A UWB based Localization System for Indoor Robot Navigation

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Abstract — **For robots to become more popular for domestic applications, the short comings of current indoor navigation technologies have to be overcome. In this paper we propose the use of UWB-IR for indoor robot navigation. Various parts of an actual implementation of a UWB-IR based robot navigation system such as system architecture, RF sub-system design, antennas and localization algorithms are discussed. It is shown that by properly addressing the various issues, a localization error of less than 25cm can be achieved at all points within a realistic indoor localization space.**

Index Terms — **UWB localization, robot navigation.**

I. Introduction

The popular use of robots in homes is expected to become a reality in the future. According to the International Federation of Robotics, about 2 million personal robots were in use around the world in 2004 and another 7 million will be installed by 2008 [1]. To increase the use of robots in homes, one of the major problems to be overcome is the difficulty in autonomous navigation within the cluttered home environment. While some solutions are available for autonomous navigation, they are still very primitive compared to the navigation abilities of a human. Thus further improvements in the navigational abilities of robots in the home or indoor environment would be necessary to bring forward the date by which one can be expected in every home.

II. Robot navigation technologies

For robot navigation, several technologies are currently in use. They can be broadly classified into odometry, ultra-sound and infra-red based systems or hybrid systems making use of a combination of these technologies.

Odometry makes use of information from wheel encoders to keep track of the distance moved in any particular direction. This methodology can be used together or separately from inertia based methods where gyroscopes and accelerometers are used to track the heading direction and linear movement of the robot. The most significant problem with this method is that the errors are cumulative. Hence, large errors in the position estimation can be expected unless some reference points are used to periodically calibrate out the errors. Also, domestic robots of the future would be expected to use some kind of limbs to climb stairs and handle uneven floors. Thus encoders that rely on the movement of the servo motors to track the robot location can lead to gross errors in the estimation. This is especially so when the robot encounters some kind of slipping due to smooth floors or missed steps.

Infra-red (IR) based methods for robot navigation have proven to provide low cost and highly precise solutions. The application scenarios are however limited by several inherent shortcomings of the technology. The most serious problem is that the system is badly affected by ambient sources of infra-red. So in highly lit rooms and rooms filled with people, the receivers easily get saturated and loose their accuracy. Such problems are not faced in typical IR communication applications such as in remote controls because the data rate is very low. But for localization applications, the sensitivity and linearity of the receiver greatly affects the performance. Another inherent problem of infra-red localization is the narrow field of vision and occlusion by even very thin opaque materials. This once again is different from the every day scenario where a remote control is able to work even when the line-of-sight (LOS) to the receiver is blocked. In that case, the reflections off the walls of the rooms would be sufficient for the very low rate communications. The difference can be appreciated when one attempts to do a high speed data transfer between the IR ports of two devices such as a mobile phone and a laptop. It will be seen that the range is very short and that the transceiver lenses have to be aligned rather precisely.

Ultra-sound is another technology that is heavily used for robot navigation. However, the common use is for the robot to find the distance between itself and some wall that it is facing. It transmits an ultra-sound pulse and listens for the echo, and from the time difference, calculates the distance between itself and the reflector (or wall). The less common application is for the robot to use a set of ultra-sound reference beacons. The time-of-arrival of the reference transmissions at the robot is used to find the range between itself and the transmitting beacon. Using three or more ranges, the robot is able to triangulate its position. Though ultra-sound technology is able to give very precise ranges, it suffers from some serious problems. Firstly, the performance of the system degrades significantly in the presence of clutter. This would certainly be the case in most domestic environments. The ranging accuracy is also affected by the presence of sharp corners such as those from walls, cabinets and other everyday items. Ultra-

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sound is also affected by ambient noise as in the presence of loud music or large number of people.

Due to the above problems with the current technologies for indoor robot navigation, we propose UWB-IR as an alternative technology for indoor robot navigation. In this paper we discuss the various issues related to implementing a UWB-IR based robot navigation system. The system architecture, component design, algorithms and results obtained from an actual implementation of UWB-IR based robot navigation system will be discussed in the following sections.

