A two-phase location measurement system for indoor static sensors

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ABSTRACT

Being able to fast and accurately measure a static object's coordinate in a complex indoor environment is very useful. For example, we can build a (sensor, coordinate) dataset for indoor sensor networks to provide a location-aware context which is necessary for an intelligent Internet of Things(IoT) system. In this report, we propose two wireless systems for the measurement task mentioned above. Each of our systems will have two measurement phases, and with our careful design, each measurement phase is in line-of-sight(LOS) condition, which boosts our measurement accuracy. We name the first system, Laser-UWB mobile relay system(LUMR), which consists of UWB indoor positioning sub-system and laser-orientation location sub-system. The second system is Mobile Relay as Mobile Anchor system(MRAMA). This system only uses UWB indoor positioning system. We show that our first system can achieve errors less than five cms in both the x and y-axis and that of the second system is less than ten cms.

1 INTRODUCTION

Nowadays, the Internet of things(IoT) gets popular again in academics and industry. Applications and concepts like smart manufacturing, smart home, and smart maintenance are emerging fast. People deploy sensors to monitor the environment and detect abnormal events. To better analyze the sensor's data and find the correlation, knowing the sensors' location is essential. Location is typically the coordinate of the object. With the location information, we can bring the location-aware ability to the sensor network, which is important for some advanced IoT services. While acquiring the location information is non-trivial, a straightforward method is to use traditional measurement tools such as a ruler or a laser measure to measure the distance and calculate coordinate from a distance. According to our real deployment experience, within a complex indoor environment, manually measuring the coordinate can have the following problems: (1) It is labor and time consuming (2) For some hard-to-measure spot, manually measuring is not applicable (3) The measurement result may be inconsistent. (4) It is not scalable for the size of the modern sensor network. So, can we find an automatic way to localize static sensors in a complex indoor environment?

There are several well-developed positioning systems available. GPS is the most popular positioning system in the world. This system can provide meter level accuracy in the outdoor environment, while it does not work well in the indoor environment. Because our application setting is an indoor environment, we cannot use the GPS. The other kind of system is the vision-based positioning system. The system uses cameras and computer vision techniques to locate objects. This system is accurate, but it needs the line of sight(LOS) condition. In other words, there should be no obstacles between cameras and target objects. Other problems with this system are that it is expensive and hard to install. It is an overkill for our problem. With the fast development of wireless network techniques, there are many wireless-based indoor positioning systems. Researchers can use WIFI, Bluetooth, UWB, and even acoustic signals to locate objects. These systems have high accuracy with LOS conditions, but the accuracy is decreased under NLOS conditions, especially when the obstacle is made of metal.

Below we are using a commercial UWB system to do a toy experiment. As shown in figure 1, we put two tags A and B one meter away from the anchor. We put a thin metal plate right in front of tag A to build a metal NLOS condition. We put nothing between tag B and the anchor. The tag can measure the distance between itself and the anchor in centimeter resolution. The average measurement result of tag B(LOS) is 1.05 meters while the result of tag A is 1.30 meters. Although the UWB system contains the advanced NLOS detection algorithm, it still suffers a lot from the influence of the metal obstacle. On the other hand, we can find the UWB system has a high localization accuracy under LOS conditions.

Our systems intuition is to break the NLOS path into two LOS paths, as shown in figure 2. The mobile relay shown in the figure helps us connect the anchor and the target with two connected LOS paths. The target location can be easily added with two coordinates:(1) the mobile relay coordinates with the anchor as the reference point. (2) the target coordinates with the mobile relay as the reference point. Following this idea, we design two practicable systems to automatically measure the static target's coordinate in a complex indoor environment. We named one system as the "laser UWB mobile relay" system, and its location result is less than 5 cm in both the x and y-axis. Another system is called "mobile

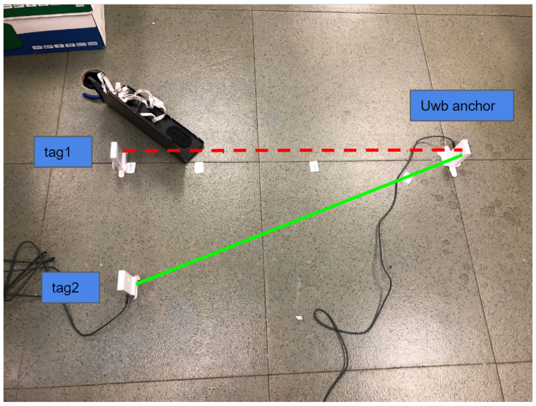

Figure 1: A toy experiment to show the poor accuracy under metal NLOS condition

relay as mobile anchor" system, and this method can achieve a sub-decimeter location error.

