AN ULTRA-WIDEBAND RF METHOD FOR LOCALIZING AN AUTONOMOUS MOBILE ROBOT

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ABSTRACT

A technique for a new ad hoc, high-speed update and high precision location system that would establish a reliable navigation technology for autonomous unmanned vehicle systems was investigated. The system would employ a new ultra-wideband (UWB) ranging & communication (RAC) concept that incorporates time arrival information into the recent direct sequence (DS) code division multiple access (CDMA) technique. Time-of-arrivals (TOA) and time-difference-of-arrivals (TDOA) methods were then developed for position triangulation. The location system would have a self-configuring scheme so that the base stations of the location system can be installed and networked in a matter of minutes at desired positions. The geographical position of an object can be determined within centimeter-to-submeter accuracy over an area of several square kilometers at an update rate of hundred updates per second. The system can be used guidance control of unmanned vehicle systems including aerial, ground, and sea vehicles.

1. INTRODUCTION

In general, for an autonomous unmanned ground vehicle (UGV) system to properly navigate to its destination, it must know its position and orientation, its destination, and knowledge of its surrounding environment. These concepts can be summarized in three questions: "Where am I?", "Where am I going?", and "How do I get there?" The following paper is concerned primarily with answering the first question with a UWB RF and TOA/TDOA based localization technique.

Localization technology is an essential feature for the navigation and guidance of a UGV. Three broad categorizations of localization are: Standalone (dead reckoning or use of landmark recognition), satellite-base Global Positioning Systems (GPS), and terrestrial-radio-based systems (Long Range Navigation "C" configurations, etc.). Depending on the requirements, conditions, and resources in an application, localization can employ a combination of these. However, there exist many navigation and guidance challenges which include precision issues, fast positioning needs, loss of signal due to environment, etc.

This paper presents a current research effort being conducted by JADI Inc., in collaboration with RDECOM-TARDEC. An accurate ultra-wideband (UWB) radio-frequency (RF) based ranging and communication system is being developed, along with systems solutions for time-of-arrival (TOA) and time-difference-of-arrival (TDOA) techniques. The resultant localization can be deployed for many practical applications in the battlefield as well as commercial arenas. The results presented herein has been filed under *US Patent 60/545,238*.

2. LOCATION SCHEME

2.1 Overall scheme

Figure 1 shows a basic overview of the configuration for an autonomous mobile robot with three or more base stations that can be swiftly set up in an ad hoc manner over an area of operation, say, a city. Base stations A, B & C are readily transportable units (mounted on tactical vehicles) and would be positioned at any suitable locations. The stations would use UWB RAC technique to coordinate with each other and automatically calibrate the geographical coordinates of position A, B & C, within a matter of a second. A mobile robot (vehicle or object) would then transmit or simply receive UWB RAC signals from A, B & C, and compute its location within the geographical frame. Hundreds of location updates per second can be achieved. A 2-dimensional location system would require a minimum of three base stations, while a 3-dimensional system would require at least four stations. In practice, several stations may be employed to provide redundancy and self-calibrations.

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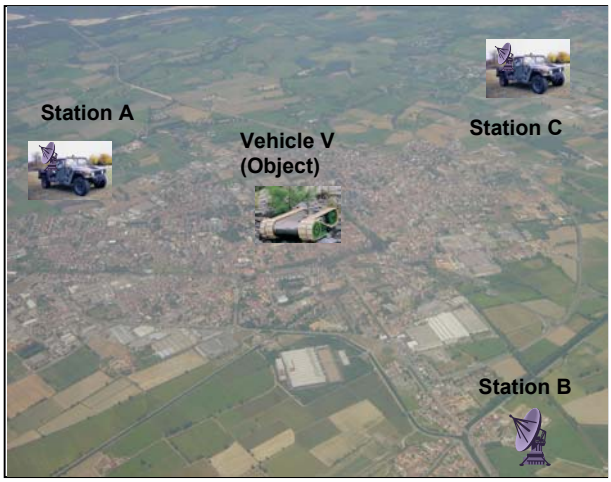

Figure 1. Configuration of Ad Hoc Stations and Vehicle/Object

2.2 Self-Organization of Station Location

In Figure 1, Stations A, B & C can be 1) fixed in position, 2) moved and placed at ad hoc locations, or 3) be mobile on the move. Coordinates of locations A, B & C can be determined in several ways including:

Global Positioning System. Stations A, B & C can determine their global coordinates by using a precision GPS, or by calculating statistical mean of the coordinates from a less accurate GPS.