UWB-IR or Ultra-Wideband Impulse Radio makes use of narrow pulses. The narrow pulses provide a fine temporal resolution and hence help to achieve high ranging accuracy [2]. Also, using narrow pulses helps to mitigate the effects of the serious phenomenon of 'multipath' faced in indoor communications. Besides being robust to multipath, it should be noted that UWB-IR is able to provide unprecedented centimeter level accuracies at low data rates or pulse repetition frequencies. This is in contrast with conventional spread spectrum based systems which would need data rates in excess of a Gigabit to provide such accuracies indoors. Furthermore, although the instantaneous levels of the transmitted pulses may be high, the average power emission is very low. Hence, UWB is able to share the spectrum with existing narrowband wireless technologies.

III. System Design

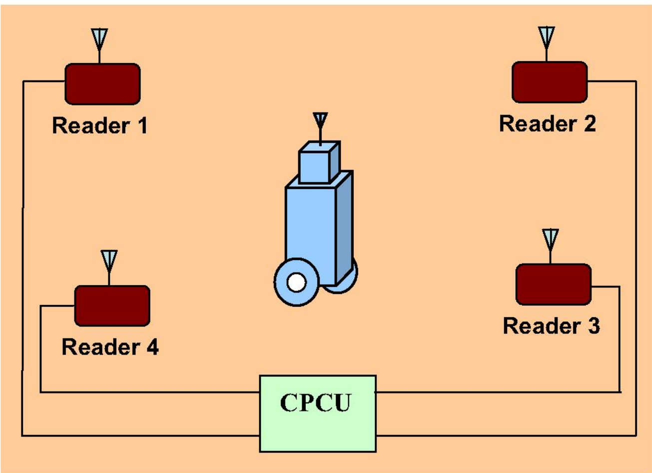

Fig. 1: TDOA based UWB localization system

The overall schematic of the localization system is shown in Fig. 1. It consists of 4 ceiling mounted reference nodes or Readers. The 4 Readers are connected to the Central Processing and Control Unit (CPCU).

