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ULTRA WIDE BAND (UWB) BASED PRECISE POSITIONING SYSTEM FOR ROBOTICS

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ABSTRACT

The advent of the Global Positioning System (GPS) provided reliable and accurate position information worldwide for outdoor environment. However, many applications are emerging where position information is required and the environment or complexity considerations prohibit the use of GPS. As a result, areas as diverse as robotics, sensor networks, and ubiquitous computing have seen an increase in research in indoor position determination systems. While the majority of current work relies on laser, ultrasound, or narrowband RF for positioning, such techniques are severely limited in harsh environments with significant multipath and/or interference. In this paper we discuss the features of Ultra Wideband-Band (UWB) precise position system because of its usefulness in harsh environment, its ability to fuse accurate position-location with low-data rate communication, and its covertness for tactical applications. This paper presents the system design options for UWB based positioning systems, and shows how they match the indoor location demands of emergency services. This paper also presents the analysis of UWB RF Channel performance as a function of the major parameters, including bandwidth, frequency component spectral spacing, transmitted signal power, and range. These results facilitate the design of UWB positioning systems for specific environment.

KEYWORDS

OFDM, Impulse Radio, TDOA, PSD, CRB

I. INTRODUCTION

There has been a growing need for wireless systems that provide accurate position location. For example, indoor positioning to track personnel or assets in laboratories, robots, warehouses, and hospitals is becoming popular. Applications of wireless positioning for search-and-rescue operations by military commanders and fire fighters have become important because of increasing interest in security services.

2. OVERVIEW: UWB

Ultra Wide Band is a new technology, which has been recently introduced for wireless communication systems. The UWB signal is defined as any signal, which occupies a bandwidth larger than 500 MHz, or has a fractional bandwidth greater than 0.20. Due to its large bandwidth, an extremely fine time resolution (i.e. range resolution) can be achieved and consequently, this provides good potential for application in ranging and positioning.

UWB signaling consists of two different formats: the first is impulse radio (IR) that uses high bandwidth analog baseband pulses to carry information. The second is a multicarrier approach which relies on orthogonal-frequency-division-multiplexing (OFDM), with multiple subbands across the UWB spectrum. The multi Carrier signal structure used in an Orthogonal Frequency Domain Multiplexed (OFDM) signal consist of many sinusoidal subcarriers. Such a signal structure has a major advantage over the ultra wideband signals that are often proposed for performing precision location in high multipath environments, as it is easily adapted to conform to existing spectral allocations. This technique is also well suited for use on ad hoc wireless networks, allowing precise determination of locations of wireless nodes with respect to one another.

3. CONVENTIONAL POSITIONING OF ROBOTS

Robotics is an area which has had much success over its many years of existence. Mobile robots consist of many sensors to discover their environment and use the information about their environment for adaptation. Infrared and ultrasonic sensors are examples of such sensors.

The infrared signal has the same properties as visible light. It cannot pass through walls or obstructions; therefore, it has a rather limited range in indoor environments. However, the propagation speed is high, approximately 3×10^8 m/s. Thus, it requires more sophisticated circuitry than ultrasound signals. Indoor lighting interferes with this type of signal and causes problems in accurate sensing. It generally has a rangeof around 5 m. The infrared devices are usually small in size compared to ultrasound devices .

Ultrasonic transceivers, traditionally, are mounted with a transmitter and a receiver. The transmitter emits a ping (sound burst) which bounces off the nearest object and the receiver is always 'listening' for the return signal. Using a microcomputer with a built in timing device to detect the time of flight, it is possible to calculate the range of the object relative to the ultrasonic sonar. Ultrasonic transceivers have been used in position determination of robots because of their availability and cost. The ultrasonic position measuring system makes use of triangulation theory to determine the position of the transmitter (mounted on the robot) with respect to the known positions of the multiple receivers.

One of the clear downside of ultrasonic transceivers is the fact that air coupled ultrasound typically operates based on mechanical systems. Therefore, they become more sensitive to environmental impacts.

A single ultrasonic sensor element has a maximum of 180 degrees directivity pattern. Hence, more than one sensor element is needed for whole space coverage. Besides, a single ultrasound sensor pattern has a wide beam. Hence, an array consisting of several ultrasonic elements is necessary for more narrow beams. Moreover, ultrasonic waves are acoustical mechanical waves. Therefore, polarization of the received waves cannot be used to differ between direct received waves and indirect ones due to reflections.

4. POSITIONING WITH UWB

The radar community has been using signals similar to UWB pulse signals for ground-penetrating radars for many years. The reason why a communication scheme using narrow pulse signals has been proposed is because of their novel properties which possess advantages over conventional narrow-band or wide-band signals. First, range resolution is extremely fine, which provides a good potential for the applications in ranging and positioning.

