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A Comparison Between UWB and TDOA Systems for Smart Space Localization

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***Abstract*—A comparison between two different systems for smart space localization is presented. A smart space implemented at the University of Nebraska-Lincoln was designed for automated and intelligent assistance for elderly and disabled people, and also for astronauts in space. Localization is a critical component of the smart space since it provides the system with the movement patterns and location of its inhabitants. Two systems have been deployed and evaluated for the purpose of localizing people in the smart space: the Ubisense ultra-wide band (UWB) system and the Cricket indoor localization system. Both systems support three-dimensional localization within the smart space. The two systems are evaluated, compared, and analyzed in the perspective of smart space development.**

Keywords: Smart Space, Ultra-wide Band system, Cricket System, Localization

I. Introduction

Research interest in smart spaces has steadily increased over the past two decades for a variety of reasons. Perhaps most important is the dramatic increase in the proportion of people over 65 years old who may require intelligent living spaces in order to remain in their homes longer. People with limited mobility such as the injured and disabled may require specialized environments to support daily living and avoid deteriorating health [1]. In the medical field, caregivers evaluate a person's ability to live independently at home by evaluating the patient's activities of daily living (ADLs).

In general, smart spaces automate interactions between the environment and its inhabitants, allowing for intelligent control and continuous health monitoring. They often rely on technologies such as Wireless Sensor Networks (WSNs) to sense changes in the environment and gather relevant data. Smart home technology has been widely applied to healthcare in order to ensure the wellbeing of elderly people living at home [2]-[4]. In addition to applications in the home, smart spaces can be extended to hospitals, clinics, offices, and even living environments in space stations and space vehicles.

The ultimate function of a smart space is to provide continuous sensing within the environment and facilitate interaction between the inhabitants and the living space. Steps necessary to achieve this goal frequently include: 1) localization, 2) tracking, 3), behavioral classification, and 4) big data analysis.

Localization is an essential component to the functionality of a smart space since location information is necessary to determine a person's activities within the space. Accurate localization over time is also necessary to achieve effective tracking within the smart space. Given sufficiently reliable localization and tracking, behavioral classification becomes possible. Finally, behavioral classification within the space obtained from the first three steps, when captured over a sufficient length of time, provides a large data set that can be used to create models and promote effective and automated interaction between the inhabitants and the environment.

Fig. 1. The MC^2 Lab smart space.

The MC^2 lab has implemented two methods for localization within a smart space: the Ubisense ultra-wide band (UWB) system [15] and the Cricket indoor localization system [17]. This paper focuses on comparing the performance of the localization data provided by the two systems. Section II provides details regarding the experimental set up in the lab. Section II-A and Section II-B examine the two systems and Section III provides a comprehensive performance analysis of the two systems.

II. Background

The MC^2 Lab includes a smart space shown in Figure 1. The dimensions of the space are approximately 9×4 meters and the ceiling is 3 meters high. The space is furnished with carpet, a bed, a chest of drawers, a sofa, tables, and chairs to simulate a regular home/office space. Both the Ubisense and Cricket systems have been installed in the space for experimentation and evaluation and both are capable of localization. However, they use different signals, technologies, and algorithms to do so. Sections II-A and II-B provide details regarding the two systems.

A. The Ubisense System

Ultra-wide band technology originated in the late 1960's at the Sperry Research Center. At that time, the technology was also referred to as *baseband, carrier-free*, or *impulse signaling*. The term "ultra-wide band" was not applied to this technology

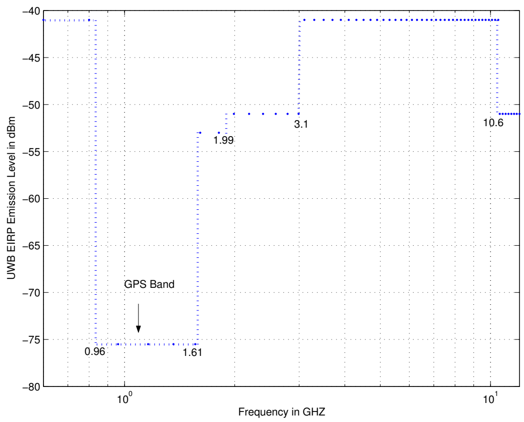

Fig. 2. UWB spectral mask for indoor communication systems.

until approximately 1989 [5]. Since then, UWB has been an active area of research. In 1998, the Federal Communication's Commission (FCC) began to regulate the spectrum for UWB applications and in February 2002 the FCC approved spectrum allocation for UWB systems [6]. This accelerated research and patents related to UWB technology.

