POSITIONING OF ROBOTS USING ULTRA-WIDEBAND SIGNALS

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Abstract: We believe that UWB is reasonable candidate for robots communication because of its low fading and good penetration. If a robot is already equipped with UWB electronics, can't it be used for positioning as well? In this paper we investigate the main theoretical concepts of ultra-wideband (UWB) as a candidate for accurate indoor geo-positioning technology. As a fundamental step we propose downsizing of Global Positioning System (GPS) using UWB. Basic principles of GPS and European GPS (GALILEO) are recalled. Open challenges and future work for this introductory contribution are concluded.

Keywords: UWB, robots, localization.

1. INTRODUCTION TO UWB

UWB is a sort of baseband communications in which very short duration pulses in the order of sub nanoseconds with very low power spectral density (- 41.5 dBm / MHz) are directly radiated to the air.

The origins of UWB technology lie in early work on time domain electromagnetics, which began in the early 1960s [4]. Until 1994 the core technology was developed variously as 'baseband', 'carrier-free' or 'impulse' communications under classified research programmes carried out by the US Department of Defense, which had identified its particular suitability for radar and highly secure communications [4]. In 1989 the term 'ultra wideband' or 'UWB', was coined by the Department of Defense and since 1994 development work has been carried out for civil applications.

UWB presents a compelling solution to many of the challenges facing today’s wireless industry and applications. These include [5]:

- **Transmission**: Unlike carrier-based systems which works on a specific carrier frequency, UWB works by transmitting a radio signal over a wide swath of frequencies, including both licensed and unlicensed spectrum which will open up a vast new applications.

- **Low power and coexistence**: Because the transmission power is spread across such a wide range of spectrum, the energy of each transmitted pulse is very low - at or beneath the level of the noise floor. Hence, UWB can be considered as a secure wireless communication and can coexist, theoretically without interference, with other radio communications systems.

- **Accurate positioning**: Thanks to the very short duration of the transmitted pulses, UWB technology offers inexpensive location with accuracy to within centimeter resolution.
Since 1998 the Federal Communications Commission (FCC) has gradually relaxed regulatory restrictions on commercially developing UWB technology for the usage of the whole spectrum, and a number of private companies have openly developed UWB technology for both military and civilian purposes [5]. According to FCC, a radiator is defined as UWB transmitter if it has a fractional bandwidth (FB) equal or greater than 0.2, where
\[
FB = \frac{\text{Signalbandwidth}}{\text{CenterFrequency}} = \frac{f_h - f_l}{(f_h + f_l)/2}.
\]
\(f_h, f_l\) are the higher and the lower 10 dB points of the signal spectrum, respectively. Alternatively, it has a UWB bandwidth equal to or greater than 500 MHz regardless the fractional bandwidth.

This paper is organized as follows. In section 2 we review briefly conventional positioning methods of robots. In section 3 the theoretical basics for some attractive ranging characteristics of UWB technology are investigated. Besides, basic principles of GPS as an important existing location system is discussed. Then downsizing of GPS is proposed for indoor positioning of robots. Furthermore, the basic principles behind GALILEO are recalled. In section 4 other related topics such as communication among robots are investigated. Finally, in section 5 we present some conclusions and discuss open challenges for future research.

2. CONVENTIONAL POSITIONING OF ROBOTS

Robotics is an area which has had much success over its many years of existence [12]. Mobile robots rely on many sensors to discover their environment and use the information about their environment for adaption. H.R. Everett, [12], has essentially classified sensors into 2 categories: (1) Visual sensors and (2) Non-visual sensors. Sensors are used for a variety of issues such as collision avoidance and position determination. Both of these issues can and have been addressed with ultrasonic sensors.

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 micro-computer 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, cost and ease of use [1]. There, the ultrasonic position measuring system will make 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 downsides of ultrasonic transceivers is the fact that air coupled ultrasound typically operates based on mechanical systems. Therefore, they become more sensitive environmental impacts. A single ultrasonic sensor element has a maximum of 180 degrees directivity pattern [15]. Hence, more than one sensor element is needed for whole space coverage. Besides, a single ultrasound sensor pattern has a wide beam [15]. 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 can not be used to differ between direct received waves and indirect ones due to reflections. Note that polarization of a radiated wave is simply defined as the direction of the electrostatic field of this wave which is only makes sense in Electromagnetic (EM) waves propagation [14]. On the other hand, UWB systems are clean electronic systems based on EM waves.