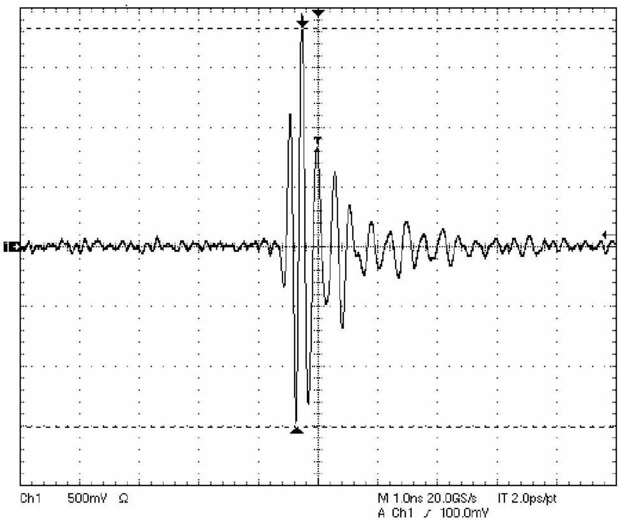

Fig.2a UWB pulses transmitted by mobile Tag

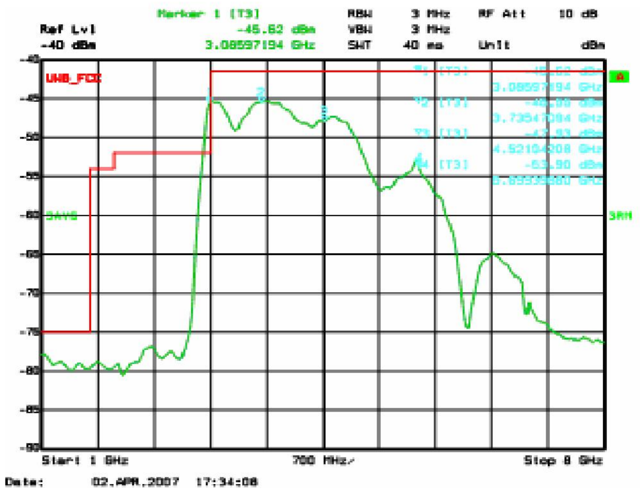

Fig. 2b: Spectrum of mobile Tag output

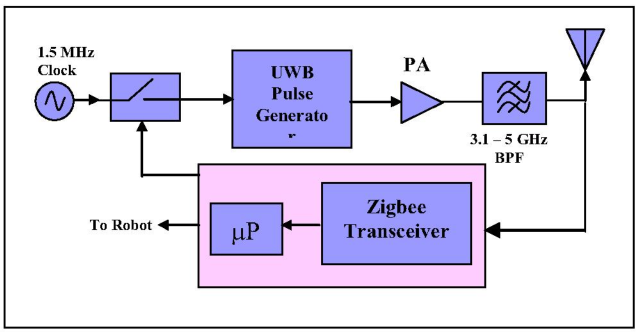

Fig. 3: Schematic of UWB transmitter in Tag

The methodology used for the localization is Time-Difference-of-Arrival. The mobile tag is mounted on the robot and it transmits a stream of UWB pulses (Fig 2a.). These narrow pulses have a spectrum (Fig. 2b) that conforms to the FCC regulations for UWB. The pulses are received by the 4 Readers and down-converted to baseband pulses. The schematic for the UWB transmitter in the Tag is shown in Fig. 3. A 1.5 MHz clock is used trigger a UWB pulse generator. The pulse is then amplified and then filtered by a 3.1 to 5 GHz bandpass filter. The mobile tag also has a Zigbee transceiver and built-in microprocessor. The Zigbee transceiver is used to receive control signals from the CPCU instructing when to transmit the UWB pulses. While it may be argued that the UWB radio itself can be used for the controls and communication, no particular advantage is seen in doing so. This is especially because at the current moment, no low rate UWB ICs are available in the market. In the future when such ICs are available, using UWB for localization and communication at the same time would certainly be considered. Due to the use of same antenna for Zigbee as well as UWB, an antenna with bandwidth of 2.2 to 6 GHz is used.

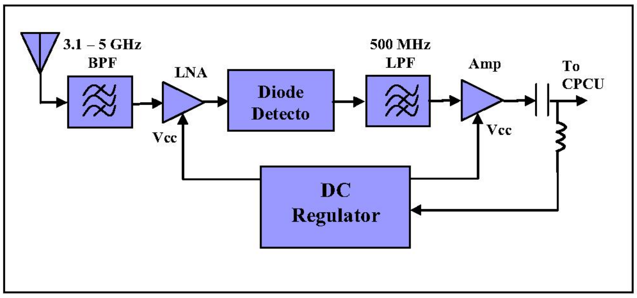

Fig. 4 Schematic of Reader receiver

The pulses transmitted by the mobile tag are received by the 4 Readers. The receiver architecture is shown in Fig. 4. At the front of the receiver, a 3.1 to 5 GHz bandpass filter is used to reject interference from wireless LAN and other out-of-band interferers. The filter is followed by an LNA, diode detector and 500MHz LPF. The LPF is necessary to reject the RF leakage and also smoothen the outgoing pulse to the CPCU. At the CPCU, the baseband pulses are input into an FPGA. All the Readers are connected to the CPCU by coaxial cables. The cables are also used to transmit DC power to the Readers from the CPCU. The use of cables greatly simplifies the architecture as all baseband processing and circuitry can be avoided in the Readers. In this way, the cost of the Readers is kept very low. The necessity to keep the cost of the Readers low will be seen later when the multi-cell localization system is discussed. The cables provide a fixed delay between the time the pulses are received at the Readers and the time at which they are detected by the FPGA. These fixed delays or offsets can be corrected easily through a one-time calibration of the setup.

