Ultra-Wideband Tracking System Design for Relative Navigation

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Abstract

This presentation briefly discusses a design effort for a prototype ultra-wideband (UWB) time-difference-of-arrival (TDOA) tracking system that is currently under development at NASA Johnson Space Center (JSC). The system is being designed for use in localization and navigation of a rover in a GPS deprived environment for surface missions. In one application enabled by the UWB tracking, a robotic vehicle carrying equipments can autonomously follow a crewed rover from work site to work site such that resources can be carried from one landing mission to the next thereby saving up-mass. The UWB Systems Group at JSC has developed a UWB TDOA High Resolution Proximity Tracking System which can achieve sub-inch tracking accuracy of a target within the radius of the tracking baseline [1]. By extending the tracking capability beyond the radius of the tracking baseline, a tracking system is being designed to enable relative navigation between two vehicles for surface missions. A prototype UWB TDOA tracking system has been designed, implemented, tested, and proven feasible for relative navigation of robotic vehicles. Future work includes testing the system with the application code to increase the tracking update rate and evaluating the linear tracking baseline to improve the flexibility of antenna mounting on the following vehicle.

References

UWB TDOA Tracking for Relative Navigation

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UWB Systems Group / EV4
Avionic Systems Division (EV)

NASA Johnson Space Center
“No one can whistle a symphony. It takes a whole orchestra to play it.”

– H.E. Luccock
UWB Systems Group
(A Functional Team Architecture)

Analysis Team
- Algorithm Development
- System Simulation
- Performance Evaluation
- Proposal Development
  - David Ni
  - Dickey Arndt
  - Brian Bourgeois
  - Richard Barton

Hardware Team
- Hardware Design
- System Testing
- Product Investigation
  - Phong Ngo
  - Chau Phan
  - John Dusl

Software Team
- Software Development
- Software Maintenance
  - David Ni
  - Kent Dekome
  - Julia Gross

Administrative Liaison
- Internal Networking
- External Networking
- Funding Channel
- Order and Purchase
  - Dickey Arndt
  - Phong Ngo
  - Chau Phan
  - Julia Gross
  - John Dusl
Outline

- UWB Technology Development at JSC
- UWB Fine Time Resolution
- TDOA Tracking Methodology
- TDOA Resolution Analysis
- Tracking System Design and Software
- Summary
UWB AOA Long Range Tracking

- UWB AOA long range tracking with the SCOUT vehicle at the Meteor Crater, Arizona in 2005 and 2006

- Excellent tracking performance with less than 1% error at ranges up to 4000 ft

- No RF interference with on-board GPS, video, audio, and telemetry systems
Use Time Difference of Arrival (TDOA) technique to provide sub-inch tracking resolution

Two tracking points on target to accurately guide the target into its docking station
UWB TDOA 3D High Resolution Tracking for Robotic Control

- UWB TDOA 3D tracking at Honeywell’s Moonyard Facility
- Real-time trajectory can be displayed and recorded
- Tracking accuracy within 1 inch in the xy plane and within 2 inches in the z direction
- Tracking data are passed to the robotic control system
Why UWB?

- Immunity to interference from narrow band RF systems due to ultra-wide bandwidth
- Low impact on other RF systems due to extremely low power spectral densities
- Capable of precise tracking due to sub-nanosecond time resolution
- Robust performance in multipath environments
Time Difference of Arrival (TDOA)

Hyperbola: $b^2 x^2 - a^2 y^2 = a^2 b^2$
Time Difference of Arrival (TDOA)

Rx1
(x1, y1)

Rx2
(x2, y2)

Rx3
(x3, y3)

