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AURORA

Precision Tracking Systems for Cultural Heritage Monitoring

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Abstract— This publication, as part of the Horizon Europe AURORA project [1] (<https://www.aurora-h2020.eu/>), describes the development of a low power consumption UltraWide Band (UWB) wireless indoor tracking device focussed on indoor localization of valuable artworks in a museum using wireless sensor network (WSN) technology. AURORA aims to advance the state of the Art in embedded tracking devices for cultural heritage artefacts, striving for minimal impact on the art object.

The goal of the Aurora project is to alert relevant museum staff to any anomalous movement of artworks and provide the base for precision real-time tracking of the location of the artefact in question. UWB technology is the most accurate wireless solution for indoor positioning. In comparison to alternative wireless technologies (e.g., Wi-Fi, BLE, LoRaWAN, ZigBee, and RFID), UWB possesses specific characteristics and capabilities that render it particularly suitable for accurate indoor localization.

Keywords— UWB tracking, Precision Localisation, Cultural Heritage Monitoring

I. INTRODUCTION

Among various wireless technologies for indoor localization, ultra-wide band (UWB) is currently one of the most accurate (cm-scale) real-time indoor positioning technology available to the consumer market [2],[3].

The specific characteristics of UWB technology for indoor localization are described below:

a) An indoor positioning system based on UWB facilitates highly accurate and precise tracking of objects or individuals within indoor spaces. UWB signals can determine locations with a location accuracy of less than 30 centimetres (under optimal conditions and deployment) and offer exceptionally low latency [5]. UWB surpasses other positioning technologies in terms of accuracy, resolution, and resistance to radio signal interference.

b) UWB can transmit radio frequency (RF) pulses at very high data rates over short ranges, and pinpoint exact

location in real-time. UWB utilizes short-range radio waves and operates with a high channel bandwidth (typically over 500 MHz) over a very wide frequency spectrum between 3.1 to 10.6 GHz. It also consumes very little direct current (DC) power, allowing for affordable and efficient hardware options, such as tracking tags with coin cell batteries that can operate for multiple years without being recharged or replaced [6].

c) Because of the low RF transmission power and wide spectrum of frequencies that UWB signals are transmitted with, allow for little to no interference with surrounding narrowband technologies, such as Wi-Fi, Bluetooth, and cellular networks. UWB also appears to be “invisible at noise floor”, making it a good choice for coexistence with narrowband RF technologies.

d) These unique properties are why UWB is quickly emerging as a premier indoor positioning technology for location-based and short-range communication applications. In the recent years, many major players have begun to realize the potential and possibilities of UWB for indoor localization and have started developing or releasing UWB-enabled solutions. Among the most notable, Apple Inc, began implementing UWB into their technology with the release of the iPhone 11, which came equipped with their new U1 ultra-wideband chip. Other companies, such as Samsung, have followed suit, implementing UWB into some of their newly released smartphones and other devices. Google is also working on developing an application programming interface (API) that will help enable UWB powered applications in Android devices [6].

e) UWB technology can so precisely detect location is due to its distance-based measurement via time-of-flight that calculates location based on how long it takes for RF pulses to travel from one device to another.

In Figure 1, the concept of an indoor localization system using UWB technology is demonstrated. The system aims to track real-time location of an artwork using an embedded wireless tracker (EWT), denoted as T, referring to a ‘tag’

that is attached to the artwork. UWB employs a two-way ranging (TWR) technique to determine the real-time location of the artwork. In TWR localization technique, a minimum of three anchors (denoted A_1 , A_2 , and A_3) are used, serving as fixed reference points. These anchors enable triangulation, facilitating the calculation of the precise position and coordinates of the Tag or EWT that the artwork it is attached to.

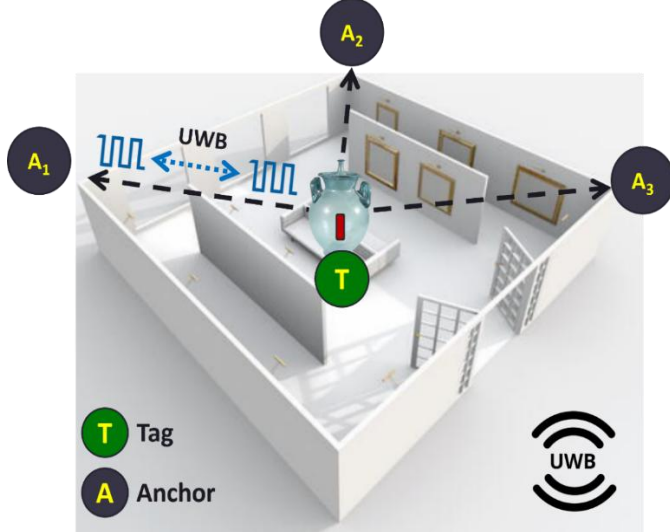


Figure 1: Concept of Indoor Localization using UWB technology.