Speed of sound in air is nominally 344m/s at 25 degrees centigrade. This leads to a resolution of few millimeters for ultrasonic transceivers. Due to the speed of EM waves (= 3 × 10^8 m/sec), UWB can provide accuracy of few centimeters which is sufficient for positioning of robots applications. It is worth to mention that at least 1GHz analog-to-digital (A/D) converter is required for UWB applications. It is available in the main time and expected to be cheaper in the coming 3 years.

3. POSITIONING WITH UWB

3.1 Motivation

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 more 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.

The radar community has been using signals similar to UWB pulse signals for ground-penetrating radars for many years [6]. The reason why a communication scheme using a 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 radar range resolution $\Delta r$ is defined as [6]:

$$\Delta r = \frac{c}{2B}.$$  \hfill (2)

where $B$ is the bandwidth of the signal and $c$ is the speed of light ($= 3 \times 10^8$ m/sec) for EM wave propagation.

![Fig. 1. Power spectral density (PSD) of typical UWB pulse.](image)

Fig. 1 demonstrates that the 10 dB bandwidth of the signal is approximately 2 GHz. The inverse proportionality to the twice of the bandwidth makes the inherent range resolution of UWB signals 100 to 1000 times finer than that of narrowband signals. Secondly, UWB signal supplies that 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 a vision of potential UWB radio applications in complex multipath environments, including indoor wireless local area network (LAN). Furthermore, the absence of a sinusoidal carrier may allow a simpler radio architecture because simply no intermediate frequency (IF) stage is necessary [6].

Moreover, 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 in $E_b/N_0$ of the received signal, often called Cramer Rao lower bound (CRLB) [9]. The equation indicates that the impact of the SNR to CRLB is linear, while the impact of the bandwidth is quadratic. In this respect, UWB is a good candidate for accurate ranging.

![Fig. 2. Low bound of ranging errors.](image)

Fig. 2 shows CRLBs on the ranging error in terms of SNR for the four different bandwidths, 0.5 GHz, 0.75 GHz, 1 GHz, and 3.3 GHz. The figure indicates that the theoretical low bounds are less than 5 cm for the entire range of the SNR experimented under the bandwidth of 3.3 GHz.

### 3.2 Navigating with GPS

There are many existing indoor and outdoor positioning systems which use different technologies and algorithms to accomplish the positioning task. Among them, the most famous GPS system, which is based on radio time-of-flight lateration, allows accuracy of 1-5 meters only in outdoor areas [7].

- **Satellite Constellation:** To provide a continuous global positioning capability, a scheme to orbit a sufficient number of satellites to ensure that (at least) four were always electronically visible was developed for GPS. Several schemes were proposed and it was found that 21 degrees evenly spaced satellites placed in circular 12-hour orbits inclined 55 degrees to the equatorial plane would provide the desired coverage for the least expense. In any event, this constellation provides a minimum of four satellites in good geometric position 24 hours per day anywhere on the earth [8].

- **Point Positioning:** The GPS satellites are configured, primarily, to provide the user with the capability of determining his position, expressed for example by latitude, longitude, and elevation. This is accomplished...
by the simple resection process using the distances measured to satellites.

Consider the satellites frozen in space at a given instant. The space coordinates \( \vec{d}_S \) relative to the earth of each satellite, see Fig. 3, is known.

![Fig. 3. Principle of satellite positioning](image)

If the ground receiver defined by its geocentric position vector \( \vec{d}_R \) employed a clock that was set precisely to GPS system time, the true distance or range \( \| \vec{d} \| \) to each satellite could be accurately measured by recording the time required for the satellite signal to reach the receiver. Each range defines a sphere (more precisely: surface of a sphere) with its center at the satellite. Hence, using this technique, ranges to only three satellites would be needed since the intersection of three spheres yields the three unknowns (e.g., latitude, longitude, and height) which could be determined from the three range equations [8]

\[
\| \vec{d}_R \| = \| \vec{d}_S - \vec{d} \|. \tag{4}
\]