Relative Positioning System. Stations A, B & C communicate with each other to determine the coordinates of their positions, relative to each other. For example, Station A initiates & sends message/signal S_A to Station B. Upon receiving signal S_A, B waits a predetermined moment D_B, and sends signal S_B back to A, which then clocks the flight time T_{ABA} from A-to-B-to-A. The time it takes radio wave to travel from A to B is given by $T_{AB} = (T_{ABA} - D_B)/2$, and D_B. The flight times, T_{BC} & T_{CA}, can similarly be determined. Distances between and locations of the station are obtained by multiplying these times with the speed (2.997925×10^8 m/s) of wave propagation.

Location Coordinates. Denote the known location of stations (A, B, C, D, etc.) and the unknown location of the vehicle or object as $\begin{bmatrix} x_1 \\ y_1 \\ z_1 \end{bmatrix}$, $\begin{bmatrix} x_2 \\ y_2 \\ z_2 \end{bmatrix}$, $\begin{bmatrix} x_3 \\ y_3 \\ z_3 \end{bmatrix}$, $\begin{bmatrix} x_4 \\ y_4 \\ z_4 \end{bmatrix}$, *etc*, and $\begin{bmatrix} x \\ y \\ z \end{bmatrix}$, respectively.

2.3 Time-of-Arrival (TOA) location scheme

In the TOA scheme, the main Object O (or vehicle) initiates the transmission of signals and times the responses of the replies from the reference stations A, B, C & D. For example, the Object first broadcasts signal S_A. Station A recognizes the signal and retransmits the same signal S_A after a short duration D_A. The Object clocks the time of flight T_{OAO} and computes $T_{OA} = (T_{OAO} - D_A)/2$. T_{OB}, T_{OC} & T_{OD} for the flights between the object O and Stations B, C & D are similarly determined. The distance OA, OB, OC & OD can therefore be calculated as r_1, r_2 & r_3. The location of O can be computed from

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \frac{1}{2} \begin{bmatrix} (x_2 - x_1) & (y_2 - y_1) & (z_2 - z_1) \\ (x_3 - x_2) & (y_3 - y_2) & (z_3 - z_2) \\ (x_4 - x_3) & (y_4 - y_3) & (z_4 - z_3) \\ (x_1 - x_4) & (y_1 - y_4) & (z_1 - z_4) \end{bmatrix}^{\#} *$$

$$\begin{bmatrix} (x_2^2 - x_1^2) + (y_2^2 - y_1^2) + (z_2^2 - z_1^2) - (r_2^2 - r_1^2) \\ (x_3^2 - x_2^2) + (y_3^2 - y_2^2) + (z_3^2 - z_2^2) - (r_3^2 - r_2^2) \\ (x_4^2 - x_3^2) + (y_4^2 - y_3^2) + (z_4^2 - z_3^2) - (r_4^2 - r_3^2) \\ (x_1^2 - x_4^2) + (y_1^2 - y_4^2) + (z_1^2 - z_4^2) - (r_1^2 - r_4^2) \end{bmatrix}$$

2.4 Time Difference-of-Arrival (TDOA) location scheme

In the TDOA scheme, one of the stations, say Station A takes the role of the master station that initiates the first transmission. Referring to Figure 2, Station A transmits Signal S_A at the clock instance C_A which is unknown to Stations B & C, and Object O. The Object clocks the arrival of S_A at the Object as time instance C_{AO}. Station B receives the signal S_A, delays for a duration of D_B, and transmit Signal S_B. The Object clocks *t*he arrival of S_B at the Object as time instance C_{BO}. Station C performs a similar operation and the arrival of Signal S_B is clocked by the Object as C_{CO}. The lower half of Figure 2 illustrates the time of arrivals $C_{AO,}$ C_{BO} & C_{CO}. Given the initialized locations of Stations A, B & C, the delays durations and these arrival times, we can determine the location of Object O.