The Tag transmits UWB pulses, and the TWR method calculates the distance between a Tag and an anchor as illustrated in Figure 2. Position information is determined by the time it takes for the UWB RF signals to pass back and forth between them (time of flight, ToF), then multiplying that time by the speed of light in a vacuum. Overall, this indoor localization system using UWB wireless technology with the TWR technique provides an effective and accurate means to monitor and trace the movement of artwork within indoor environments, enhancing security and tracking capabilities for valuable items in museums [4].

II. UWB LOCALISATION

A. Trilateration Concept for Localization

In localization systems employing anchors and tags, a minimum of three anchors is typically essential for accurate positioning, as shown in Figure 2. However, to enhance localization precision, additional anchors can be integrated into the system. Each anchor operates by reporting its respective distance from the tag, denoted as d_1 to d_3 . Leveraging the known locations of these anchors and the measured distances d_1 to d_3 , trilateration methods are employed to calculate the precise position of the tag. This process involves analysing the intersection points of spheres centered at the anchors to determine the tag's location. By utilizing trilateration techniques, such systems can achieve reliable and real-time tracking capabilities, vital for various applications ranging from indoor navigation to asset monitoring [2], [4].

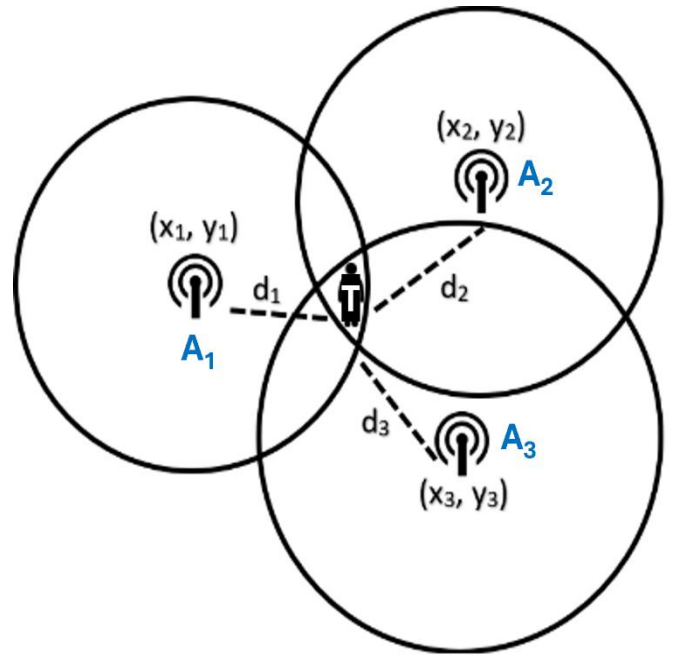


Figure 2: Trilateration approach of indoor localization [4].

B. Two-Way Ranging (TWR) Localization Technique

The TWR method calculates the distance between a tag and an anchor by determining the time it takes for UWB RF signals to pass back and forth between them (ToF) and then multiplying that time by the speed of light [7]. With multiple anchors, each requiring its own antenna, TWR can be used to determine the absolute position of mobile devices or other tags. An anchor is generally a fixed UWB device with a known location. A tag generally refers to a mobile UWB device. An anchor and tag exchange information to establish the distance between them. The exact location of a tag can be determined by wirelessly communicating with multiple anchors. By determining the distance to three or more anchors in known locations, the device can estimate its location with great accuracy on a cm-scale. The tag can then communicate the distance via UWB or another wireless technology such as Wi-Fi to location-based applications in the cloud, to gateways, or to a remote computer for display, as shown in Figure 3.