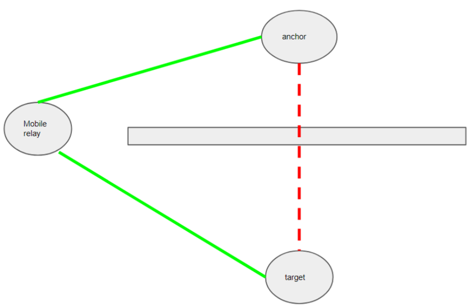

Figure 2: A diagram to demonstrate our idea

We review previous related work in section 2, introduce some background for the UWB location technique in section 3. Then we will describe our two systems in detail in section 4. In section 5, we will show our two systems' implementations and how we build our experiment environment. We will compare our two systems with a baseline method and give a thorough analysis in section 6. In the last two sections, 7 and 8, we will discuss the limitation, future work, and summarize our work.

2 RELATED WORK

Current existing NLOS UWB localization algorithm mainly consists two categories, based on whether NLOS identification is involved.

The first category to alleviated the effect of NLOS does not involving a NLOS identification, i.e. does not determinate whether the target chip is NLOS or not. Approaches in this category does not have clear classification, nonetheless here are some examples: [9][10][7]

The second method, which is most common one, is to identify NLOS before localization and utilized the information extract from such process and then perform some sort of adjustment in the localization process. Conventional NLOS identification have three subcategories, range based identification, channel based identification, and location based identification[8][1]. Range based NLOS identification mainly employs the probability density function to identify whether the target is NLOS. Channel based identification applies the channel impulse response to distinguish NLOS from LOS[5]. Differ from two previously mentioned cases, which identify NLOS prior to the localization, location based identify NLOS during the localization process. Location based identification uses redundant range estimation (location estimates produced by different subsets of range estimates [2]) to identify NLOS. In addition to the above three method, NLOS can also be deduced from environment information such as map of the operation terrain. However, this method involves extra information, therefore will not be considered.

In addition to previous two category, there are some novel approaches using deep learning to mitigated the effect of NLOS, here are some example: [3][6][4]

3 PRIMER

3.1 Ultra-wideband(UWB)

Ultra-wideband is a radio technology with several features: (1) low energy consumption (2) high-bandwidth(500MHZ) (3) short-range (4) high frequency. The Ultra-wideband was formerly known as pulse radio. Unlike other radio technology such as Bluetooth and WIFI, its signal consists of many short pulses(2 nanosecond pulses) in the time domain. Because of its short pulse nature, UWB is robust to multipath fading, a common problem for other radio technology with low bandwidth. That advantage makes UWB a good choice for time-of-flight based localization. Using UWB, a modern indoor positioning system can achieve decimeter level accuracy.

3.2 UWB indoor positioning system

Two different positioning techniques are available with the UWB radio technique: (1) two-way ranging(TWR) (2) time difference of arrival(TDoA). Because we are using TWR in our system, we will give a brief introduction to the principle of TWR based positioning system. In a minimal positioning system, there are several anchors and a tag. The anchor is typically static(hanging on the ceiling). The tag can be mobile or fixed and is attached to the target. In each measurement, the tag will first synchronize the clock with all anchors. Then the tag will get the time-of-flight between itself and each anchor. The tag multiplies the time-of-flight with the light's speed to get the distance between itself and each anchor.

If there are four anchors, the tag will get four distances. Finally, the tag will use some trilateration algorithms to get its coordinate with anchors as references.

4 SYSTEM DESIGN

As we discussed above, we can easily get the target's absolute coordinate by summing two coordinates(the relative coordinate of the mobile relay and the relative coordinate of the target) together. Though the idea is simple, there are two challenges we need to solve before we can get an accurate result. The first challenge is how can we measure the coordinate of the mobile relay accurately. The second challenge is, with the restricted of the size and the portability of the mobile relay, how can we measure the relative coordinate of the target from the mobile relay

Our solution to the first challenge is to leverage the commercial UWB indoor location system. As we discussed in the toy experiment, we can find that, in the LOS condition, the system has acceptable accuracy. The problem is how can we maximize the probability of the LOS condition for our mobile relay. Our design is to embed the mobile relay into a goggle. Our intuition is there are rare obstacles between the head and the UWB anchors hanging on the ceiling, so that most time, the UWB tag on the mobile relay will be in a LOS condition. Even when the mobile relay is in an NLOS condition, the operator wearing the goggle can easily detect it and adjust his/her location to a LOS area. Another benefit is the operator can easily adjust his/her position to "convert" an NLOS path to two LOS paths. We can see our system cannot get rid of human participation. Compared to the manual measurement methods, as we will discuss in the following parts, our method is simpler and user friendly. We want to call it semi-automatic measurement.

