known as Mini-AERCam (Autonomous Extra-vehicular Robotic Camera), which is being developed at the NASA Johnson Space Center (JSC) to assist in 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 is also applicable to inspect the surface damage of the Space Shuttle to assure flight safety.

This system can be readily applied to tracking for Lunar/Mars rovers in early exploration phases. After a Moon/Mars base has been established, it will be necessary to track a rover or an astronaut's position while working around the base. The UWB system with robust to multipath interference can coexist with other communication systems used by the landing vehicle. The SCOUT testbed vehicle, a Moon rover prototype under development at JSC, is available to test the proposed UWB tracking system.

Analysis of Tracking Algorithm

The Time Difference of Arrival (TDOA) tracking algorithm currently used in the mini-AERCam tracking system is developed in Chan and Ho's study of an efficient closed-form localization solution where the statistical properties of the algorithm are analyzed to some extent.[4] While the analysis presented is essentially correct, it is also sketchy and incomplete, making a thorough performance evaluation of the algorithm problematic. To correct this deficiency, we performed a careful and complete analysis of the statistical properties of this algorithm in two dimensions.

Assume that there is one transmitter located at an unknown location (x_0,y_0) in two-dimensional space and $M+1$ receivers located at positions $\{(0,0), (x_1,y_1), (x_2,y_2),\ldots,(x_M,y_M)\}$, which are assumed to be known precisely. Further, assume that measurements of the relative time delays $\{d_1,d_2,\ldots,d_M\}$ between the arrival of the transmitted signal at receiver (0,0) and each of the other locations $(x_1,y_1),\ldots,(x_M,y_M)$ are available. 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:

$$\mathbf{G}_0\mathbf{u}_0 = \mathbf{h}_0, \tag{1}$$

where

$$\mathbf{u}_0 = \begin{bmatrix} x_0 \\ y_0 \\ r_0 \end{bmatrix}, \quad r_0 = \sqrt{x_0^2 + y_0^2}, \quad \mathbf{G}_0 = -2\cdot\begin{bmatrix} x_1 & y_1 & cd_1 \\ x_2 & y_2 & cd_2 \\ \vdots & \vdots & \vdots \\ x_M & y_M & cd_M \end{bmatrix},$$

$$\mathbf{h}_0 = \begin{bmatrix} c^2d_1^2 - x_1^2 - y_1^2 \\ c^2d_2^2 - x_2^2 - y_2^2 \\ \vdots \\ c^2d_M^2 - x_M^2 - y_M^2 \end{bmatrix}.$$

If the time delay measurements are not precisely correct, we have instead the system

$$\mathbf{G}_1\mathbf{u}_0 = \mathbf{h}_0 - (\Delta\mathbf{h}_1 - \mathbf{G}_1\mathbf{u}_0), \tag{2}$$

where

$$\mathbf{G}_1 = \mathbf{G}_0 + \Delta\mathbf{G}_1, \quad \mathbf{h}_1 = \mathbf{h}_0 + \Delta\mathbf{h}_1, \quad \Delta\mathbf{G}_1 = -2\cdot\begin{bmatrix} 0 & 0 & c\delta_1 \\ 0 & 0 & c\delta_2 \\ \vdots & \vdots & \vdots \\ 0 & 0 & c\delta_M \end{bmatrix},$$

$$\Delta\mathbf{h}_1 = \begin{bmatrix} c^2\delta_1^2 + 2c^2d_1\delta_1 \\ c^2\delta_1^2 + 2c^2d_2\delta_2 \\ \vdots \\ c^2\delta_M^2 + 2c^2d_M\delta_M \end{bmatrix}.$$

and $\delta = [\delta_1\ \delta_2\ \ldots\ \delta_M]^T$ represents the vector of errors in relative time delay measurements, which is assumed to be a zero-mean Gaussian random vector with covariance matrix $\mathbf{Q} = E\{\delta\delta^T\}$. By going through three stages of the algorithm, we derive the final approximations for the bias vector and autocorrelation matrix of the algorithm. Due to space limitations, the results are not presented here. Instead, we derive and present the mean-squared-error (MSE) for a simple far-field example. In particular, we let $M = 3$, $\mathbf{Q} = \sigma^2\mathbf{I}$, and

$$r_0 >> \max_{1\le i\le M}\left(\max\left\{|x_1|,|y_1|,cd_i\right\}\right).$$

If we consider an orbit tracking in two-dimensional space (r_0 is the radius of the orbit and r is radius of the area in which the receivers are placed), and let $x_0 = r_0\cos\theta$, $y_0 = r_0\sin\theta$, $x_i = r\cos\phi$, $y_i = r\sin\phi_i$, and ri = r20 + r2 - 2r0rcos(w-fi), then the total MSE is given by

$$\mathrm{MSE} = \frac{c^2\sigma^2r_0^2\sum_{i=1}^{3}\left(a_i^2 + b_i^2\right)}{r^2\left(\sum_{i=1}^{3}a_i^2\sum_{i=1}^{3}b_i^2 - \left(\sum_{i=1}^{3}a_ib_i\right)^2\right)}, \tag{3}$$

where

$$a_i = \cos\phi_i + \frac{r_i - r_0}{r}\cos\theta, \ b_i = \sin\phi_i + \frac{r_i - r_0}{r}\sin\theta.$$

It is shown that MSE is a function of parameters σ, r_0, r, ω and ϕ, and it is linear to the variance σ^2 of the TDOA estimates. Although the relation between MSE and r_0 (or r) is not obvious, given a receiver configuration region and a tracking area, there exists an optimal configuration of receivers that minimizes MSE. This optimization problem will be studied in the future.