UWB operates by transmitting and receiving an exceptionally short duration burst of RF energy – typically a few tenths of a picosecond to a few nanoseconds in duration. The bandwidth of the resultant waveforms are so wide that it is often difficult to determine an actual RF center frequency – thus, the term "carrier-free" [6].

UWB has both a common definition, widely used by researchers, and a formal FCC definition. The common definition of UWB is given in terms of the fractional bandwidth

$$BW_{\text{fractional}} = \frac{f_H - f_L}{f_C} > 25\%$$

and the total bandwidth

$$BW_{\text{total}} > 1.5\text{GHz},$$

where f_H is the highest frequency, f_L is the lowest frequency and f_C is the center frequency in the UWB signal spectrum. The FCC definition is given by

$$BW_{\text{fractional}} = \frac{f_H - f_L}{f_C} > 20\%$$

and

$$BW_{\text{total}} > 500\text{MHz},$$

where the fractional bandwidth is measured at the -10dB points and the total bandwidth is the whole range of bandwidth from -3dB to $+3$dB.

In addition, the FCC defines UWB as any signal that occupies more than 500 MHz of bandwidth in the 3.1 to 10.6 GHz band and conforms to the spectral mask limitations given in Figure 2 [11]. This is by far the largest spectrum allocation for unlicensed use that the FCC has ever granted.

Two different approaches to UWB signal design are commonly used - one design is impulse based and the other is based on pulsed multicarrier technology [12]. An impulse based UWB system occupying a bandwidth ranging from 3-6 GHz generates a single pulse that spans this bandwidth and satisfies the requirements of the FCC spectral mask, and then transmits this pulse with a pulse repetition frequency (PRF) that satisfies the data rate and ranging requirements. The pulsed multicarrier UWB system is similar to an orthogonal frequency division multiplexed (OFDM) signal. It is based on multiple narrowband pulses that are "stacked" in the frequency domain to create an effective UWB pulse. The FCC Report & Order (R&O) specifies a minimum "instantaneous" bandwidth of 500 MHz.

There are many well-known advantages to UWB, including:

- Low power consumption
- High multipath immunity
- Precise distance measurement capabilities

The last property has been applied in radar applications because UWB pulses provide very fine range resolution. The range resolution Δr is defined as

$$\Delta r = \frac{c}{2BW},$$

where BW is the bandwidth of the signal and c is the speed of light. The inverse relationship to the bandwidth makes the range resolution of UWB signals 100 to 1000 times finer than that of narrow-band signals [14].

The Ubisense system is a Real-Time Localization System (RTLS) using UWB signaling. The components of the Ubisense system include four Ubisense Series 7000 Sensors and Ten Ubisense Series 7000 Compact Tags. An example of a tag is depicted in Figure 3. The tag can be put in any orientation as long as it is configured to the "Wake-Up" state.

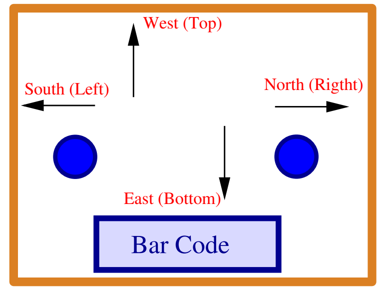

Fig. 3. The orientation of tags on the ground.

Four UWB receivers are mounted to the four corners of the ceiling. The tags send signals to the receivers and the information is processed using either angle-of-arrival (AOA) or time-difference-of-arrival (TDOA) to get the location data. For the AOA method, the mobile target's location is estimated by first measuring the angle of arrival of a signal transmitted by the target as shown in Figure 4. Estimation of the AOA, commonly referred to as direction finding, can be accomplished with a narrow beamwidth antenna or with an array of antennas [16]. The AOA localization method requires two nodes A and B,

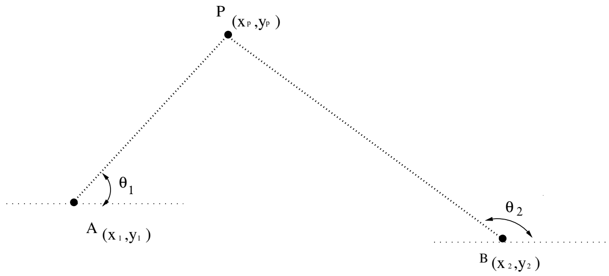

Fig. 4. AOA ranging where A and B are fixed nodes and P is a target.

