Real-Time Noncoherent UWB Positioning Radar with Millimeter Range Accuracy in a 3D Indoor Environment

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***Abstract*- In this work, we have successfully developed a stand-alone system for positioning both static and dynamic targets in an indoor environment with approximately 2 mm and 6 mm of 3-D accuracy, respectively. The results are considered a great milestone in developing such technology. 1D and 3D experiments have been carried out and validated using an optical reference system which provides better than 0.3 mm 3D accuracy. Such a high accuracy wireless localization system should have a great impact on many applications that require such high positioning precision.**

***Index*- ultra-wide band (UWB), positioning, localization, ranging, noncoherent.**

I. Introduction

More than ever, businesses and organizations need reliable, real-time location information. In many cases, knowing the location of your resources/assets can be the difference between success and failure and can have serious effects in surgical operations. Therefore, there is a great demand to develop a wireless local positioning technology as it has many diverse applications and has been extensively studied [1]. While Global Positioning Systems (GPS) use ultra high precision atomic clocks to measure the time-of-flight, a more standard method for indoor localization systems is the use of Time Difference of Arrival (TDOA), where all of the base stations or receivers are synchronized, and the difference in time is measured between each pair of receivers to triangulate the position of an unsynchronized tag [1].

A precise localization system in an indoor environment has been developed. The developed system has been built on our previous work [2-3] and based on transmitting and receiving picosecond pulses and carrying out a complete narrow-pulse, signal detection and processing scheme in the time domain. The challenges in developing such a system include: generating ultra wideband (UWB) pulses, pulse dispersion due to antennas, modeling of complex propagation channels with severe multipath effects, need for extremely high sampling rates for digital processing, synchronization between the tag and receivers' clocks, clock jitter, local oscillator (LO) phase noise, frequency offset between the tag and receivers' LOs, and antenna phase center variation. For such a high precision system with mm or even sub-mm accuracy, all these effects should be accounted for and minimized. Many of these effects have been already addressed in [3], however the reported 3-D localization results were based on utilizing a Tektronix TDS8200 oscilloscope and the system was coherent, i.e. the transmitter and receiver were wired.

In this paper, a novel localization receiver architecture will be first presented in comparison to our previous one. The proposed UWB architecture combines the carrier based and the energy detection based UWB receiver schemes and uses an advanced sub-sampling technique to allow for sampling of the time extended UWB pulses by a conventional analog-to-digital converter (ADC). Second, a real-time 1D noncoherent experiment measured at distinct static points will be discussed in detail. Finally, a dynamic experiment with a tag moving randomly in a 3D space will be demonstrated.

II. Novel UWB Localization System Architecture

In our system, we modulate an UWB pulse with an 8 GHz carrier signal which resides at the upper end of the 3.1 – 10.6 GHz band. The use of this band reduces the size of the wideband RF components in the transmitter and receiver and also bypasses many of the interfering frequency bands that exist at the lower end of the 3.1 – 10.6 GHz band. A complete experimental setup of the developed system is shown in Fig. 1. In this developed system, we transmit a modulated narrow Gaussian pulse with a carrier frequency and demodulate it at the receiver side. The source of our UWB positioning system is a step-recovery diode (SRD) based pulse generator with a controlled pulse width and a bandwidth greater than 1 GHz. We use a 300 ps pulse that has produced greater than 3 GHz bandwidth signal in our implementation. The modulated Gaussian pulse is then transmitted through an omni-directional UWB antenna. Multiple base stations are located at distinct positions in an indoor environment to receive the modulated pulse signal. The received double sideband (DSB) modulated Gaussian pulse at each base station first goes through a directional Vivaldi receiving antenna and then is amplified through a low noise amplifier (LNA). Next, through demodulation, we combine the upper and lower bands and obtain UWB pulse signals. After going through a low pass filter (LPF) with a passband of DC-5 GHz to suppress the 8 GHz carrier leakage signal, the down-converted UWB signals are sub-sampled using an UWB sub-sampling mixer (an equivalent time sampler) [4], extending them to a larger time scale (i.e. µs range) while maintaining the same pulse shape. The sub-sampling mixer uses sequential-time sampling techniques to achieve equivalent sampling rates in excess of 100 GS/s, which yields mm-range sample spacing and provides our leading edge detection algorithm with ample digital data, needed for detecting the arrival time of the pulse with high (e.g. mm or sub-mm) accuracy. The extended signals then pass through an energy detector to recover the envelope of the extended Gaussian pulse signal. Finally, the extended signals are processed by a conventional low cost and low speed analog to digital converter (ADC) and a standard Field Programmable Gate Array (FPGA) unit. A novel leading edge detection algorithm is incorporated on the FPGA which, combined with a quick cable length calibration procedure on the computer, allows for robust arrival time calculation and highly accurate TDOA computations of the tag's 3D position [5]. The major improvements of the system setup compared to our previous approach in [3] are:

a) Single channel of down-conversion has been used instead of I/Q, which lowers the cost and reduces the system complexity;
b) Following the sampling mixer, the energy detectors are added which helps in getting rid of the carrier offset due to the frequency difference between the transmitter and receiver LOs, and increases the signal to noise ratio;
c) Low phase noise LOs are used at both the transmitter and receiver sides.

