EmbedUWB: Low Power Embedded High-Precision and Low Latency UWB Localization

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EmbedUWB: Low Power Embedded High-Precision and Low Latency UWB Localization

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Abstract— **Positioning based on Ultra-wideband (UWB) wireless communication promises multipath immunity, high resolution, and strong wall penetration. Hence, many academic and industrial researchers are proposing UWB positioning systems especially to track and locate objects and person in indoor environments. UWB indoor localization, based on stationary "anchors" tracking mobile "tags", is already a reality in many application scenarios. However, most of the available systems either perform tracking on servers which collect data from tags and anchors or delegate to the anchors to calculate the actual position of the tags. Both approaches imply long latency and limited throughput in terms of position fixes per unit time. In this paper, we present the design and the implementation of a highly accurate and low latency asymmetric double-sided two-way ranging algorithm that runs at very modest energy budget on low-power tags based on ARM Cortex-M4F microcontrollers (MCUs). We implemented a complete tag platform, which hosts the MCU and the UWB module, and we evaluated the algorithm in the field. Experimental results demonstrate high accuracy (4.3cm) and position fix rate (20Hz), the energy cost of only 4.9mJ for a single fix, and a cold-start first position fix in only 81ms.**

Keywords— Indoor Localization, Ultra Wide Band, Geo Localization, Low power design, embedded intelligence.

I. INTRODUCTION

Ultra-wideband radio technology has enabled a wide range of applications from monitoring to tracking and positioning. UWB is used in industrial [2], medical [3], automotive [4] and consumer products [5], but also, for short-range communication with high bandwidth requirements, for instance, in-car communication [6] or general short- and medium range communication [7]. However, one of the most promising applications of UWB today is to localize and track objects and people indoor. UWB is becoming the gold standard for indoor localization: the most important features of UWB are the high precision of the position due to very short impulse duration and the robustness with respect to multipath propagation and noise [8]. In a few cases, UWB is used in outdoor positioning systems as well, mostly together with GPS [9]: in fact, UWB outperforms GPS in sample rate (only 1-10Hz for the GPS) and low latency of the startup phase (many seconds or minutes for the GPS) [10]. In the last decade, researchers have been very prolific in the field of indoor positioning [11],[12]. Different indoor positioning technologies as RFID, Infrared, Bluetooth or WLAN have been compared in [13]. However, as can be noticed following the Microsoft Indoor Localization Challenge, started in 2014 at IPSN conference, there is a clear trend toward academic and industrial solution exploiting UWB. This is clearer looking at the recent results of the 2018 competition [15] where more than half of the solutions employed UWB technology. Moreover, today it is possible to find off-the-shelf UWB modules, as the Decawave DW1000 [16]. As a result, testing UWB has become affordable and easy.

Due to these important features, it is not surprising that the first two teams of the Microsoft competition 2018 have been using UWB. Another interesting data coming from the report [15] is the average error, which results of 27 cm for the winning team, calculated following an objected in a building over several fixed points. It is important to notice that all the presented prototypes are not running the localization algorithm on the mobile tags, but on the fixed anchors or in the cloud. In fact, in many cases, the anchors need to be wired to work as they need to be always connected to each other or to a remote server. This is also confirmed in [17], where a survey of recent work is presented. In [17] the authors present the most recent trend of having very simple mobile UWB tags that can work even without batteries, where however the detection of the position is performed externally to the tag. To the best of our knowledge, there is no previous work that investigates on the capability of a low power microcontroller to perform the trilateration needed to detect the position on the mobile tag. One key advantage in bringing the processing on board of the tag using an ultra-low-power microcontroller is the major latency reduction for the mobile object to get its position, which improves the precision in trajectory tracking.

This paper presents an embedded hardware and software solution to achieve highly accurate and low latency UWB indoor/outdoor localization by computing position on the tag. An STM32L4 microcontroller (ARM Cortex-M4F) is the core processor where we optimize and implement an asymmetric double-sided two-way ranging algorithm. The system is able to calculate on-board its own position exploiting anchor messages. Experimental results show the very high accuracy of 4.3cm and the low latency that allow to achieve up to 20Hz of position fix rate with an energy consumption of only 4.9mJ per detection.

II. SYSTEM ARCHITECTURE

Fig. 1 illustrates the block diagram of the designed hardware platform for the tag, which exploits a modular approach to address rapid developments. The proposed design is based on a Cortex M4F microcontroller and allows to test and compare state-of-the-art wireless communication standards as well as emerging research concepts such as transient computing and zero-power-sensing [18]-[21]. This section is divided into two subsections. Section II-A presents the low power embedded UWB algorithm for localization and communication, section II-B describes the hardware architecture.