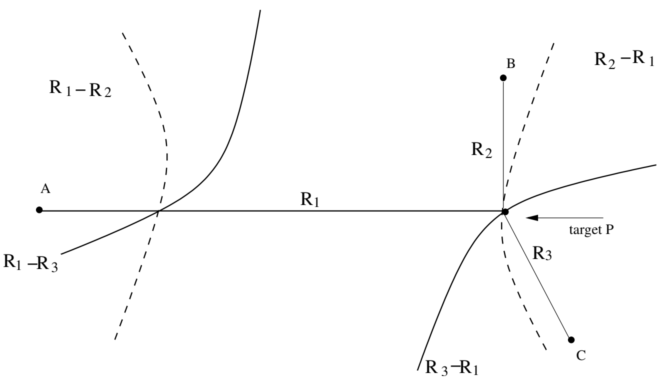

Fig. 5. Positioning based on TDOA measurements.

with known locations, and two measured angles to derive the location of the target P in two dimensions.

The idea behind TDOA is to determine the relative position of the target by examining the difference in the times at which the signal arrives at multiple nodes, rather than the absolute arrival time. Each TDOA measurement determines that the transmitter must lie on a hyperboloid with a constant range difference between the two receivers. The equation of the hyperboloid is given [16] by

$$R_{i,j} = \sqrt{(x_i\text{-}x_p)^2+(y_i\text{-}y_p)^2+(z_i\text{-}z_p)^2} - \sqrt{(x_j\text{-}x_p)^2+(y_j\text{-}y_p)^2+(z_j\text{-}z_p)^2},$$

where (x_i, y_i, z_i) and (x_j, y_j, z_j) represent the locations of fixed nodes i and j, (x_p, y_p, z_p) represents the coordinate of the target, and $R_{i,j}$ is the constant range difference between the two receivers.

The two-dimensional target location can be estimated from the intersection of the two hyperboloids, as shown in Figure 5. In this figure, A, B and C are three nodes and r_1, r_2 and r_3 are the distances from the three nodes to the target, respectively. Two hyperbolas are formed from TDOA measurements at three fixed nodes to provide an intersection point which locates the target. Three-dimensional localization requires at least four independent TDOA measurements [16] to formulate three hyperboloidal equations.

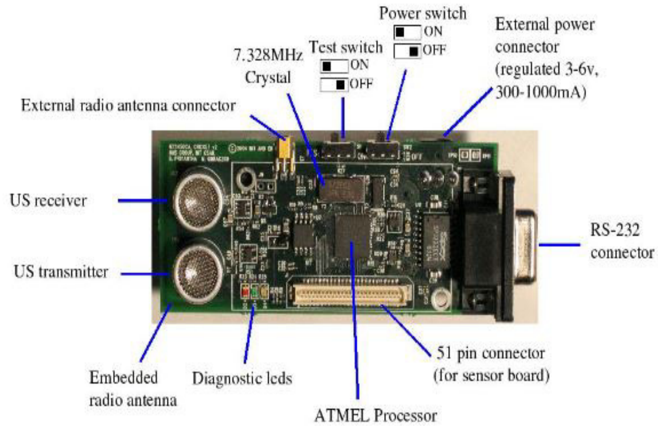

Fig. 6. The Cricket wireless sensor node.

B. The Cricket System

The Cricket system was developed at the MIT Artificial Intelligence Laboratory [17]. It uses the time difference of arrival (TDOA) between radio frequency (RF) signals and ultrasonic pulses in order to make range estimates. Figure 6 shows a Cricket sensor node which includes the following submodules: a microcontroller, an RF transceiver, an ultrasonic transmitter, an ultrasonic receiver, a temperature sensor, a unique ID, and an RS 232 interface [18].

The basic concept of the time difference of arrival used in the Cricket system is different than the standard TDOA method. In a standard active localization system, TDOA means the time difference of arrival of a signal from the target to two different nodes. In the Cricket system, because RF signals travel about 10^6 times faster than ultrasound signals, the listener uses the *time difference of arrival* at the receiver of the RF signal and the corresponding ultrasonic pulse to make a range measurement. Thus, the TDOA ranging method in the Cricket system refers to the time difference of arrival between two types of signals from the same node.