The Readers for the system are ceiling mounted to reduce the chances of the line-of-sight between the mobile Tag and the Readers being occluded by objects. For this reason, the mobile Tag antenna is mounted at the top of the Robot. Going by the geometry of the localization space and the position of the receiving and transmitting antennas, it is easy to assume that a broad-side antenna pattern would be a good choice.

However, there are also other factors to be taken into account before choosing the antenna with the most suitable radiation pattern. It has been shown [3] that the pulse energy to noise ratio (E_p/N_0) critically affects the timing jitter of the received signals and in turn the accuracy of a ranging or localization system. As the noise (N_0) is determined by the bandwidth and components used in the receiver, it remains unaffected by the position of the transmitter and receiver antennas. While the receiver gain can be adjusted using open or closed-loop variable gain controls, it should be noted that the first stage low noise amplifier (LNA) is most often of fixed gain. It is only the later RF or IF stages that may have variable gain capabilities. Consequently, the receiver noise figure and hence the E_p/N_0 is only very minimally affected by the variation in receiver gain. The other component of E_p/N_0, the pulse energy (E_p), however is significantly affected by the combined effect of the gain patterns of the transmit and receive antennas and the range between them.

Thus the radiation pattern of both the mobile tag antennas and reference reader antennas in a localization system have to be carefully chosen to ensure that the accuracy is not greatly affected by the position of the tracked object in the localization space. By ensuring minimal variation in the received power at the antenna port, more consistent localization results can be expected at all points within the localization space.

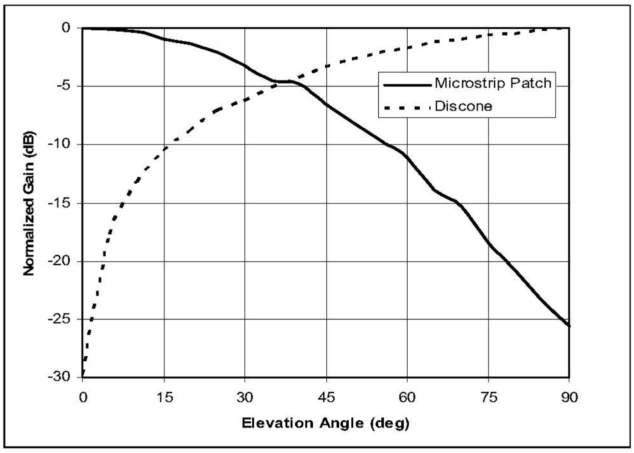

Fig. 5 Radiation pattern of Patch and Discone antennas

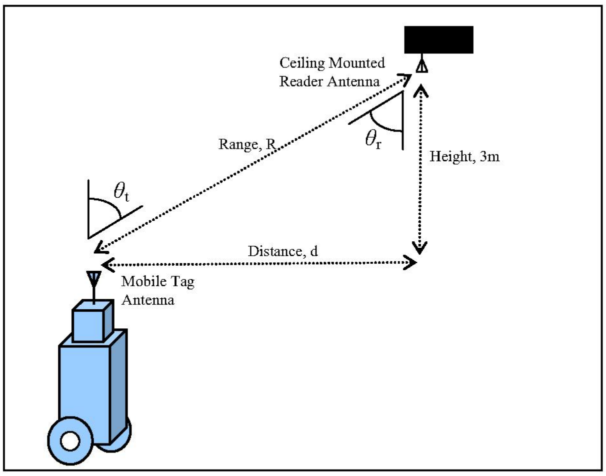

Fig. 6 Relative orientation of mobile Tag and Reader antennas

In order to illustrate the various considerations in the choice of the antennas, let us consider two types of antennas. One is a discone [4], another is a wideband aperture coupled microstrip patch[5]. The antennas have distinct patterns, which are representative of those typically exhibited by dipole/monopole and patch type of antennas. The radiation pattern of these antennas at 3.5 GHz is shown in Fig. 5. The relative orientation of the antenna on the mobile Tag and the antenna on the ceiling mounted Reader is shown in Fig. 6. Using the radiation pattern and Friis pathloss formula, the relative change in received power can be expressed as

$$\Delta P_r(dB) = [10\log G_t(\tan^{-1}(d/3) + 10\log G_r(\tan^{-1}(d/3) - 10\log(d^2+3^2)] - [10\log G_t(0)) + 10\log G_r(0) - 10\log(3^2)] \quad (1)$$