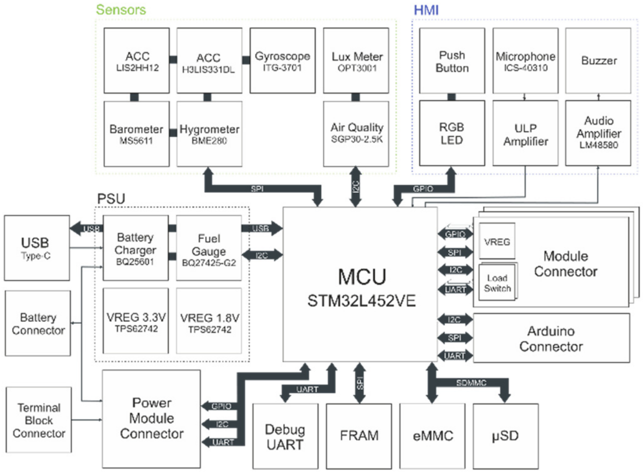

Fig. 1. Adaptable multisensor IoT platform.

A. Real-time Localization Algorithm

The UWB module used in this work is the well-known Decawave DW1000 transceiver. The UWB IC is capable of wireless communication compliant the IEEE802.15.4-2011 standard and distance measurements with a time difference of arrival (TDOA). The Decawave transceiver allows data rates of up to 6.8Mbit/s in a frequency range between 3.5GHz and 6.5GHz. It is one of the most popular modules for indoor localization [16]. This work evaluates the feasibility to run the positioning algorithm on the tag-hosted microcontroller instead than on the anchors or on a server. To achieve the maximal possible range, while preserving the localization accuracy, it is crucial to use the best-suited configuration of the transceiver in combination with a two-way ranging algorithm capable of clock error suppression.

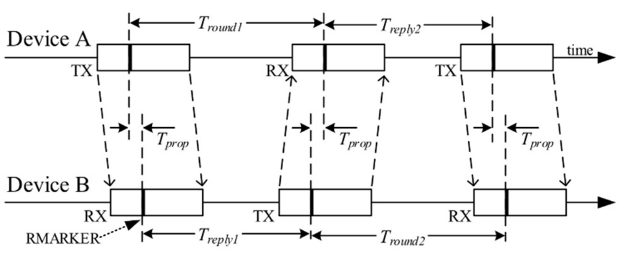

Fig. 2. Double-sided two-way ranging (DS-TWR) with three messages between two devices. [1]

To achieve high accuracy and low complexity to run the algorithm on a microcontroller, we selected a two-way ranging scheme [23]. In the two-way ranging (TWR) scheme, a time-stamped message is exchanged between two devices with synchronized clocks, and the distance is calculated from the time-of-flight information. To achieve this goal, a single timestamped message is sent from one device to another. The receiving node adds the arrival time and responds to the initiator. From the round trip and replay time, the average propagation time and thus the distance can be calculated.

The limited frequency stability of the oscillators in both nodes cause a ranging error which increases with the distance between the nodes. To suppress this error while keeping the overhead low, double-sided two-way ranging (DS-TWR) with three messages, shown in Fig. 2, can be used. The algorithm uses two round trip measurements where the reply of the first-round trip is used as the initiator of the second one. [1] The average signal propagation time can be calculated with equation (1).

$$\hat{T}_{prop} = \frac{(T_{round1}T_{round2} - T_{reply1}T_{reply2})}{(T_{round1} + T_{round2} + T_{reply1} + T_{reply2})} \qquad (1)$$

The real-time localization is implemented exploiting CMSIS API functions for ARM Cortex-M4F. To fulfill the strict timing requirements of time-of-flight distance measurements with electromagnetic waves in air - 1ns represents approximately 30cm - the timestamping is carried out by the UWB transceiver IC with 64GHz resolution and under consideration of the antenna delay.

After the UWB transceiver initialization via SPI, two tasks are launched:

1) *Distance measurement DS-TWR algorithm*: The tag initiates the DS-TWR algorithm by sending a timestamped broadcast message to all anchor nodes in the transmission range. Subsequent the anchors add a receive and transmit timestamp to the message and respond in the order of their ID. If the tag receives valid data, the transceiver IC triggers an interrupt of microcontroller and forces the readout of the data via SPI. To apply double sided ranging, the timing information from the previous round-trip messages are used. Thus, after the second broadcast, the two round-trip and reply times are calculated from the timestamps. Subsequent the distances are calculated under consideration of equation (1) with two 64-bit multiplications, three additions and one double precision floating point multiplication and division for every anchor.