The two kinds of devices used in the system are listeners and beacons. In active mode, listeners have known fixed coordinates and beacons are attached to the targets to be localized and tracked. Both the listeners and beacons use the MICA2 hardware platform that was developed at UC Berkeley [19]. The range of the RF signal is limited by the radio power level, and the range of the ultrasonic signal is limited by both transmission power and the presence of obstacles, i.e., line-of-sight is essential. Figure 7 illustrates the TDOA technique used by the Cricket system to estimate the distance between two sensors. Cricket beacons periodically transmit an RF message containing beacon specific information such as a unique identifier, coordinates, space ID, and measured ambient temperature. At the start of each message, each beacon transmits a narrow ultrasonic pulse. When a listener receives an RF message from some beacon, followed by an ultrasonic signal, it measures the time interval δT between the

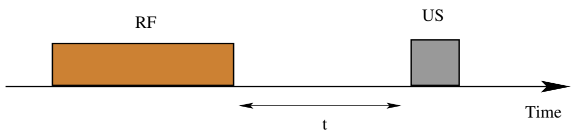

Fig. 7. An illustration of TDOA used by the Cricket system.

start of the RF message and the arrival of the ultrasonic signal at the listener. The listener can compute the distance d to the beacon by

$$\delta T = \frac{d}{v_{us}} - \frac{d}{v_{rf}}.$$

The system measures the time difference between ultrasonic pulse arrivals and then estimates the three-dimensional position using trilateration. The results of localization experiments conducted using the Cricket system are summarized in Section III.

III. Results

In this section, experimental results are presented that compare the localization accuracy of the two systems. To provide a common basis for comparison, the Visualization True Ground system is used. The Visualization True Ground system is a localization system that utilizes a checkerboard patterned image tag and a fixed camera. The method operates by moving the tag to various locations while allowing the camera to take pictures. Visual localization is achieved by detecting the checkerboard in the image and calculating the pose of the camera relative to the checkerboard. An 18 megapixel SLR was used to provide millimeter-level localization accuracy, thus providing a common basis with which to evaluate the accuracy of the other localization systems [20].

A total of 15 measurement points were used in the experiment. The three kinds of tags rigidly mounted to one another include the Ubisense tag, the Cricket mote and Visualization tag. At every location, a picture is taken by the camera to provide an accurate position estimate and the Ubisense system and Cricket system also estimated the location of the target. Thus, for each of the 15 locations, there are three sets of localization data to compare. Figure 8 presents the localization results for the 15 locations where the red circles are the Visualization data, the blue stars represent the Ubisense data and the red squares are the Cricket data.

Figures 9 and 10 summarize the accuracy of the two localization methods by showing the distribution of errors when compared with the Visualization True Ground system. The localization data from the two systems shows that both of the systems are able to reliably localize targets. Each of the measurements obtained from the Ubisense system is within 0.17 meter of the target's true positions and each of the measurements obtained from the Cricket system is within 0.05 meter of the target's true positions. Overall, 40% of the location estimates using the Ubisense system have an absolute error of less than 0.06 meters. Furthermore, more than 50% of Ubisense location error data are within the 0.1m. Considering

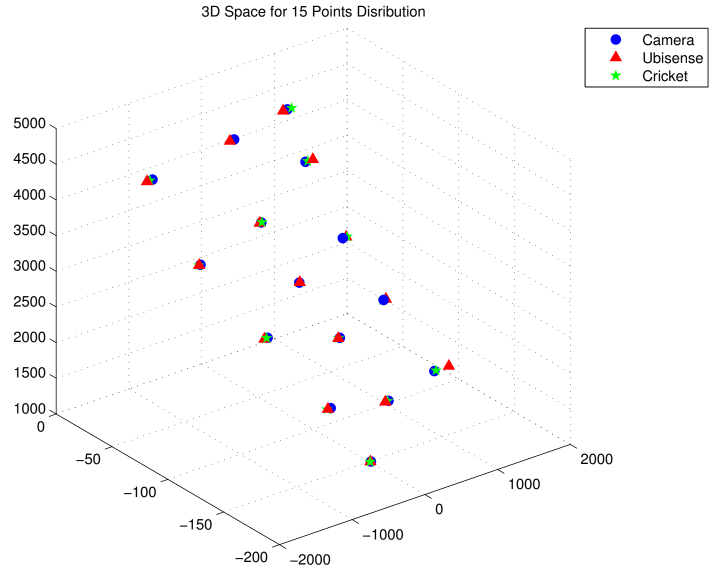

Fig. 8. Localization Results of the Tag Distribution.