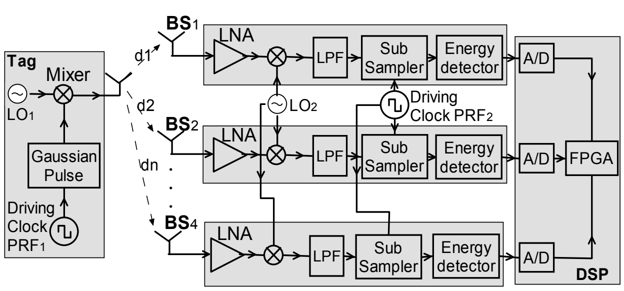


Fig. 1 3D experiment setup of unsynchronized localization system using a single channel demodulation with energy detection.

III. 1D Noncoherent Experiment

Two 1D experiments with unsynchronized LOs and PRF clock sources were carried out to test the robustness of our system. The two experimental setups are shown in Fig. 2, where only two base stations are needed for the 1D measurements. The differences between the two 1D experimental setups in Fig. 2 are listed below:

i. In Fig. 2(a) free running VCOs with a relatively high phase noise (-80 dBc/Hz@10 kHz) are used at both the transmitter and receiver whereas in Fig. 2(b), low phase noise LO sources (-100 dBc/Hz@10 kHz) are used at both the tag and receiver, respectively;
ii. The envelope detectors are used following the sub-sampler at the receiver in Fig. 2(b), whereas in Fig. 2(a) no envelope detectors are used.

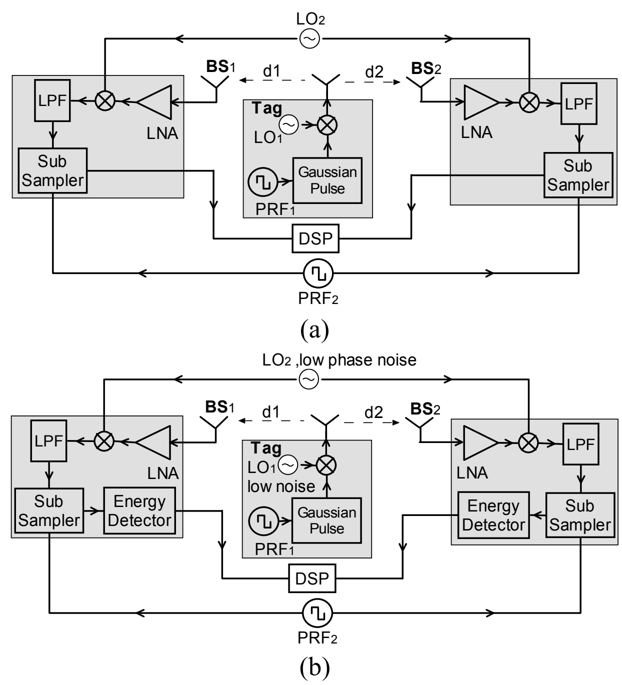
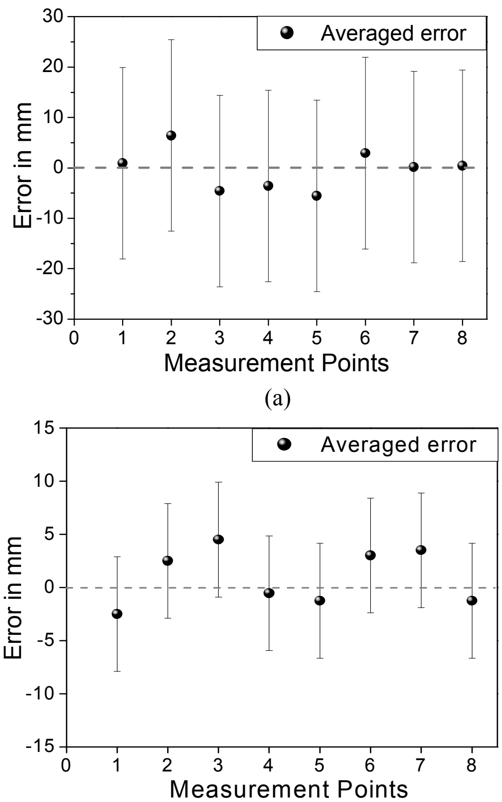


Fig. 2 Experimental setup for 1D unsynchronized positioning measurement: (a) LOs with high phase noise at the tag and receiver, no energy detector; (b) low phase noise LOs at the tag and receiver, with energy detection after the sub-sampler.