The power spectral density of UWB systems is generally considered to be extremely low, especially for communication applications. The power spectral density (PSD) is defined as

$$PSD=P/B.$$

Where P is the power transmitted in Watts (W), B is the Bandwidth of the signal in Hertz (Hz) and the unit of PSD is Watts/Hz (W/Hz). Historically wireless communications have only used a narrow bandwidth and can hence have a relatively high power spectral density.

We know that frequency and time are inversely proportional, sinusoidal systems have narrow B and long time duration t. For a UWB system the pulses have a short t and very wide bandwidth (B). The energy used to transmit a wireless signal is not infinite and, in general, should be as low as possible, especially for today's consumer electronic devices. If we have fixed amount of energy we can either transmit a great deal of energy density over a small bandwidth or a very small amount of energy density over a large bandwidth.

For UWB systems the energy is spread out over a very large bandwidth (hence the name Ultra Wide Band) and, in general, is of a very low power spectral density. The major exception to this general rule of thumb is UWB radar systems which transmit high power over a large bandwidth. However, here we will restrict ourselves to the communications area.

UWB signal supplies the high bandwidth at a lower center frequency, which is advantageous for penetration of materials and for operation in shadowed environments. Resolvable multipath and the penetration capability enable UWB radio applications in complex multipath environments, including indoor wireless local area network (LAN). Furthermore, the absence of a sinusoidal carrier may allow simpler radio architecture because simply no intermediate frequency (IF) stage is necessary.

5. MC-UWB SYSTEM FOR POSITIONING

In UWB based positioning system, Multi Carrier (MC) techniques can efficiently combat frequency selective fading. Such robustness in presence of frequency selective fading is very useful, especially for applications involving high data rate. One of the problems with a single carrier signal structure is that as the symbol rate increases the symbol interval becomes shorter than the delay spread. A Multi Carrier signal structure solves this problem by decreasing the symbol rate and increasing the number of carriers. The basic idea behind the OFDM signal is to take a signal and send it over multiple low rate carriers instead of a single high rate carrier.

An OFDM signal consists of many sinusoidal subcarriers. These subcarriers are orthogonal and therefore do not overlap with each other. The advantages of using a Multi Carrier signal structure are listed below:

- Improved spectral efficiency
- Robust in fading environment
- Simplified equalization needed
- High data rate can be achieved
- Signal generation is simple

The structure of the OFDM signal proposed is of the form:

$$Sc(t) = \sum_{m=0}^{M-1} A_c e^{2\pi j\,(fo + m\Delta f)\,t + \Phi m}$$

Where M is the number of sinusoidal carriers with frequency spacing Δf and each carrier has arbitrary phase Φm. The signal proposed occupies a very wide bandwidth but each subcarrier occupies a very low portion of the total band and hence it is also called Multi band Ultra wideband (MB-UWB).

6. POSITION LOCATION ALGORITHM (TDOA) FOR MC-UWB

The proposed precise positioning system uses this MC-UWB signaling technique. The system uses four or more receivers to calculate a three dimensional position of the transmitter. The position location algorithms are based on Time Difference of Arrival technique (TDOA).

For the case of real signals, is described as follows the signal structure

$$S(t)=Sc(t)+ Sc^*(t) \quad (1)$$

$$Sc(t) = \sum_{m=0}^{M-1} A\,Cos(2\pi\,(fo + m\Delta f)\,t+\Phi m) \quad (2)$$

equation in terms of the sampled signal system as $\Delta f = K\delta f$ and $fo = Mof$, where $\delta f = fs/N$ is the DFT frequency sample separation.

$$S(t) = \sum_{m=0}^{M-1} A\,Cos(2\pi\,(Mo + mK)\,\delta f\,t+\Phi m) \quad (3)$$

If this signal is received at reference sites, with distances d_k from the source giving rise to propagation delays $\tau_k = d_k/c$, then each carrier component is shifted by a phase shift which depends both upon τ_k and the carriers frequency.

In equation (3) it may be noted that if the reference sites have synchronized clocks and the source clock has some unknown offset, this offset induces another unknown phase shift dependent on to carrier index. Let's now assume that the sampled received signal at the k_{th} reference is of the form

$\Psi_m = 2\pi\,(fo + m\Delta f)\,to$

for $n = 0\ldots N-1$ with DFT

$r_k(n) = s_k(n)+n_k(n)$

$$R_k(n) = S_k(n)+N_k(n) \quad (4)$$

The phase difference between adjacent carriers for the signal

The phase difference between adjacent carriers for the signal received at reference node k, S_k (M_o+mK) for $m = 0...M-1$, corrected for the known phases Φ_m satisfies

$$\begin{aligned}\Delta\theta_k &= \Phi_{mk} - \Phi_{m-1,\,k} - \Phi_m + \Phi_{m-1} \\ &= -2\pi\Delta f\,\tau_k + \Psi_m - \Psi_{m-1} \\ &= -2\pi\Delta f\,\tau_k + m\Delta\Psi \end{aligned} \quad (5)$$