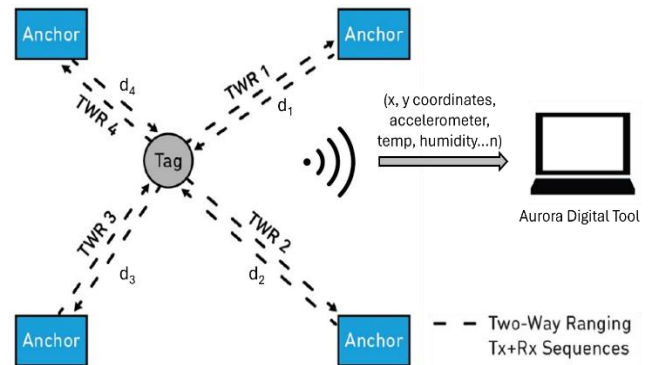


Figure 3: Two-way ranging (TWR) and wireless dataflow to a remote monitor [7].

As illustrated in Figure 4, the tag initiates TWR by sending a poll message containing the known address of an anchor. Upon receiving the poll message, the anchor records the time and promptly responds. According to Equation 1, when the tag receives the response, it calculates the signal time of flight (ToF) based on the signal round-trip time (T_{round}) and the time it took for the anchor to process and reply to the initial poll message (T_{reply}). The distance is then calculated by multiplying the ToF by the speed of light. The tag can then pass the calculated distance to the anchor in a final message, if required [7].

$$Time\ of\ Flight\ (ToF) = \frac{T_{round} - T_{reply}}{2} \quad (1)$$

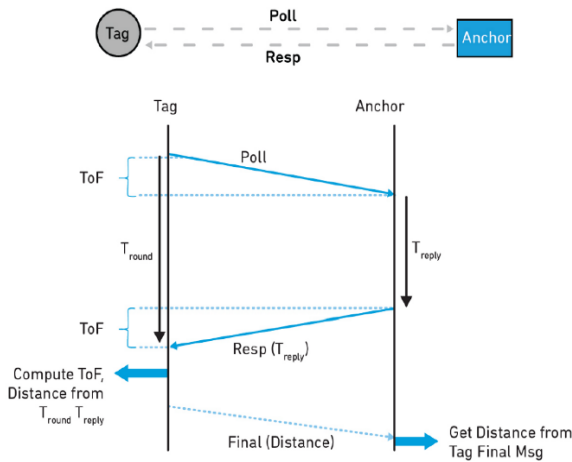


Figure 4: Secure two-way ranging between UWB tag and anchor [7].

III. ARCHITECTURE OF THE TRACKING SYSTEM

Using UWB and TWR technologies, a functional prototype for indoor localization has been developed. The architecture and data flow for the current working demo setup are depicted in Figure 5. As illustrated in Figure 5, Tag T_1 wirelessly collects distance information (d_1 , d_2 , d_3 , and d_4) from anchors A_1 , A_2 , A_3 , and A_4 , respectively. The tag is connected to a Raspberry Pi (R-Pi) module via a wired interface, and the localization engine algorithm runs on the R-Pi to calculate the real-time location data (x , y coordinates) of the tag. Finally, the graphical user interface (GUI) for the measured location data is sent to a laptop over Wi-Fi for display.

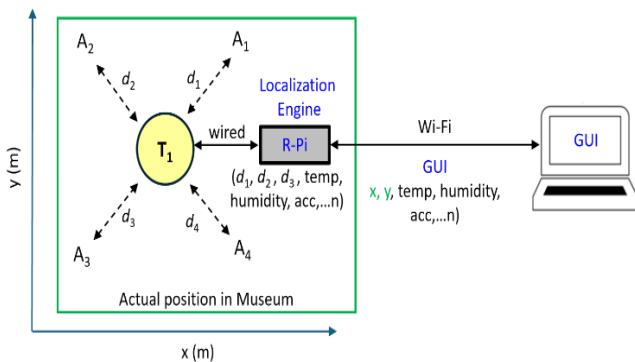


Figure 5: Architecture and dataflow for the developed demo setup.

As illustrated in Figure 5, the developed localization demonstration employs one tag/initiator and four anchors/responders. The demonstration comprises a tag T_1 (museum artwork object) to be localized using four anchors (A_1 , A_2 , A_3 , and A_4) installed at specified known locations. By utilizing the measured distances from the tag to each of the anchors, the x and y coordinates of the tag are calculated. The tag reports the four distances (d_1 , d_2 , d_3 , and d_4) from itself to the four anchors, which are then streamed on a serial port. Subsequently, an application on a Raspberry Pi facilitates the collection of the streamed data from the serial port and utilizes the known distances of the four anchors to compute the real-time location of the tag based on a trilateration algorithm.

The role of the tag (initiator) and anchors (responders) is summarized below:

1 tag: This includes a Qorvo DWM3001CDK module set to behave as an initiator and a Raspberry Pi that collects the distances and uses a trilateration algorithm to calculate the location of the tag in space.