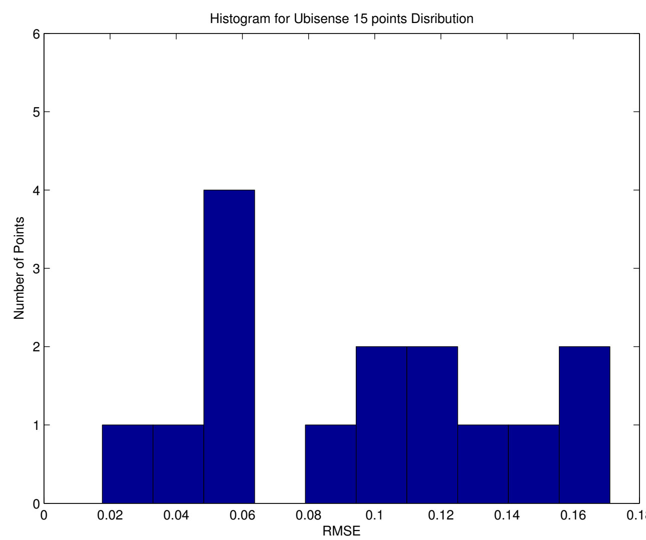

Fig. 9. The Ubisense System Localization Performance.

the experiment has been performed in a dense multipath environment, it is expected that this accuracy is representative of a worst-case scenario. Using the Cricket system, 40% of localization measurements had an error of less than 0.015 meters. In total, nearly 99% of localization measurements had an error of less than 0.04 meters.

Whereas the UWB signal works well under Non Line-of-Sight(NLOS) conditions, the Cricket system requires a line-of-sight (LOS) between the transmitter and the receivers. The Cricket system, on the other hand, is cheaper compared to the Ubisense system with each device costing less than U.S. $10. The Ubisense system is robust to orientation variation and thus tag placement does not have a significant impact on location accuracy. Due to the nature of UWB signals, the system works well when operated in a rich multipath environment.

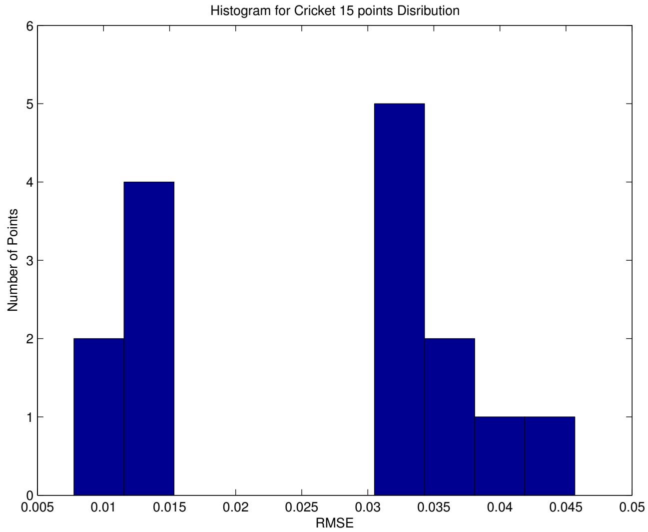

Fig. 10. The Cricket System Localization Performance.

The update rate for Ubisense system is exceptionally fast and can be adjusted to 8ms for one data update. From the power consumption perspective, the Cricket v1 hardware design is relatively inefficient and battery changes are frequently required, which is a significant drawback for semi-permanent deployments. Cricket v2 has been designed to improve the power consumption issue and is more accurate. The Ubisense system assigns a different status for tags that are idle or busy and thus when tags are idle, the tags can automatically go into a sleep or a deep sleep status, providing increased power-efficiency.

IV. Conclusion

The experiments on localization systems demonstrate that both the Ubisense system and the Cricket system provide localization accuracy that is typically within a few centimeters of the actual location. Thus, both systems are excellent candidates for indoor localization system. The Ubisense system is suitable for use in a multipath environment and is also power-efficient. The Cricket system has lower cost and is capable of self-localization which requires very little manual configuration.

The localization experiments using the two systems shows that the Cricket localization data is more accurate. As the systems are significantly different, more experiments must be conducted to thoroughly understand the tradeoffs between them. For example, the same NLOS condition can be employed by purposely placing obstacles between receivers and tags. Future work includes further analyzing the systems, modifying them to improve the localization results, and implementing temporal processing to achieve more reliable tracking performance.

Based on the further research and analysis, the smart space would be designed to facilitate automated interactions between people and the environment. The strategy of the smart space project is to first achieve localization and tracking functionalities. Then, based upon the provided data, the possibility of behavioral classification can be explored by building a corresponding database of behaviors over time for health status monitoring.

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