A closed-form solution to the problem of determining location using TDOA information follows:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} r_1 + \begin{bmatrix} b_x \\ b_y \\ b_z \end{bmatrix}$$

$$\begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} = \begin{bmatrix} x_{2,1} & y_{2,1} & z_{2,1} \\ x_{3,1} & y_{3,1} & z_{3,1} \\ \vdots & \vdots & \vdots \\ x_{N,1} & y_{N,1} & z_{N,1} \end{bmatrix}^{\#} \begin{bmatrix} r_{2,1} \\ r_{3,1} \\ \vdots \\ r_{N,1} \end{bmatrix}$$

$$\begin{bmatrix} b_x \\ b_y \\ b_z \end{bmatrix} = \frac{1}{2} \begin{bmatrix} x_{2,1} & y_{2,1} & z_{2,1} \\ x_{3,1} & y_{3,1} & z_{3,1} \\ \vdots & \vdots & \vdots \\ x_{N,1} & y_{N,1} & z_{N,1} \end{bmatrix}^{\#} \begin{bmatrix} h_2^2 - h_1^2 - r_{2,1}^2 \\ h_3^2 - h_1^2 - r_{3,1}^2 \\ \vdots \\ h_N^2 - h_1^2 - r_{N,1}^2 \end{bmatrix}$$

$$(a_x^{\,2} + a_y^{\,2} + a_z^{\,2} - 1) r_1^{\,2} - 2(a_x(x_1 - b_x) + a_y(y_1 - b_y) + a_z(z_1 - b_z)) r_1 + (x_1 - b_x)^2 + (y_1 - b_y)^2 + (z_1 - b_z)^2 = 0$$

$$h_i^2 = x_i^2 + y_i^2 + y_i^2$$
$$x_{i,1} = x_i - x_1$$
$$y_{i,1} = y_i - y_1$$
$$z_{i,1} = z_i - z_1$$
$$r_{i,1} = r_i - r_1$$

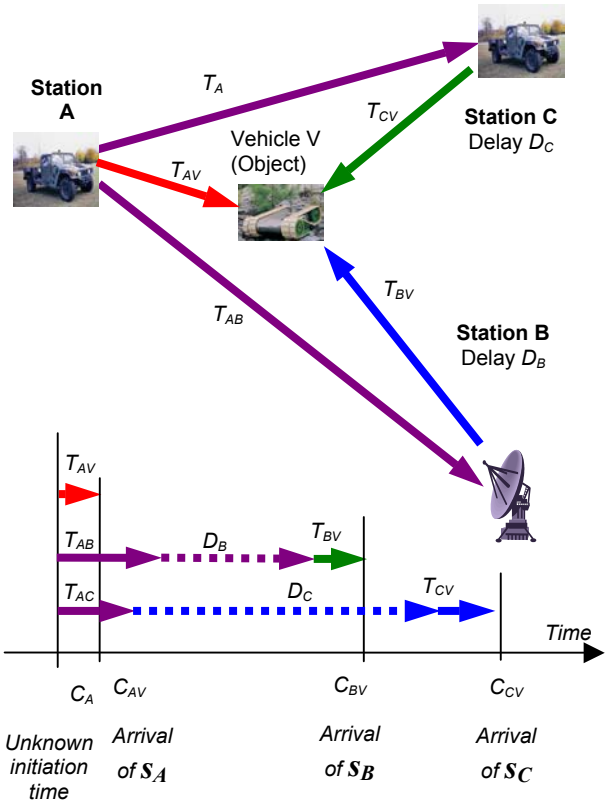

Figure 2. Time-difference of-arrival scheme

3. UWBRAC Scheme

3.1 Principle Overview

Figure 3 shows a UWBRAC scheme that uses amplitude modulation and digital correlation technique to determine the precision timing of the radio signals. The UWB digital codes s_A, s_B, & s_C (with chip rate of 0.1 – 2 Gbits/s) modulate the amplitude of a carrier signal (1 – 20 GHz), which is power amplified and transmitted via an antenna array. The received signals are demodulated and sampled at a sampling frequency higher (4 to 10 times) than the chip rate of the UWB signals. The sampled signal is sequenced and cross-correlated with the digital codes s_A, s_B, & s_C. The result yields accurate timing of signal arrivals and identification of the transmitting source in a single operation. This is extremely useful for self-organizing schemes.