4 anchors: These consist of Qorvo DWM3001CDK modules set as responders.

Each Qorvo DWM3001CDK module connects to the Raspberry Pi via USB, and at the laptop end, RealTerm software is employed to send commands to configure the module.

IV. INDOOR LOCALIZATION DEMONSTRATION IN A MUSEUM

The indoor localization demonstration was performed at the Cork Public Museum in Cork, Ireland [11]. As depicted in Figure 6, the museum is housed in a mid-19th-century building located in Fitzgerald Park, in the Mardyke area of the city. The museum's exhibits primarily highlight the history and archaeology of the Cork region. The aim of the demonstration was to assess the performance and accuracy of the developed Embedded Wireless Tracking (EWT) system within a realistic museum environment.



Figure 6: Demonstration site-Cork public museum, Cork, Ireland [11].



Figure 7: Tag and Anchors inside a room at Cork public museum [11].

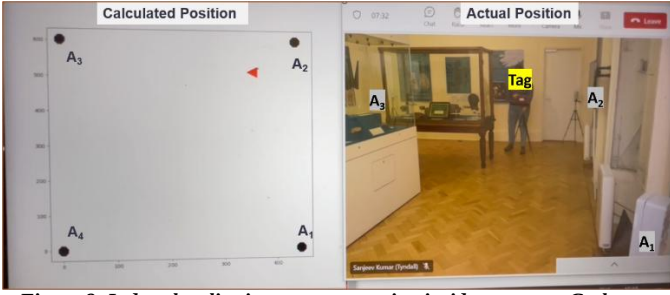


Figure 8: Indoor localization accuracy testing inside a room at Cork public museum.

Typical objects that are found in a museum environment are made of diverse materials such as metal, wood, stone, ceramic, bone, and glass, all of which can interfere with radio frequency signal propagation to varying degrees. Each material interacts with propagating RF signals uniquely, affecting the signal's strength, direction, and quality of service. Metallic objects, for instance, are highly reflective and can scatter signals and lead to undesirable effects such as multipath fading where signals take multiple paths to reach the receiver, causing signal distortion and inaccuracies in localization [12]. While stone, ceramic, and bone are less reflective than metal, they can also absorb RF energy, leading to signal attenuation, and thus affecting the reliability of indoor localization systems [13]. Furthermore, depending on density and moisture content, materials such as wood can absorb RF energy to varying degrees, impacting signal propagation unpredictably [14].

The developed Embedded Wireless Tracking (EWT) system aims to accurately locate valuable museum artworks in real-time within a museum room that simulates a typical museum space, comprising various valuable items made of different materials such as wood, glass, stone, metal, and clay. To establish reference points, four anchors labelled A_1 , A_2 , A_3 , and A_4 were strategically positioned at the room's corners using tripods as shown in Figure 7. The tracking process involved moving the tag across the room and measuring its position in real-time. The tag communicates with the anchors via UWB wireless technology, which allows for precise distance measurements. These distance measurements are then used to compute the tag's real-time position within the room. During the demonstration, the calculated position of the tag was compared against its actual position to assess the accuracy and effectiveness of the tracking system.

In our design, we intentionally opted for the use of UWB technology due to its inherent resilience against multi-path fading effects. UWB exhibits strong immunity to multi-path fading because it measures time of flight rather than relying on signal strength or RSSI methods [6]. Despite the presence of several metal objects in the museum room, as depicted in Figure 7 and 8, we observed no discernible effect on the UWB performance. Additionally, the room contained extensive cabling along the walls, which also had no observable impact on the localization accuracy that we measured.

Throughout our trials at the Cork Public Museum, we compared actual and calculated/measured distances. The actual and calculated positions of the tag within the museum room space at six distinct coordinate points (A, B, C, D, E, and F) with x, y coordinates (in cm) are respectively shown in Figure 9 and Figure 10.