Simulation Results

RMSE vs. TDOA Noise

A set of two-dimensional orbit (radius 100m) tracking simulations is implemented to analyze the factor of TDOA variance. The simulations give the root-mean-square-errors (RMSE) for the reference-centered configuration. The results are summarized in Table 1. Simulation results show that the tracking error is linear to the standard deviation of TDOA data, which coincides with the analytical result in (3).

Static Reference vs. Dynamic Reference

The TDOA algorithm used in this research effort requires one receiver as the reference located at the origin. Besides using the static reference, a scheme dynamically using different receiver as reference is studied. The simulation shows that the tracking resolution is improved from 1.7660m to 0.8762m at the TDOA noise level std = 0.01 by using the dynamic reference (Fig. 1).

Table 1. Error Analysis of Orbit Tracking with Different TDOA Noise Levels

Standard Deviation (std) of TDOA (ns)	Tracking Range (m)	RMSE (m)
0.01	100	1.7660
0.001	100	0.1729
0.0001	100	0.0172

Prototype Design and Laboratory Experiment

We have designed and implemented a prototype of the UWB tracking system and conducted a laboratory experiment to test the UWB tracking capability using the TDOA estimates in a general lab environment at JSC. In this section, some issues including design philosophy, key hardware, TDOA estimates, and experiment results will be discussed.

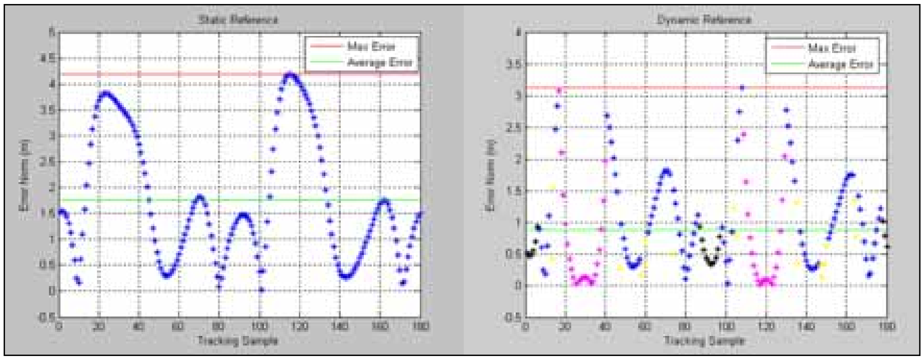

Figure 1. Error Analysis (Static Reference vs. Dynamic Reference)

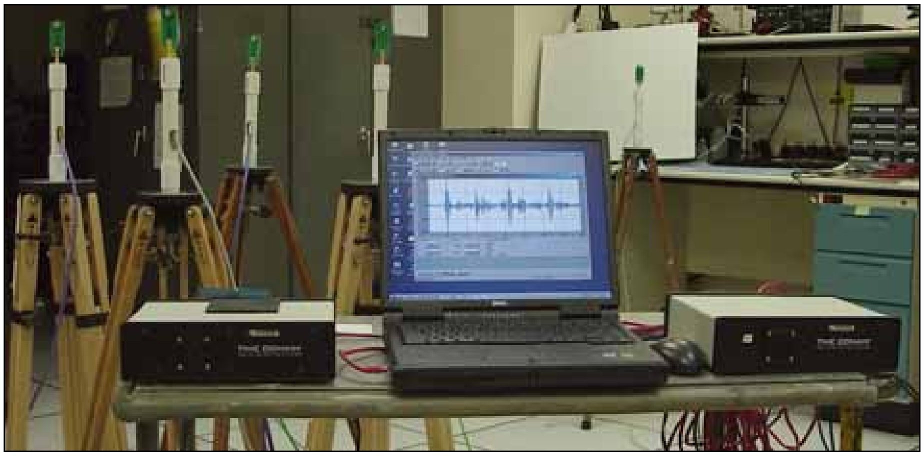

Figure 2. UWB TDOA Tracking Experiment Set-up

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 TDOA technique was adopted for tracking in order to avoid the degradation in time resolution introduced by synchronization errors between the transmitter and receiver. Similarly, to eliminate the complicated synchronization problem required when implementing the TDOA algorithm with four separate receivers, a four-element receiving antenna array was designed, which connects four antennas through a power combiner to one UWB receiver using low-loss, phase-aligned interconnect cables with precisely calibrated delays. In this way, four delayed versions of the received UWB pulse are obtained at the receiver within a scanning window. Since the cable delays are known precisely, it is straightforward to measure the TDOA estimates between the four antennas. The TDOA data are fed into the TSWLSS algorithm, and the transmitter position is computed and displayed in the tracking window.