3.2 RF Transmitter & Receiver

Application specific integrated circuits (ASIC) technology offers a persuasive means of boosting integration and reducing cost for developing high frequency radio transceivers. Figure 4 shows an electronics block configuration of a wideband RF transmitter & receiver. Current high-speed electronics can readily achieve RF frequencies at 400MHz to 2500MHz, and IF frequencies from 10MHz to 500MHz. For example, typical blocks to achieve 2500MHz RF and 500MHz IF may use the following components: MAX2641 for the LNA and Wideband Gain Blocks; MAX2682 for the Downconverter; MAX2660 for the Upconverter, MAX2620 for the RF & IF Oscillators; MAX9987 for the Dual RF & IF VCO Buffers, MAX2244 for the PA with AGC; MAX2308 for the I/Q Demodulator; and MAX2450 for the I/Q Modulator.

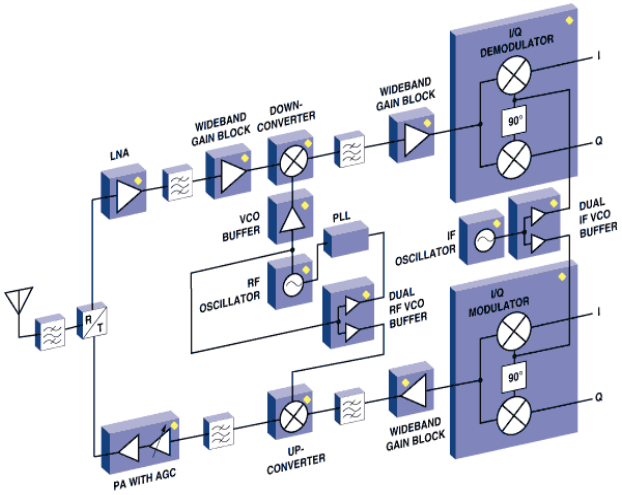

Figure 4. Electronics configuration for UWB RF transmitter & receiver

3.3 DS-CDMA Technique

The UWBRAC will use a direct sequence (DS) code division multiple access (CDMA) technique (e.g., Onodera et al), which has been employed in digital communication including fiber optics network and cellular phones. Figure 5 shows an example of a DS modulation and demodulation process together with an RF transmission. CDMA is achieved by assignment of various N-pulse code sequences. In the UWBRAC case, base stations and vehicles will have their own code sequences. The technique therefore lets a receiver simultaneously recognize the identity of the transmitting units, and decode the data or message it receives.

As an example, the transmitter may send a message (shown as In (Data) in the figure) at a data rate of 10Mbits/s, which is DS modulated by a PN code at a chip rate of 300Mbits/s. The DS modulated message is then up-converted to an RF of 3.0GHz for a wireless transmission. The receiver demodulates received RF into an IF (300Mbit/s) which is then sampled by a high-speed analog-to-digital converter at 1.5GSPS (giga-samples per sec) (e.g., NI ADC081000 8-bit 1.6GSPS A/D converter). The samples (shown as In) is then correlated with the PN code at the receiver. A digital correlator can be designed using high speed field programmable gated arrays (FPGA). An alternate analog approach would be to process the IF message with high speed switching electronics rather than use of high speed ADC and digital correlator.

For ranging purposes, time stamps for a match (peak) in correlation would be recorded. At 1.5GSPS, the time stamp interval would translate to a resolution of 0.2 meter. The time information will be processed by TOA or TDOA computation to produce desired estimate of the location.

CONCLUSION

The groundwork to substantiate the feasibility of realizing the proposed ad hoc mobile precision location network system was provided. It requires the state-of-the-art high speed electronics & microcomputers to realize the proposed UWBRAC and TOA/TDOA schemes today. The network would be beneficial for asset locations and navigation systems, including guidance of unmanned vehicle systems.