Where ΔP_r is the change in the power of the received signal, $G_t(\theta_t)$ and $G_r(\theta_r)$ are the gain along the line-of-sight direction between the transmit and receive antennas respectively.

The calculated results are plotted in Fig. 7. It is seen that using discone antennas causes very little variation in received power from 2 to 8 metres. In comparison, using patch antennas results in almost 50 dB variation in received power. Thus discone antennas are shown to be more suited for this application. Of course, it should be acknowledged that the discone is a 3-dimensional antenna, and so due to its weight and cost, may not be favored for use in tags. However, there are many planar antennas which have been shown to have similar radiation patterns and bandwidth characteristics as the discone [6] and hence would be found to be equally suitable for this application.

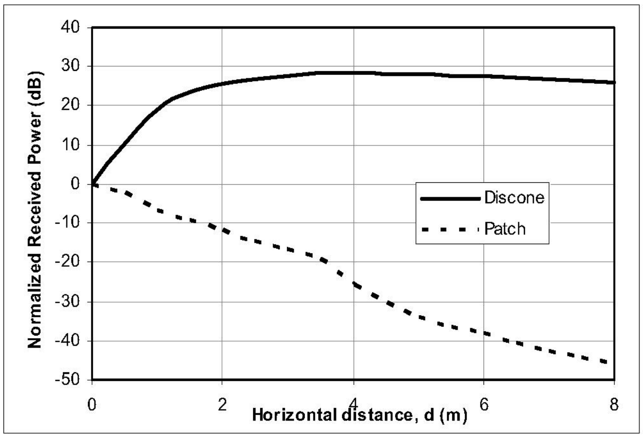

Fig. 7 Received power variation with distance

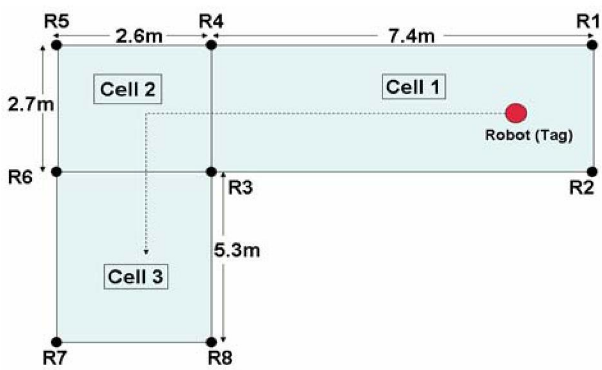

Fig. 8 Geometry of localization space

IV. ALGORITHM

The low transmit levels stipulated for UWB by the various regulatory bodies has resulted in a rather short range between the mobile Tag and Readers. So in order to cover large areas, the localization space has to be divided into several cells. The localization space of the robot navigation application considered in this paper is shown in Fig. 8. It consists of 3 cells monitored by 8 Readers. It is seen that the number of Readers has increased by 2 times as compared to a single cell system. It is for this reason that the Reader architecture is kept very simple. In this way, a multi-cell implementation to cover large spaces remains cost effective.

Although the multi-cell implementation appears to be just a simple extension of the single cell, there is the important issue of overlapped cell coverage to be addressed. A robust technique is needed to handle the NLOS condition that arises due to the blockage by the walls and also the errors that appear at inter-cell boundaries.