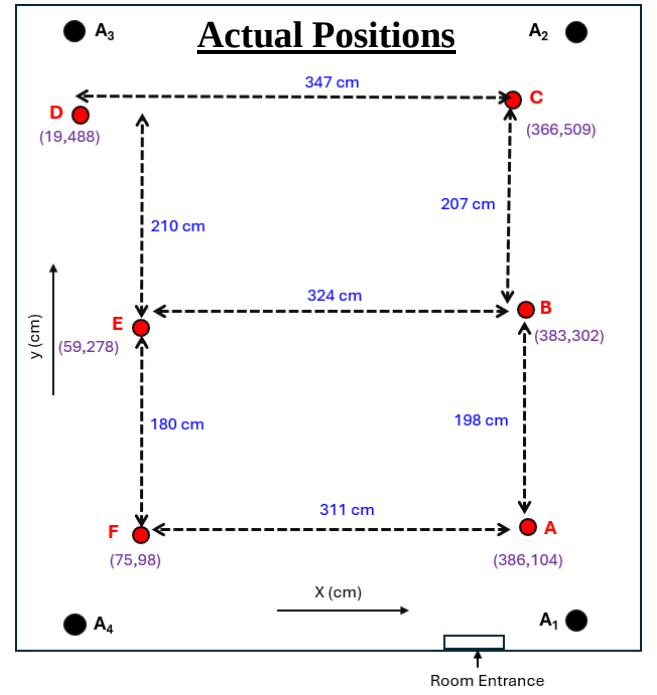


Figure 9: Representation of the actual position of the tag within the museum room space with x,y co-ordinate system defined.

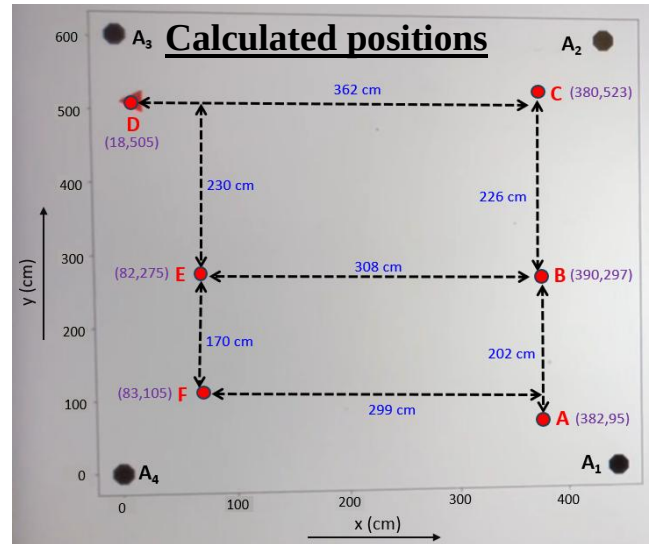


Figure 10: Calculated position of the tag within the museum room space.

Table 1: Actual vs calculated position.

Po int	Actual Position (cm)		Calculated Position (cm)		Error (cm)	
	x	y	x	y	x	y
A	386	104	382	95	4	9
B	383	302	390	297	7	5
C	366	509	380	523	14	14
D	19	488	18	505	1	17
E	59	278	82	275	23	3
F	75	98	83	105	8	7

The actual and calculated positions of the tag at six distinct coordinate points, along with the localization error are summarized in Table 1. It is evident from the data in Table 1 that the maximum error between actual and calculated positions is 23 cm. In this task, it has been demonstrated that UWB technology enables accurate indoor distance measurements and, through trilateration, allows for pinpointing the location of an object with an average accuracy of <23 cm. This setup not only provides valuable insights into the system's performance but also demonstrates its potential application in safeguarding and managing museum artifacts.

CONCLUSIONS

This manuscript has presented the technical work completed as part of the AURORA project in demonstrating a prototype, UWB wireless indoor tracking system for localizing cultural objects within a museum environment. An evaluation-kit based prototype of the proposed embedded wireless tracking (EWT) device was realized and demonstrated in this task. Ultra-wideband (UWB) wireless technology was chosen because of its inherent cm-level localization accuracy. Firstly, the theoretical background for indoor localization using the Two-Way Ranging (TWR) technique was discussed. The two key system level modules are the Qorvo DWM3001C module [8] [9] with integrated UWB and BLE antennas, and a Raspberry Pi [10].

Finally, the developed prototype was successfully demonstrated in a museum scenario to track the movement of a target cultural object in the Cork Public Museum in Cork, Ireland. This study demonstrated that the developed wireless tracker was capable of real-time indoor localization with a best-case positional accuracy of 3 cm, a worst-case accuracy of 23 cm and an average accuracy of just under 10 cm as illustrated in Table 1. These accuracy figures compare well with the 30 cm localization accuracy specified in [5]. The next task will develop a custom designed embedded wireless tracker, focussed on miniaturisation of the tracker device as well as minimizing energy consumption and positioning optimisation to enable long term monitoring and tracking of cultural artifacts in museums.

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