REFERENCE

"Ad hoc Mobile Precision Location Network using UWBRAC & TOA/TDOA Techniques," *US Patent 60/545,238*.

Angelides, J., "The Benefits of U-TDOA," www.wtb2.com

Bechler, D. & K Kroschel, "Reliable Measurement of Time Difference of Arrival Estimators for Multiple Sound Source Localization," *Institue fur Nachrichtentechnik*, Universitat Karlsruhe, Germany.

Belanger, S.P., "Multisensor TDOA Estimation in a Multipath Propagation Environment using Expectation-Maximum Algorithm," *Procs of the 29th Asilomar Conference on Signals, Systems and Computers*, Pacific Grove, CA, Oct 30 - Nov 02, 1995.

"Enabling high value location-based services," www.trueposition.com

Gustafsson, F. & F. Gunnarsson, "Positioning Time-Difference of Arrival Measurements," *Procs of the IEEEE ICASSP 2003.*

"Location methods for E-911 Phase II," www.raddcomm.com/E-911

"Method and System for Performing Ranging Function in an Ultrawide Bandwidth System," *US Patent Pub. No. US2003/0232620 A1.*

Onodera, K & Paul R Gray, "DS-CDMA Baseband Correlator for High Speed Wireless Application," view graph presentation

"System and Method for Position Determination by Impulse Radio," *US Patent Pub. No. US2003/01977643 A1.*

"Systems and Methods for Estimating Separation Distance between Impulse Radios using Impulse Signal Amplitude," *US Patent Pub. No. US 6,700,538 B1.*

Test & Measurement Catalog 2003/04, Agilent Technologies, www.agilent.com

"Time Difference of Arrival Principle," www.era.cz/en/tdoa.shtml

"Transmitter Location for Ultra-Wideband Transmitted-Reference CDMA Communication System," *US Patent Pub. No. US2003/0069025 A1.*

"Ultra-Wideband Geographic Location Systems & Method," *US Patent Pub. No. US2004/0002346 A1.*

"Ultra-high Performance Signal Control Equipment," www.gigabaudics.com

"White Cloud – Naval Ocean Surveillance Systems," www.fas.org/spp/military/program/noss.html

www.maxim-ic.com

Zhao, Y., "Standardization of Mobile Phone Positioning for 3G Systems," *IEEE Communications*, July 2002.