Tx
(x, y)
Advantages of TDOA

- No synchronization between Tx and Rx
- Simplex (one-way) data estimation
- Cross-correlation plus Peak Detection (CCPD) works well to obtain TDOA
TDOA Equations (2D)

\[ D_{12} = \sqrt{(x_1 - x)^2 + (y_1 - y)^2} - \sqrt{(x_2 - x)^2 + (y_2 - y)^2} = \tau_{12} c \]

\[ D_{13} = \sqrt{(x_1 - x)^2 + (y_1 - y)^2} - \sqrt{(x_3 - x)^2 + (y_3 - y)^2} = \tau_{13} c \]

\[ D_{23} = \sqrt{(x_2 - x)^2 + (y_2 - y)^2} - \sqrt{(x_3 - x)^2 + (y_3 - y)^2} = \tau_{23} c \]
- Taylor Series Expansion Least Squares
- Iterative Algorithm
  (Initialization problem and convergence problem)
- Two-Stage Weighted Least Squares Algorithm
  (one more receiver)
Resolution Analysis (MSE/CRLB)

\[
\text{MSE} \approx \frac{4c^2 \sigma^2 r_0^4}{Mr^4 \bar{v}^4}
\]

\[
\text{CRLB} \approx \frac{2c^2 \sigma^2 r_0^2}{Mr^2}
\]

where

\[
\bar{v}^4 = \frac{1}{M} \sum_{i=1}^{M} v_i^4 = \begin{cases} 
\frac{3}{8}, & M \neq 4 \\
\frac{3}{8} + \frac{1}{8} \cos(4\theta), & M = 4 
\end{cases}
\]
Proximity Case

\[ \text{MSE} \approx \frac{8c^2 \sigma^2 r_0^4}{(3 + \cos(4\theta))r^4} \]

Proximity case: rang is close to baseline size

\[ \text{MSE} \approx 4c^2 \sigma^2 \]
Proximity High Resolution

\[ \text{MSE} \approx 4c^2 \sigma^2 \]

\[ \bar{\varepsilon} = 2c\sigma \]

\[ c = 3 \times 10^8 \text{ m/s} \]

\[ \sigma = 10^{-9} \text{ s}, \quad \bar{\varepsilon} = 0.6 \text{ m} \]

\[ \sigma = 10^{-11} \text{ s}, \quad \bar{\varepsilon} = 0.006 \text{ m} \]
Tracking Performance
(radius = 4 feet, range = 10 feet)
Error Analysis
(radius = 4 feet, range=10 feet)
Tracking Performance
(radius = 4 feet, range = 60 feet)

TDOA Tracking Performance (noise std = 0.01)
Error Analysis
(radius = 4 feet, range = 60 feet)
Tracking Performance vs. Range

Error Analysis (vs. Range)

Tracking Range (foot)

Error Norm (foot)
Tracking Performance vs. Range
(Comparison with Baseline Radius)

Tracking Error Analysis

- Baseline Radius = 2 feet
- Baseline Radius = 4 feet
Tracking System Set-up

Following Vehicle

Leading Vehicle
Tracking Software

Experimental Code Version
- Coded with Matlab
- Pros: flexibility for change
- Cons: slower speed

Application Code Version
- Coded with C++
- Pros: faster update rate
- Cons: need compile
A prototype UWB TDOA tracking system has been designed, implemented, tested, and proven feasible for relative navigation of robotic vehicles.

Future work includes testing the system with the application code to increase the tracking update rate and evaluating the linear tracking baseline to improve the flexibility of antenna mounting on the following vehicle.
Backup Slides

Demo to ER personnel at Antenna Range
Behind B14.

Collect comments and suggestions to improve the system performance to meet ER’s needs.
TDOA (3' BL, 2' AE at 10')

Resolution vs. Angle

- TrackingError
- MaxError
- MeanError
- MinError

Error Norm (feet)

X (feet)

Angle of Target

Antenna Position
Actual Position
Tracked Position

0 2 4 6 8 10 12 14 16 18 20
-10 -8 -6 -4 -2 0 2 4 6 8 10

20 40 60 80 100 120 140 160

-10 -8 -6 -4 -2 0 2 4 6 8 10

-6 -4 -2 0 2 4 6 8 10 12 14 16 18 20

-10 -8 -6 -4 -2 0 2 4 6 8 10

TDOA-Tracking (noisy TDOA)
TDOA (6' BL, 0.5' AE at 10')

TDOA-Tracking (noisy TDOA)

Resolution vs. Angle

TrackingError
MaxError
MeanError
MinError

Antenna Position
Actual Position
Tracked Position

Error Norm (feet)

Angle of Target

X (feet)

Y (feet)