2) *Trilateration*: When distance information from at least three anchors with a known position is valid the trilateration task is triggered as shown in Fig. 3b. It calculates the position under consideration that the point of interest has to lie on the intersection point of three spheres. The algorithm uses linear algebra in a three-dimensional Euclidean space and simplifies the problem to solve quadratic equations. Our implementation is based on the source code from Decawave which has been optimized for execution on Cortex-M microcontrollers.

First, the algorithm checks if three of the four anchors, $p_1 \ldots p_4$, are not concentric with each other by calculation the distance between them, $|\overrightarrow{p_{12}}| > 0$, $|\overrightarrow{p_{13}}| > 0$, $|\overrightarrow{p_{23}}| > 0$ (Fig. 3.a). In the case of concentric anchors, an error will be iteratively added until the anchor points are nonconcentric. In (the second stage, a local coordinate system $(\overrightarrow{e_z}, \overrightarrow{e_x}, \overrightarrow{e_y})$ gets introduced according to equation (2).

$$\overrightarrow{e_x} = \frac{\overrightarrow{p_{12}}}{|\overrightarrow{p_{12}}|}\ ,\ \overrightarrow{e_y} = \frac{\overrightarrow{p_{13}}-(\overrightarrow{e_x}\cdot\overrightarrow{p_{13}})\overrightarrow{e_x}}{|\overrightarrow{p_{13}}-(\overrightarrow{e_x}\cdot\overrightarrow{p_{13}})\overrightarrow{e_x}|}\ ,\ \overrightarrow{e_z} = \overrightarrow{e_x} \times \overrightarrow{e_y} \qquad (2)$$

Subsequent, the local coordinates of the unknown point (x', y', z') can be calculated by applying the equations (3).

$$x' = \frac{r_1^2 - r_2^2 + x_{p2}^2}{2x_2}\ ,\ y' = \frac{r_1^2 - r_3^2 + x_{p3}^2 + y_{p3}^2 - (2x_{p3}x)}{2y_{p3}}\ , \qquad (3)$$
$$z' = \pm\sqrt{r_1^2 - x^2 - y^2}$$

Resulting in two solutions, s_1 and s_2, which can be transformed back into the global coordinate system. If distance measurements of only three anchors are available, the calculation is completed, and the higher solution is chosen as a tag position. A fourth anchor allows to further improve the result by intersecting a sphere with radius r_4 in a line between the two trilateration solutions. This results in solving the quadratic equation (4) and applying an approximation procedure depending on to the found solutions as presented in [25].

$$(s_1 + t(s_2 - s_1) - p_4)^2 = r_4^2 \qquad (4)$$

Afterward, the calculation is three times repeated for every combination of initial anchors, and the best fitting solution is determined by calculation the geometric dilution of precision (GDOP) with equation (5).

$$\min_{1 \le n \le 4} \sqrt{\sum_{i=1}^{4} (\lceil solution_n - p_i \rceil - r_i)^2} \qquad (5)$$

On an STM32L4 clocked at 80 MHz the execution time to calculate a single position from four anchors is on average 316µs.

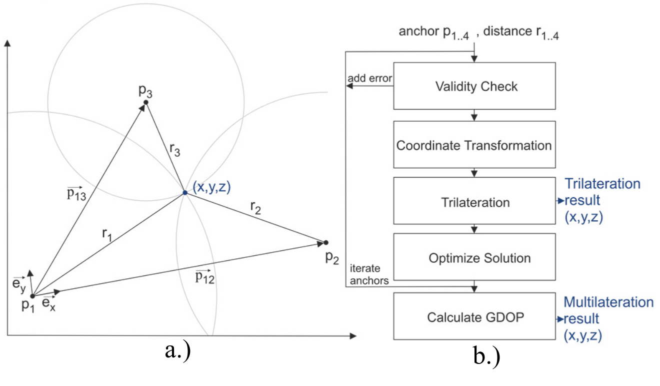

Fig. 3. a.) Simplified trilateration with three fixed anchors. b.) Implemented multilateration algorithm.

The whole optimized real-time localization algorithm implemented uses only 48kB flash and 15kB RAM. Due to these small memory requirements and the use of CMSIS it can be implemented on all cores of the ARM Cortex-M family.

Finally, for the targeted wide application range, the transceiver is configured according to TABLE I. to achieve maximal transmission range.