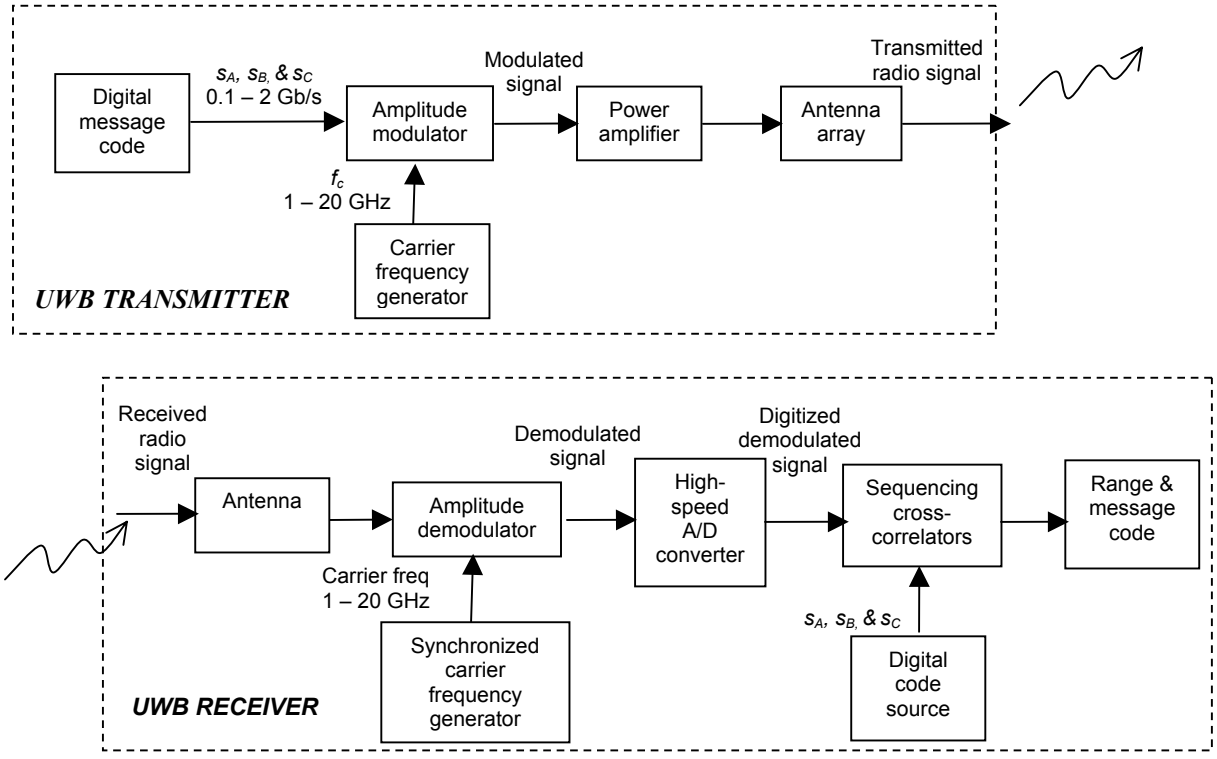

Figure 3. Function configuration for UWB RAC system

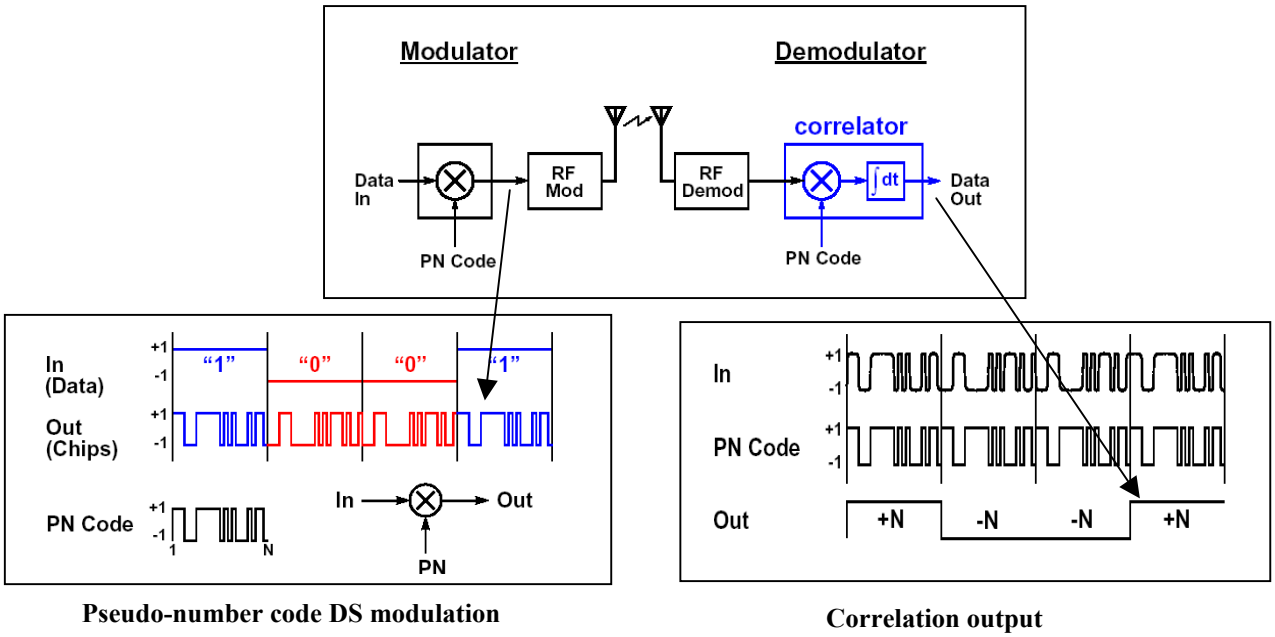

Figure 5. Illustration of DS-CDMA technique (Onodera et al)