For both cases, a mm-range accuracy was consistently achieved for the 1D unsynchronized measurements at 8 separate locations along the Newport optical rail with a 5 cm distance between any two successive measurements. As shown in Fig. 3(a), the system jitter can cause noticeable short term variation in the error at each static point of roughly ±19 mm. This short term variation was mitigated by averaging 32 pulses at each static point. For the single channel scheme with a low phase noise carrier and energy detection, results shown in Fig. 3(b) demonstrate the system's jitter has a much smaller short term variation of roughly ±6 mm at each static point, compared to the ±19 mm shown in Fig. 3(a). This small short term variation was mitigated by averaging only 4 pulses at each static point, thus speeding up the processing time.



(a)

(b)

Fig. 3 Measured error of the 1D unsynchronized experiment: (a) LOs with high phase noise at the tag and receiver, no energy detection; (b) low phase noise LOs at the tag and receiver, with energy detection after sub-sampling.

Table 1 – Comparison of the Noncoherent 1D Experiment Results

	w/o energy detection	w/ energy detection
Static Variation	±19 mm	±6 mm
Mean Error (mm)	3.07	2.38
Std Dev. Error (mm)	2.39	2.66
Worst Case (mm)	6.4	4.50
Number of averaging	32	4
LO Carrier Phase noise	High	Low
Energy Detection	No	yes

In Table 1 we compare the results between both cases and it is clear that the single channel scheme with a low phase noise carrier and energy detection requires less times of averaging and produces less 1D error. Compared to the coherent experimental results in our previous work [3], the mean error in measuring the 1D static data increases from 1.49 mm to 2.38 mm. The increase in error of 0.89 mm is comparable to the measured error of 1.05 mm due to the PRF clock jitter discussed in [3].

IV. 3D Noncoherent Experiment

Figure 4 shows a four base stations distribution with pre-defined locations for each base station utilizing the Optotrak 3020 system, which is also served as the reference of our UWB localization system and provides a 3D accuracy of better than 0.3 mm. Notice that the spatial spread of the base stations along the z-axis is the largest (2498 mm), while along the x-axis is the smallest (1375 mm).

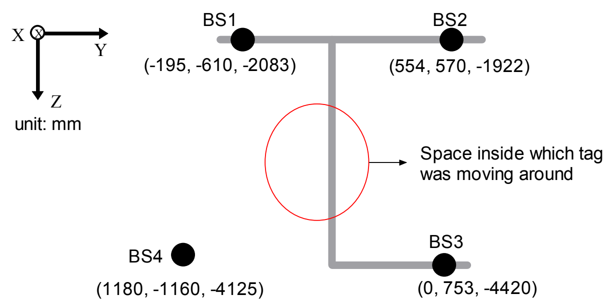
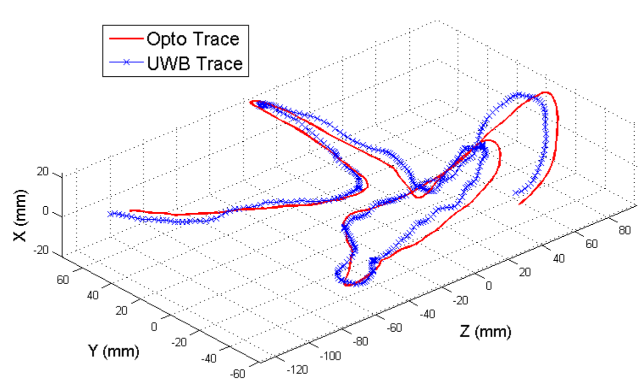
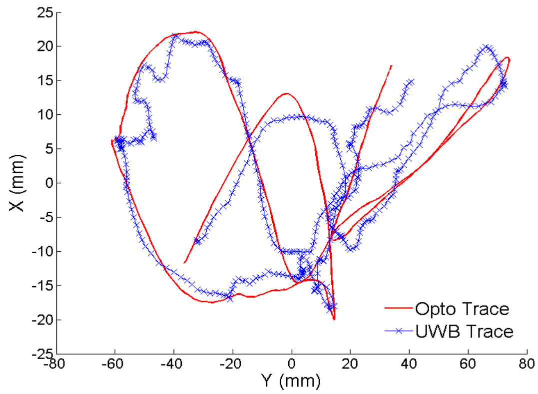


Fig. 4 3D unsynchronized localization experiments, 4 base station distribution with locations for each base station.