While many works can be found in the literature on various techniques to handle NLOS conditions in UWB localization, a few factors have to be considered in choosing the most suitable algorithm. It is found that when the direct path between the transmitter and receiver is blocked, in most circumstances the received multipath signals are of rather very low amplitudes and even lower than the levels set for threshold detection by the baseband circuitry. In these cases, the system is simply unable to make use of the received signals and hence the algorithm is rendered useless though it has the capacity to handle NLOS conditions. Of course a more complex architecture consisting of multi-bit ADCs may be able to make use of the advanced algorithms. But such implementations will be expensive and are still not expected to give the high precision that UWB-IR is capable of. It should be remembered that UWB-IR will be found suitable for robot navigation in the indoor environment, such as homes and offices, only if it is able to provide high precision at low complexity and cost. Thus it appears that the best way to handle NLOS condition is to avoid it as much as possible by choosing the Reader positions judiciously and having greater redundancy in the number of Readers. Once this is done, Chan's method [7] which takes advantage of redundant Time-of-Arrival information is found to provide a very accurate estimate of the mobile tag's position within each cell. However, at cell boundaries, as mentioned, the estimation using information from one set of Readers may be less accurate than those of the adjoining cell [8,9]. Hence, a heuristics based approach is used to choose the best estimate at these boundaries. Basically, a prediction of the Robot's path is made based on current speed and past direction of movement. The error between the various estimates obtained using Chan's method and the predicted value is calculated. The estimate that gives the lowest error is chosen and the position is displayed on the GUI.

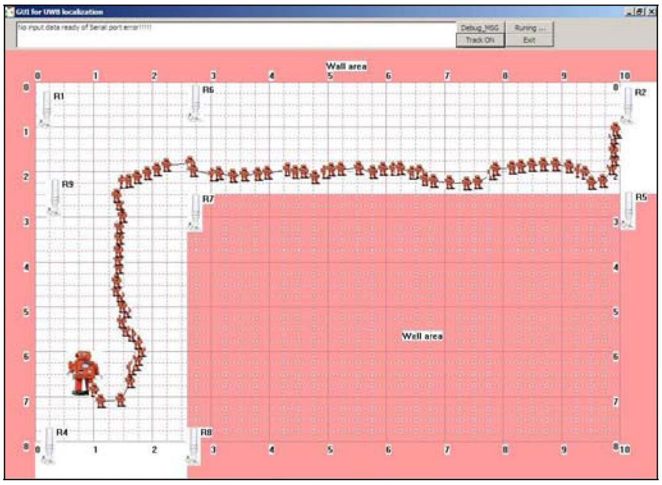

Fig. 9 Tracking of Robot using UWB-IR localization system

V. RESULTS AND ANALYSIS

The proposed UWB-IR based localization system was setup and the performance was measured. The robot was made to move between cells and cover the entire length of the localization space. The results are shown in Fig. 9. The tiny robots in the figure show the estimated position of the Robot as displayed on a screen attached to the CPCU. It is found that the system provides very good accuracy with RMS errors less than 15cm. The maximum error at any point in the localization space was observed to be 25cm. The movement of the robot between cells is seen to be smooth with no observable increase in error.

One reason for the very good accuracy is the use of cables to connect the Readers to the CPCU. In this way, synchronization errors are almost completely eliminated. Indeed, most localization algorithms make the assumption of perfect synchronization – something that is closely approximated by using cables. Although a purely wireless solution would look elegant, the errors due to synchronization between wireless Readers is expected to reduce the overall accuracy of the system significantly. It could lead to very large maximum errors although RMS errors may still be small [9]. For the robot application, the maximum error is more important than the RMS error. This is because when and where the maximum error would occur cannot be predicted. Hence the accuracy of the system is only as good as the maximum error. The RMS error is only an indication of how much better the system can be made if techniques to avoid the occasional large errors are available.

VI. Conclusion

In this paper, the use of UWB-IR for indoor robot navigation has been discussed in detail for the first time. Compared to other existing navigation systems, UWB-IR is expected to provide a more robust solution for absolute location of robots in indoor environments. The design, algorithm and results for an actual UWB-IR localization system have been presented. It is shown that by making a practical choice for the system design and localization algorithm, a low cost and yet very accurate solution is indeed possible.

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