Finally, the difference of the phases obtained as above for carrier m at two sites, q and r, is $\theta_{qr} = \Delta\theta_r - \Delta\theta_q$, from which we can recover the Time Difference of Arrival (TDOA) of the signals at those sites,

$$\Delta\tau_{qr} = -\,\theta_{qr}/2\pi\Delta f = (d_2 - d_1)/c \quad (6)$$

in which c is the velocity of the wave in our medium. by choosing Δf sufficiently small, we can make our TDOA solution unambiguous throughout a ranging cell which is defined by the locus of points within distance $R= c/\Delta f$ of any receiving site with respect to the particular robot.

7. CRAMER RAO BOUND FOR FREQUENCY ESTIMATION

Cramer and Rao suggested a lower bound on estimation of the delay accuracy (which reduces to the ranging accuracy) based on the bandwidth and the SNR of the received signal, often called Cramer Rao lower bound (CRLB).

The problem of estimating the frequencies of multiple, arbitrarily spaced, sinusoidal signals from a noisy linear combination provide an expression for the Cramer Rao Lower Bound (CRLB) for estimation of the frequency coefficient $\Delta\theta_k$, which expressed in terms of variables defined above, is

$$E\,\{\Delta\theta^2_k\} = (6/M^3)\,\sigma^2_n/|c_1| \quad (7)$$

where σ_n is the standard deviation of the additive white Gaussian noise (AWGN) associated with each frequency sample and c_1 is the amplitude of the complex sinusoid formed by the frequency sample values. CRB given in terms of total received power (P_s), total noise power (P_n) by

$$E\,\{\Delta\theta^2_k\} = 12\,P_n/M^2\,NP_s \quad (8)$$

since the time delay associated with the phase progression parameter is given by

$$\tau = \Delta\theta/2\pi K\delta f = N\Delta\theta/2\pi K f_s \quad (9)$$

We can write the CRB bound for the variance of the time estimates as

$$\sigma_\tau^2 = 3NP_n/\pi^2 K^2 f_s M^2 P_s^{\,2} \quad (10)$$

In the case of a heterodyne receiver in which a sub-band of width B Hz is sampled at rate $B = 2f_s$ for a time window of $T = N/2B$

$$\sigma_\tau^2 = 3N_o/8\pi^2 B^2\,T\,P_s^{\,2} \quad (11)$$

8. CRB FOR POSITION ESTIMATION AND RECEIVER SIDE COMBINED LOCATION PERFORMANCE FOR ROBOTS

A. Position Estimation

An estimate is obtained by combining the Cramer Rao Bound for the Time Difference Of Arrival (TDOA) estimate and the multi-carrier signal for positioning of robots. This expression was used to perform validation of our position estimator subsystem.

We can now combine the results of the last two sections to obtain the performance of the locator with respect to received signal characteristics. Furthermore, we will substitute particular sensor geometry into the equation in order to obtain a simple parameterized model.

Where in six sensors are used, three placed in the z=0 (ground level) plane in a triangle comprising the origin and two points *w* meters offset in the x and y directions from origin. The remaining three sensors are each *h* meters above the first set. Likewise, we fix the position of the robot at approximately *w* units from all the sensors, that is, essentially at the far corner of the cube, three sides of which are defined by the sensors. Inserting this geometry in equation (11) we can obtain CRB for the time of arrival estimation of positioning

$$\sigma_r = \frac{C\sqrt{6N_o}\sqrt{5h^2+2w^2}}{8\pi\sqrt{P_s}^{2}\, T\, B\, h} \qquad (12)$$

B. Receiver Combined RF Channel Performance

The performance of the RF channel over which these signals transit can be calculated using Friis formula. The Friis Transmission formula expresses the received power (P_s) in terms of the transmitted power (*Ptr*), the antenna gains etc.:

$$P_s = \frac{P_{tr}\, G_{tr}\, G_{rec}\, \lambda^2}{16\, \pi^2\, r_o^{\,2}} \qquad (13)$$

in which r_o is, as before, the distance from the target to the various sensors, and G_{tr} ,G_{rec} are the transmitting and receiving antenna power gains, respectively. If we take the antennas to be omni directional, then the antenna gains both become unity and may be omitted from the following equations. Finally, λ is the wavelength of the RF signal in meters.