We have two methods to measure the target coordinates from the mobile relay(challenge 2), and those two methods also lead to our two systems. One is called "laser-UWB mobile relay" system. The other one is called "mobile relay as mobile anchor" system. Note the two systems share the solution to the first challenge, so we will only discuss how we measure the target coordinate from the mobile relay.

4.1 Laser-UWB mobile relay system

The system design can be illustrated with figure 3. In this design, we use the laser emitter, laser distance sensor, and the orientation sensor on the mobile relay and the laser receiver on the target to build a system to measure the target coordinate. We use the laser emitter on the mobile relay and the laser receiver to aim the target and trigger the measurement process. The laser distance sensor can accurately measure the distance between the mobile relay and the target. We use the orientation sensor to measure the orientation of the mobile relay. These sensors' reading can be easily fused based on the basic geometry formula to get the target coordinate with the mobile relay as the reference point. Below we list the auto measurement process.

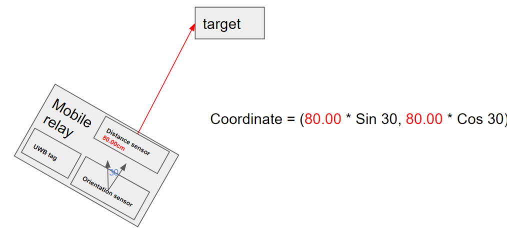

Figure 3: An illustration of Laser-UWB mobile relay system

The user needs to use the laser on the goggle to aim the laser receiver. When the laser hits the laser receiver on the sensor, it will trigger several measurements and communications.

(1) The measurement operator uses the laser on the goggle to aim the target with a laser receiver on it.
(2) After the laser receiver is receive the laser signal. It will send a its ID and a measurement request to the server.
(3) The server will collect the current mobile relay's location from the UWB location system and collect the mobile relay's orientation and the distance between the mobile relay and the target.
(4) The server will use the collected data to calculate the coordinate of the target.
(5) After getting the target's coordinate, the server will store the (target ID, coordinate) key-value pair in a specific database.

4.2 Mobile Relay as Mobile Anchor system

We use figure 4 to illustrate our idea of this system. With our observation, the obstacles will not totally block all UWB anchors from the target. The most common case is the target is attached behind a surface, so at least two anchors are still in the LOS condition. With this observation, we propose our second system.

In the left part of figure 4, we illustrate the common NLOS condition in a 2D localization scenario. As shown in the figure, the target is behind a metal surface. Only two of the anchors(bottom left and bottom right ones) are in LOS condition, providing accurate distance and enough information for trilateration. In contrast, two of the anchors(top right and top left ones) are in NLOS condition, which will provide

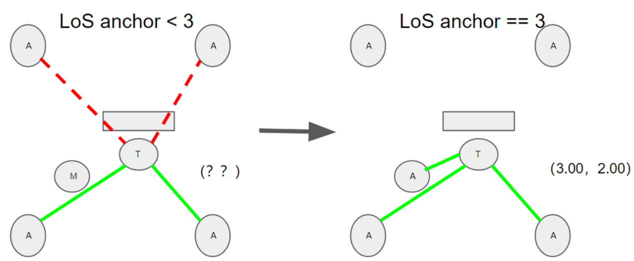

Figure 4: An illustration of Mobile Relay as Mobile Anchor system

the wrong distance to trilateration. If we directly fuse those four distances, we will get a bad result, as discussed in the result section. To get an accurate result, we need to detect the NLOS anchor in the trilateration process and only use the distance from LOS anchors.

In the 3D localization scenario, two LOS anchors are not enough to perform trilateration as shown in the left part of image 4. We cannot calculate the coordinate of the target in this case. Besides detecting NLOS anchors, we also need to add one LOS anchor to the current UWB positioning system. We notice the mobile relay(as a UWB tag) can be easily set up as a UWB anchor. We can use the mobile relay as the extra anchor to increase the count of the LOS anchor to three so that we can successfully do trilateration in a 3D scenario as shown in the right part of figure 4. The detailed measurement process is listed below.