GPS receivers apply a slightly different technique. They typically use an inexpensive crystal clock which is set approximately to GPS time [8]. Thus, the clock of the ground receiver is offset from true GPS time, and because of this offset, the distance measured to the satellite is slightly longer or shorter than the "true" range. The receiver can overcome this problem by measuring the distance to four satellites (simultaneously) [8]. Note that the four satellites are fitted with an atomic clock measuring time very accurately for perfect synchronization. These distances are called pseudoranges since they are the true range plus a small (positive or negative) range correction \( \Delta d \) resulting for the receiver clock error or bias \( \delta \). A simple model for the pseudorange is [7]

\[
\| \vec{d} \| = c \, \Delta t + \Delta d = c \, \Delta t + c \, \delta \tag{5}
\]

with \( \Delta t \) being the propagation delay between one of the satellites and the GPS receiver.

The point position can be solved by resection as before except that now four pseudoranges are needed to solve for the four unknowns; these are three components of position plus the clock bias.

Downsizing of GPS is proposed here as an indoor UWB positioning system. On behalf of the four satellites, four wired-connected access points will be replaced as shown in Fig. 4. The travelling time of the signal between these access points will be taken into account for perfect synchronization and hence, accurate pseudorange measurements.

![Fig. 4. Downsizing of GPS for indoor positioning](image)

Let us assume that the access points A and the robot are located, relative to an arbitrary point, at \((x_A, y_A, z_A)\) and \((x_0, y_0, z_0)\) respectively. Hence, the pseudorange between the robot and access point A \((d_{A0})\) could be written as

\[
\| \vec{d}_{A0} \| = c \, \Delta t_{A0} + \Delta d \\
= \sqrt{(x_0 - x_A)^2 + (y_0 - y_A)^2 + (z_0 - z_A)^2} + c \, \delta \tag{6}
\]

where \( \delta \) is the clock error between the robot and the access point and \( \Delta t_{A0} \) is the propagation time of the EM wave from access point A to the robot which could be calculated as the duration between 2 successive received pulses taking into account the processing time at the access point and the robot and assuming no reflections are taking place.

Similarly, we can write the following three equations:

\[
\| \vec{d}_{B0} \| = c \, \Delta t_{B0} + \Delta d \\
= \sqrt{(x_0 - x_B)^2 + (y_0 - y_B)^2 + (z_0 - z_B)^2} + c \, \delta \tag{7}
\]
activity to a range of high-bandwidth services and
few meters). It will also enable wireless connec-
distances (up to several hundred Mbits/s over a
accurate positioning systems but also for high-
is not only a promising technology for indoor
with a third-party is absolutely necessary. UWB
goal in some situations where communication be-
Positioning of robots, however, is not the main
calculate the exact position.

From equations (6), (7), (8) and (9) \((x_0, y_0, z_0, \delta)\) could be calculated and hence the robot location.

Note that, in this scenario, it is assumed that the robot will locate himself. It is also possible that the access points will locate him. In this case the transmission of EM waves should be from the robot side.

### 3.3 Navigating with GALILEO

In few years the GALILEO satellite radio navigation system, an initiative launched by the European Union and the European Space Agency will ensure complementarity with the current GPS system [13].

GALILEO is based on a constellation of 30 satellites and ground stations providing information concerning the positioning of users in many sectors [13].

The operating principle is quite similar to GPS. It is summarized as follows [13]:

The satellites in the constellation are fitted with an atomic clock for perfect synchronization. Each satellite emits personalised signal. The ground receiver has in its memory the precise details of the location of all the satellites in the space. By analyzing the incoming signal, it can thus recognize the particular satellite, determine the time taken by the signal to arrive and calculate the distance from the satellite. Reception from at least four satellites simultaneously is needed to calculate the exact position.

### 4. RELATED TOPICS

Positioning of robots, however, is not the main goal in some situations where communication between more than one robot or communication with a third-party is absolutely necessary. UWB is not only a promising technology for indoor accurate positioning systems but also for high-speed, secure wireless data connections over short distances (up to several hundred Mbits/s over a few meters). It will also enable wireless connectivity to a range of high-bandwidth services and applications that cannot be served by the limited capabilities of Bluetooth and infrared (IrDA).

