Design and Performance Analysis of a UWB Tracking System for Space Applications

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This paper discusses an ultra-wideband (UWB) tracking system design effort for a free-flying video camera system for aid in inspection around the International Space Station and the Space Shuttle. 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 system design using commercially available UWB products is implemented. A tracking algorithm TDOA (Time Difference of Arrival) is investigated and the performance analysis provides guidance to improve the system design. Simulations show that the TDOA algorithm can achieve the fine resolution with low noise data. The laboratory experiments demonstrate the UWB tracking feasibility.

I. Introduction

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]. 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 [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 NASA Johnson Space Center (JSC) 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 is also applicable to inspect the surface damage of the Space Shuttle to assure the 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 is necessary to track the rover or astronaut's positions while working around the base. The UWB system is robust to multipath interference, can co-exist with other communication systems used by the landing vehicle. The SCOUT testbed vehicle, a Moon rover prototype is under development at JSC, is available to test the proposed UWB tracking system.

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II. Analysis of Tracking Algorithm

The Time Difference of Arrival (TDOA) tracking algorithm currently used in the mini-AERCam tracking system is developed in [4]. The statistical properties of the algorithm are analyzed to some extent in [4], and while the analysis presented there 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

$$\mathbf{u}_0 = \begin{bmatrix} x_0 \\ y_0 \\ r_0 \end{bmatrix}, \quad r_0 = \sqrt{x_0^2 + y_0^2}, \quad \mathbf{G}_0 = -2\cdot\begin{bmatrix} x_1 & y_1 & cd_1 \\ x_2 & y_2 & cd_2 \\ \vdots & \vdots & \vdots \\ x_M & y_M & cd_M \end{bmatrix}, \quad \mathbf{h}_0 = \begin{bmatrix} c^2d_1^2 - x_1^2 - y_1^2 \\ c^2d_2^2 - x_2^2 - y_2^2 \\ \vdots \\ c^2d_M^2 - x_M^2 - y_M^2 \end{bmatrix}.$$

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

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

where

$$\mathbf{G}_1 = \mathbf{G}_0 + \Delta\mathbf{G}_1, \quad \mathbf{h}_1 = \mathbf{h}_0 + \Delta\mathbf{h}_1, \quad \Delta\mathbf{G}_1 = -2\cdot\begin{bmatrix} 0 & 0 & c\delta_1 \\ 0 & 0 & c\delta_2 \\ \vdots & \vdots & \vdots \\ 0 & 0 & c\delta_M \end{bmatrix}, \quad \Delta\mathbf{h}_1 = \begin{bmatrix} c^2\delta_1^2 + 2c^2d_1\delta_1 \\ c^2\delta_2^2 + 2c^2d_2\delta_2 \\ \vdots \\ c^2\delta_M^2 + 2c^2d_M\delta_M \end{bmatrix},$$

and $\delta = [\delta_1 \ \ \delta_2 \ \ \cdots \ \ \delta_M]^T$ represents the vector of errors in the 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 the paper length limit, 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 $r_0 >> \max_{1\le i\le M}\left(\max\{|x_i|,|y_i|,cd_i\}\right)$. 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 the receivers are placed), and let $x_0 = r_0\cos\theta$, $y_0 = r_0\sin\theta$, $x_i = r\cos\phi_i$, $y_i = r\sin\phi_i$, and $r_i = \sqrt{r_0^2 + r^2 - 2r_0r\cos(\theta-\phi_i)}$, then the total MSE is given by

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

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, θ and ϕ_i, 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.

IV. Simulation Results

A. RMSE vs. TDOA Noise

A set of 2D 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. The simulation results show that the tracking error is linear to the standard deviation of TDOA data, which coincides with the analytical result in (3).

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

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

B . 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. (Figure 1)

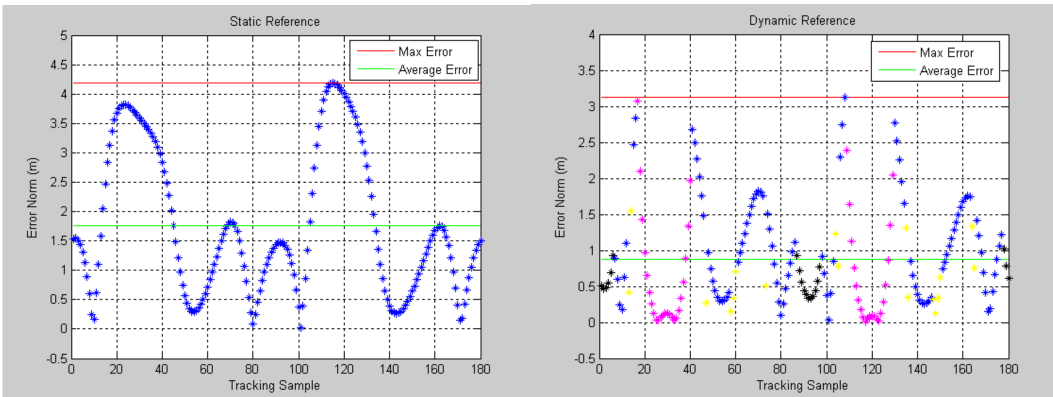

Figure 1. Error Analysis (Static Reference vs. Dynamic Reference).

V. Laboratory Experiment

A preliminary laboratory experiment is designed to test the UWB tracking capability using the TDOA estimates in a lab environment. To avoid the 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 is shown in Figure 2.

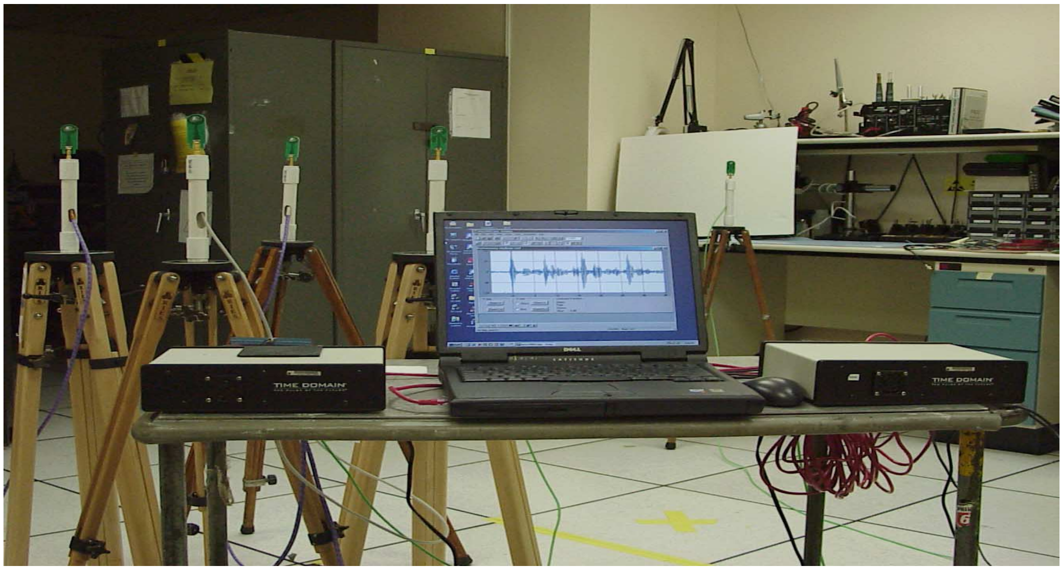

Figure 2. UWB TDOA Tracking Experiment Set-up.

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. The TDOA data are feed into the tracking 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 foot is achieved.

VI. Conclusion

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

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