Given a received signal with a noise figure (*NF*) and antenna temperature of T_a degrees Kelvin, then we can express the noise power spectral density of the received signal as

$$N_o = 4\, K_B T_a 10^{\,NF/10} \qquad (14)$$

where K_B Boltzmann's constant. We can now substitute these expressions for the noise power density and the received signal power into our earlier equation for the estimated standard deviation of location error. The particular geometry of target and sensor chosen before, omnidirectional antennas, a front end noise figure of 3 dB, antenna temperature of 290 K and a wavelength equal to the shortest wavelength in the signal (hence worst case attenuation, that associated with *f max*). With these substitutions we obtain

$$\sigma_r = \frac{38\times10^{-8}\sqrt{5h^2+2w^2}\;\, f_{max}\, w}{B\, h\, \sqrt{Ptr.T}} \qquad (15)$$

This can be further simplified by noting that *E =Ptr.T* is the energy in each period of the transmitted waveform and that $F=B/f_{max}$ is the fractional bandwidth of the signal. Thus, for the case under study:

$$\sigma_r = \frac{38\times10^{-8}\sqrt{5h^2+2w^2}\;\, w}{F\, h\, \sqrt{E}} \qquad (16)$$

Remarkable aspect of this result is that performance is not directly a function of the number of carriers used or the band in which these carriers are deployed, or the speed of the signal in its medium (c), but rather only of the geometry, the fractional bandwidth of the signal and the energy per signal period. Also remarkable is the high precision that can be achieved with relatively modest power levels and fractional bandwidths if the sensors and target are closely co-located. This is best seen by generating a system design graph from these equations which targets a given performance level.

We have a graph that relates the required values of *w,* with different values of *E* and *F* for the case of a robot location standard deviation of 10 cm and a height separation of sensors of 5 meters. The above analysis and simulation results can be used to construct precise positioning systems for robotics.

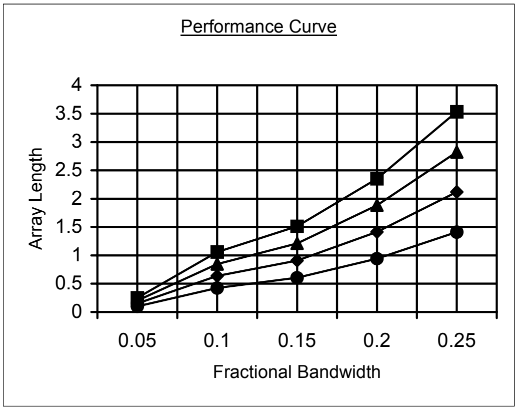

Figure 1 Performance curve generated from the design equations for the 6-sensor geometry targeted location with different transmitted signal power level

9. CONCLUSION

In the robot positioning system, performance analysis as a function of transmitted signal power and bandwidth and system geometry has yielded encouraging results and has produced performance equations, which can be used for design of positioning systems to achieve desired performance levels. For future work, we would like to investigate ranging in multipath environments. This is a major limiting factor in location determination using GPS in urban areas or indoors. A novel aspect of UWB ranging is the capability to detect the direct path signal accurately using the fine time resolution of an UWB signal.

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11. REFERENCES

[1] M.Ghavami, L. B. Michael, R. Kohno “Ultra Wideband Signals and systems in communication engineering” John Wiley & Sons, Ltd.

[2] S. M. Kay, “Spectrum Analysis - A Modern Perspective," Proc. IEEE, vol. 69, no. 11, pp. 1380-1419, Nov. 1981.

[3] B. D. Rao, K. S. Arun, “Model Based Processing of Signals: A State Space Approach," Proc. IEEE, vol. 80, no. 2, pp. 283-309, Feb. 1992.

[4] Y. Huang, J. Benesty, W. Elko, R. M. Mersereau, “Real-Time Passive Source Localization: A Practical Linear-Correction Least-Squares Approach," IEEE Trans. on Speech and Audio Processing, Vol. 9, no. 8, November 2001, pp. 943-956.

[5] J. D. Bard, F. M. Ham, W. L. Jones, “An Algebraic Solution of the Time Difference of Arrival Equations," Proceedings of IEEE South east con ’96, April 1996, pp.

[6] H. K. Parikh, W. R. Michalson and R. James Duckworth, “Performance Evaluation of the RF Receiver for Precision Positioning System”, Proc. Institute of Navigation GPS/GNSS 2004, September 21-24, Long Beach, CA.

[7] D. P. Young, C. M. Keller, D. W Bliss and K. W. Forsythe, “Ultra-wideband (UWB) transmitter location using time difference of arrival (TDOA) techniques”, Proc. IEEE Signals, Systems & Computers, 2003 November 9-12, Volume: 2, Pages: 1225

[8] H. R. Everett, “Sensors for Mobile Robots: Theory and Applications”, TJ211.415.E83, A K Peters, Ltd., Wellesley, MA., 1995