The most popular current modulation schemes are Pulse-Position Modulation (PPM), Pulse-Amplitude Modulation (PAM) and Orthogonal Frequency Division Multiplex (OFDM), whereas the extensions Direct Sequence (DS) and Time Hopping (TH) enable multiple accesses to the common transmission medium.

PPM encodes the data through different positions in time and PAM encodes the data through signal amplitudes. TH assigns to multiple different codes, where the codes in turn represent a particular pattern in a series of pulses per transmitted bit, i.e. the transmitted signal in time hopping is represented by

\[
s^k(t) = \sum_{j=-\infty}^{\infty} p(t-jT_f - c^k_jT_c - \delta b^k_j (\frac{1}{T_p})). \quad (10)
\]

Here, \(p(t)\) with duration \(T_p\) represents the transmitted monocyte waveform. \(T_f\) represents the pulse repetition time which is typically a hundred to a thousand times the monocyte length leading to a very low duty cycle, i.e. \(\frac{T_f}{T_p} \ll 1\).

Superscript \(k\) denotes the user \(k\) assumed in multi-user environment. So, the signal emitted by user \(k\) consists of monocytes shifted to different times, the \(j\)-th monocyte nominally begin at time \(jT_f - c^k_jT_c - \delta b^k_j (\frac{1}{T_p})\).

If multiple-access signals would have been composed only with uniformly spaced pulses then a perfect chance for catastrophic collisions can occur, where a large number of pulses from two signals are received at the same time instants and this can corrupt irreversibly the message. Therefore, a random (or pseudorandom) time hopping sequence \(c^k_j\) is employed. These sequences have a period \(N_p\) with each element a finite integer in the range \(0,1,...,N_p-1\). Each element has a chip duration of \(T_c\).

Thus, this code provides an additional time shift to each pulse in the pulse train, with the \(j\)-th monocyte additionally shifted with \(c^k_jT_c\) seconds. Hence the added time shifts caused by the code are discrete between 0 and \(N_p T_c\) seconds. Also the greatest shift generated by the code \((N_p T_c\) seconds) is required to be less than the length of the basic train pulses period \(T_f\). The additional shift of \(\delta\) is to differ between the sequence representing bit 0 \((b = 0)\) and the one representing bit 1 \((b = 1)\). This additional time shift could be chosen to be greater than or equal the chip duration \(T_c\). Hence, the two sequences become fully orthogonal to each other and better performance could be achieved. See [1] for more information about modulation techniques and higher data rates in
UWB. Recently, wireless sensor networking has been becoming a disruptive technology in such fields as industrial control and monitoring, building automation, security and automotive sensing [3]. In many applications that use sensing, the devices will be battery powered where their replacement or recharging in relatively short intervals is impractical; therefore the power consumption is of significant concern. Due to the ultra low power consumption of UWB technology and its coexistence, we believe that it is also a promising candidate for wireless sensor networking.

5. CONCLUSIONS AND OPEN CHALLENGES

As have been illustrated in this contribution UWB transmission has a number of distinct advantages over carrier-based systems. The fundamental physics of UWB mean that it has extremely good radio propagation characteristics; it has proved highly resistant to external radio frequency (RF) interference (from other communications systems) and also to ‘object interface’ from both natural and most manmade materials. These key issues lead us to safely say that UWB radio is a candidate for future communications and ranging applications to augment existing narrow-band systems.

Besides, conventional positioning of robots using ultrasound transceivers has been investigated. Furthermore, basic concepts behind GPS as one of the most famous positioning systems have been recalled. Then downsizing for GPS is proposed for indoor UWB ranging systems. Moreover, navigating with GALILEO has been discussed.

The UWB technology holds some further features like cheap transmitters because mixer and oscillator are not required. Besides, jamming in UWB is already rather difficult because of the low spectral density, but the UWB inherent ranging facility further complicates jamming. This might be beneficial in particular for intrusion detectors [2]. TH and multiband OFDM have been proposed as ways of indoor communication between robots. At last but not least, we can safely say that by using UWB technology positioning, communication and sensing can be achieved by one single frontend, i.e. the antenna(s) can be used for all three purposes. This may reduce complexity significantly and leads to space savings.

For future work, we would like to investigate ranging in multipath environments. This is a major limiting factor in location 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. However, it is still an open problem because of a number of unknown spatial variables which make the characterization of UWB signal propagation rather complicated.

REFERENCES