TABLE I. THE CONFIGURATION OF THE DW1000 TRANSCEIVER FOR LONG-RANGE TDOA MEASUREMENTS

Parameter	***Setting***
Data rate	110 kbit/s
Channel number	1 (f_0=3494.4 MHz)
Preamble length	2048 symbols
Preamble accumulation chunks length	32 symbols
Puls repetition frequency	16 MHz
Transmit power spectral density	-41.3 dBm/MHz

B. IoT Platform: Hardware Architecture

Fig. 4 shows the prototype of the developed IoT platform and its extension with the UWB module for localization and communication. The platform is based on an STM32L452VE microcontroller with a single 32bit ARM Cortex M4F core with floating point unit (FPU) operating at a frequency of up to 80MHz. Along with 512kB flash memory and 160kB SRAM the MCU is suited for edge computing up to medium complexity such as motion and audio recognition. To allow non-volatile data storage the board comprises 4Mbit ferroelectric random access memory (FRAM) enabling write operations at bus speed with a typical current consumption of 300uA@1MHz. Furthermore, a 16GB embedded multimedia card (eMMC) and a uSD card interface allow long-time data logging.

The board supports battery powered operation from single-cell lithium ion battery which can be charged via a USB type-C connector with up to 3.2A. Additional to the power path management by a BQ25601 converter the battery is monitored with a BQ27425-G2 fuel gauge form Texas Instruments. Two TPS62742 ultra-low-power step-down converters provide 1.8V and 3.3V for the whole system. These two converters allow a light load efficiency of up to 90%@10µA with a quiescent current of 360nA. Precise subsystem power consumption measurements are supported due to the optional supply splitting of the different functional domains. The extension module connectors, which can be used to add communication modules as well as additional sensors, comprise low leakage load switches to minimize sleep consumption. Optional to the board supply, every extension module connector includes a dedicated switching regulator with a selectable output voltage between 1.8V and 3.3V in 0.1V steps. For self-sustainable applications, the hardware can be expanded with an energy-harvesting or power managing subcircuit.

To reduce the overall system power consumption, three power states have been implemented. In particular, it is possible to switch among three power states. In the UWB-OFF state, the load switches disconnect the UWB module, which has a leakage current below 1nA. In this power state, the transceiver configuration is lost, and it need has to be reinitialized after changing the power state. A UWB-SLEEP mode allows the retention of the configuration with a power consumption of

165nW and a turn-on time of 3ms. In the UWB-IDLE mode, the module consumption is 38mW, and a transition to the transmitting or receiving state is possible without delay. A trade-off between power consumption and latency to start-up needs to be considered according to the application scenario.

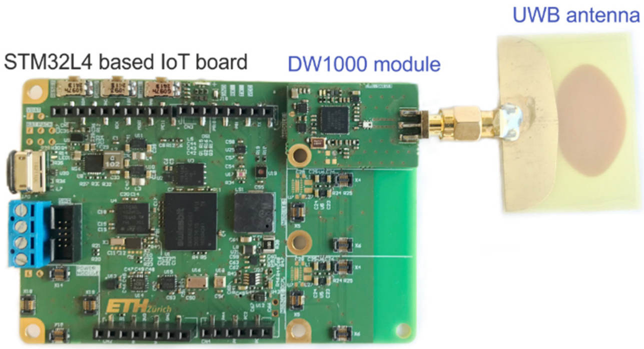

Fig. 4. The prototype of the 90x60mm large IoT board connected to a UWB transceiver circuit for data transmission and real-time localization.

III. Experimental Results

In the following section, the in Fig. 4 shown prototype that incorporates the proposed IoT edge device with UWB localization capabilities has been tested in terms of functionality, maximal range, accuracy, precision, and power consumption.

A. Two-way Ranging

To test the maximum range of the UWB communication, we progressively distanced the IoT platform (tag) from the anchor and evaluated the packet error rate. The measured maximal achievable distance between two nodes is 603m in optimal conditions of open-field. Above a distance of 500m, the packet loss rate increased to over 90% in contrast to less than 3% below 300m. To evaluate the accuracy and precision of the implemented algorithm, we placed an anchor in a fix position at the begin of an athletic field and moved the tag (Fig. 5). The average accuracy for our two-way ranging implementation is 43mm, and the corresponding precision is 33.6mm. The precision represents a mean of the standard deviations calculated from 1000 measurements at the stationary condition and at different distances below 150m. As a baseline, a laser rangefinder DLE 70 from Bosch is used. It is worth noticing that neither accuracy nor precision diminishes with increasing distance and thus the DS-TWR algorithm effectively reduces clock errors.