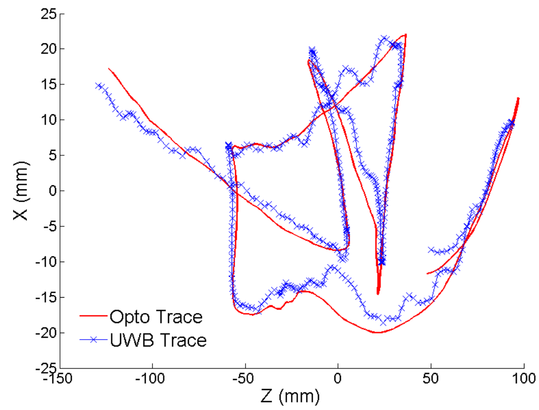
In the dynamic mode, the tag is moving randomly inside the 3D space indicated in Fig. 4. The 3D motion traces of the tag are then plotted and UWB measured traces are compared with the Optotrak measured traces. Root mean square error (RMSE) is used to report the error since it is a good measure of error resulting from both the accuracy and precision. Figure 5 plots the UWB trace and Optotrak trace in the 3D dynamic mode with energy detection. Both the 3D view and 2-D views from different planes are shown.



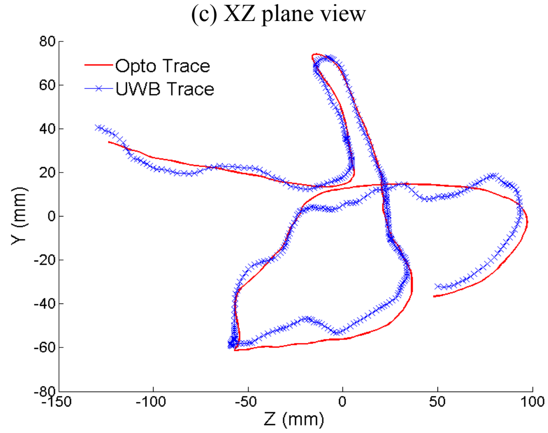
(a) 3D view



(b) XY plane view



(c) XZ plane view



(d) YZ plane view

Fig. 5 3D dynamic mode with energy detection, UWB trace compared to Optotrak trace: (a) 3D view; (b) XY plane view; (c) XZ plane view; (d) YZ plane view.

Figure 6 shows the 3D dynamic errors at *x, y,* and *z* axes over 1000 measurement points. The overall 3D RMSE error is 6.37 mm. The error along the *x-axis* contributed most to the overall distance error, which can be explained by the limited spatial spread of base stations along the *x-axis*. Such error can be easily mitigated through better arrangement of the base stations along the *x-axis*.

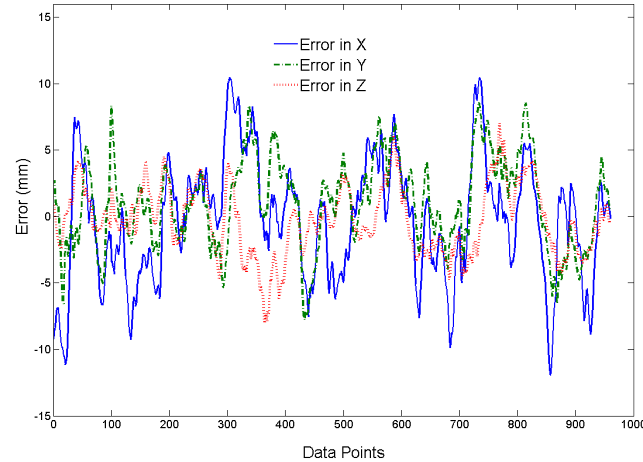


Fig. 6 3D dynamic mode with energy detection, *x, y* and *z* axes error compared to Optotrak System.

VI. Conclusion

In this paper, noncoherent 1D and 3D localization experiments have been performed where mm-range accuracy has been consistently achieved. By comparing with two 1D experiments the ranging error has been improved significantly with the reduced timing jitter through applying low phase noise carrier based IR-UWB architecture together with advanced sub-sampling and energy detection. A 3D dynamic experiment has been performed with a tag moving randomly in a 3D space. The RMSE error is in the mm-range. The achieved mm-range accuracy in the developed real-time noncoherent system represents a milestone in developing this technology.

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