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. EVK radios can be configured for testing or utilized 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,…, 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 U.S.-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® Microprocessor for Embedded Applications Development

The EVK radios can provide ten picosecond time resolution by using appropriate data extraction algorithms.

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 developed. Cable delays were chosen such that the four delayed versions of the signal from different antennas 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 four 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.

Laboratory Experiments

The experiment set-up is as follows: (Fig. 2)

- 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 also mounted on a tripod for mobility.
- PC: Dell Latitude laptop running Waveform Scan software.

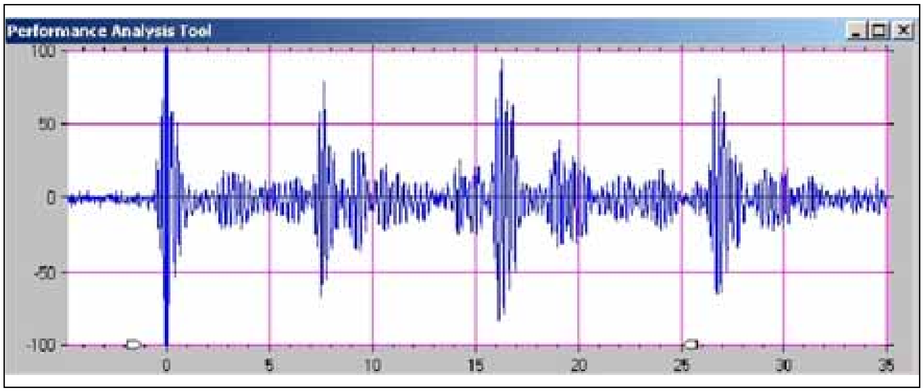

Figure 3. Signals Recieved from Four Antennas at one Receiver

Figure 4. The Joint Tracking Test with the SCOUT Vehicle

- Hub: Two radios are connected to the PC through standard Ethernet cables just for radio configuration.

The Pulse Repetition Frequency (PRF) of the EVK radio is 9.6 MHz; that is, a single UWB pulse is transmitted every 104 nanoseconds. If the delays of the antenna interconnect cables are known, it is straightforward to measure the TDOA estimates from four antennas. Figure 3 shows four delayed versions of one received pulse with multipath components in a scanning window.

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 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 from the above scan at the accuracy of ten picoseconds. TDOA data are fed into the TSWLSS algorithm coded in Matlab and the transmitter position is calculated as the output. In the 15-by-15 foot lab environment, a tracking resolution of less than one foot is achieved.

Outdoor Test

Outdoor tests were 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, a low noise amplifier (LNA) was added at the receiving side after each receiving antenna.

A joint tracking test was conducted with the SCOUT vehicle behind Building 14 at JSC (Fig. 4). One UWB radio was integrated with the vehicle as the transmitter. The objectives of the test were to:

1. Test the interference with other communication systems on the vehicle (GPS (1.6 GHz), Video (5.8 GHz), Data Communication (2.4 GHz)).
2. Test the tracking capability for a moving target.

The baseline radius was increased to 7.5 meters for this test. Tracking was tested at ranges from 100 to 200 feet within an azimuth range from –60 degrees to +60 degrees (0 degrees = boresight) with the SCOUT vehicle running at normal speed (6-8 miles/hour). In order to test the real-time tracking capability of the system, several tracking trajectories were tested in the tracking area. The tracking update rate for all trajectories was approximately 5 Hz. A laser range finder (LIDAR) was used to determine the range between the target and the center of the baseline.

Observations from the outdoor test with the SCOUT vehicle are as follows.

- The UWB tracking system can track the SCOUT vehicle in real-time with resolution less than 2 feet at a range of up to 200 feet.
- The UWB tracking system does not interfere with the Video system. Other communication systems were not active. These will be tested in the future.
- Some false localization results shown around the baseline area resulted from a defect in the current evaluation of the UWB radio. This seems to be caused by a partial power spectrum drop at the transmitter. Such false localization results would be filtered out in a fully operational system by integrating a motion model into the tracking system using a Kalman filter or similar technique.
- Some signal strength decrease has been observed when the vehicle turns. This is due to the 3 dB loss when the omni-antennas are in the edge-to-face orientation, as compared to the 0-dB face-to-face orientation. The use of high gain horn antennas in the future can compensate for this loss and boost the received signal.

Above all, this joint test with the SCOUT vehicle demonstrates that the UWB tracking system is capable of tracking the moving target and can co-exist with other RF communication systems on board.

Conclusion

UWB technology is exploited to design a tracking system for space applications. A system design using commercially available UWB products has been implemented. A tracking algorithm TDOA has been investigated and the performance analysis provides insight for system design. Simulations show that it can achieve fine resolution and that the dynamic reference scheme improves resolution. Outdoor tests demonstrate the UWB tracking feasibility. Advanced schemes to improve the tracking resolution and range will be investigated in the future.

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(Continued from page 22.)

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