B. Real-time Localization

To demonstrate the system performance including hardware and software, four identical constructed nodes acting as an anchor with the fixed position are placed at the corners of a soccer field. A fifth node acting as a mobile tag is moved on the penalty line of the field. During the motion, the tag is measuring the distance to all anchors and calculates its position with the onboard running trilateration algorithm. The raw trilateration output is visualized in Fig. 6. For the presented setup with four anchors, the system achieves a sampling rate of 20Hz based on the algorithm with overlapping round trip measurements. With the exception of six recorded outliers, the calculated position follows precisely the movement.

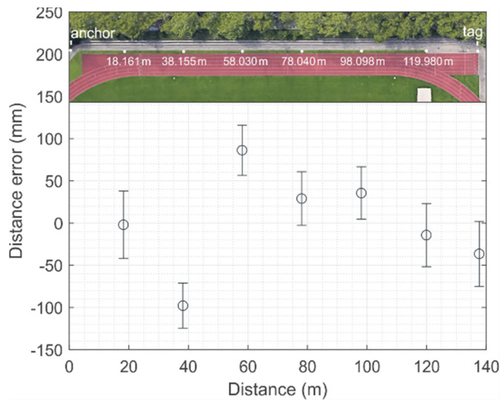

Fig. 5. Experimental set-up and distance error measured.

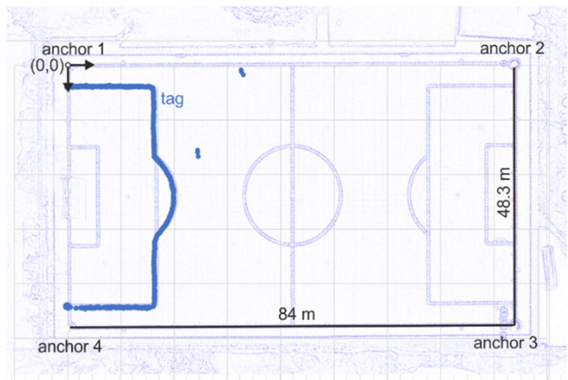

Fig. 6. Raw trilateration output in a four anchor setup. The tag is moved on the penalty line of the soccer field.

C. Energy Consumption

To evaluate the energy consumption of the UWB implementation, the DW1000 module is directly supplied by a Keysight N6705B DC power analyzer. The consumed power on the 1.8V and 3.3V supply rail are measured during position measurements with four anchor nodes. The average power consumption of the UWB module during a single localization is shown in Fig. 7. At t = 0 the tag initiates the two-way ranging by transmitting a single message to all anchor nodes. Subsequent the anchors respond in the order of their programmed ID.

To apply the DS-TWR algorithm the roundtrip information from the previous measurement is used to calculate the distance to the anchors. In average the energy required for a single localization is 4.9mJ. The peak power consumption during transmission is 226mW and 358mW during the reception. Compared to GPS based localization approaches, such as the state of the art low power GPS module ZEO-M8B from U-blox, there is a significantly reduced time to first fix from 30s to 81ms with an energy consumption of 2.4J, and 11mJ, respectively. Besides the reduced energy consumption, UWB is operational in indoor environments.

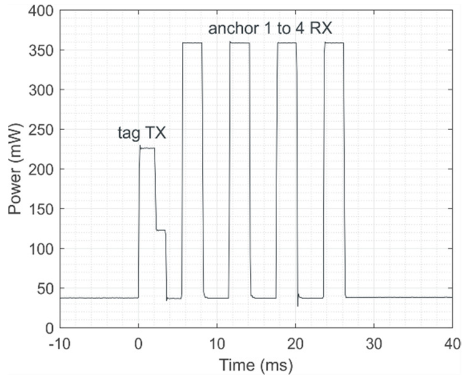

Fig. 7. The power consumption of the DW1000 implementation during two-way ranging with four anchor nodes.

IV. CONCLUSION

In this work, a highly accurate and low latency asymmetric double-sided two-way ranging algorithm that runs internally on an ARM Cortex-M4F microcontroller is presented. The algorithm is optimized for execution time, and a hardware platform is designed to evaluate the performance in terms of accuracy, precision, range, energy and sample rate. Experimental results show that the algorithm achieves 4.3cm of accuracy and 3.36cm of precision. Finally, the measured maximum sample rate achieved is of 20Hz with a localization time from the cold start of only 81ms, while consuming only 4.9mJ for position detected.

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