(1) The measurement operator wear the mobile relay and move to a position where he is in LOS condition with at least three anchors and the target.
(2) The measurement operator uses the laser emitter-receiver triggering system to start the measurement process.
(3) After receiving the triggered signal, the server will first measure the location L of the mobile relay.
(4) Then, the server will set the mobile relay as a new anchor in the system and set the anchor location to L.
(5) The server will use the new UWB anchor system to measure the target coordinate.
(6) Finally, the server will store the (target ID, coordinate) key-value pair in a specific database.

5 IMPLEMENTATION

5.1 UWB indoor positioning system

We use a commercial UWB localization development kit from DecaWave company. The kit consists of 12 development boards, and we can set up each of them as a tag or an anchor. We can use a lithium battery or a USB charger to power each development board. Each board embeds a firmware for two-way-ranging trilateration and an Android app where we can view the localization result and change the system settings. The lowest level of information provided by the development board is the distance between an anchor and a tag. We cannot get the raw signal from the boards. Each board has an embedded circuit and firmware to convert the raw signal to the output distance. The official advertised accuracy is at the decimeter level(error less than 10 cm). We used four development boards to build a 2D positioning system, as shown in the following experiment setup section.

5.2 Mobile Relay

We build a mobile relay we discussed in the above section, as shown in figure 5. We embed a UWB development board, an orientation sensor(BNo055), a distance sensor(VL53L0X), a laser emitter, and a portable charger on a 3D printed module raspberry pi zero w to the mobile relay. The BNo055 orientation sensor is a 9-DOF sensor with an embedded sensor fusion algorithm. We can directly read out the absolute orientation in Euler vector format with a 100HZ frequency. We can get a very accurate orientation measurement with a careful calibration(calibration time is about 1 minute). The VL53L0x distance sensor works with the time-of-flight principle and can accurately measure the distance from 30mm to 1000mm. We didn't calibrate the above two sensors very carefully because the total error introduced from the sensors is negligible to the UWB positioning system's typical error. The UWB development board has an interface for raspberry pi to connect to the raspberry pi directly. The raspberry pi works as the server we mentioned in our system design. It can: (1) receive the triggering signal from the laser receiver(the laser receiver sends the signal to a raspberry pi, and the raspberry pi sends the signal to the raspberry pi on the mobile relay.) (2) use UART interface to communicate with the UWB tag to get the coordinate, set a tag to anchor, etc. (3) calculate the target's coordinate. The building price of this mobile relay is about 50 dollars.

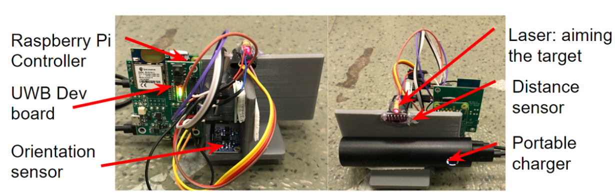

Figure 5: Mobile relay

5.3 Experiment environment setup

In this project, we finish our experiment in a 2D localization scenario instead of 3D to simplify the experiment. The 3D experiment will be a part of our future work. As shown in figure 6, we set 4 anchors(1.83m x 2.44m) at four corners and put a metal object in the middle of our experiment. We use the UWB tag as our target and directly attach it to the back of the metal object to mimic a scenario that a sensor is attached at the back of metal equipment. The mobile relay is put at the bottom left corner of the target. We make sure the mobile relay is in LOS condition with all anchors.

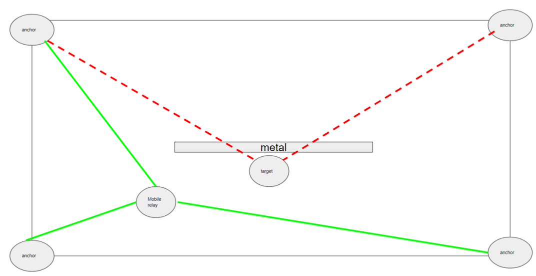

Figure 6: Diagram of our experiment environment setup

The real deployment is shown in 7. We find the two-way ranging distance is more accurate if we set the anchor and the tag with an angle smaller than plus/minus 45 degrees. To maximize accuracy, we adjust each anchor's orientation and make each of them face the center of our environment. We use a desktop as a metal obstacle. We use a tag as our target.

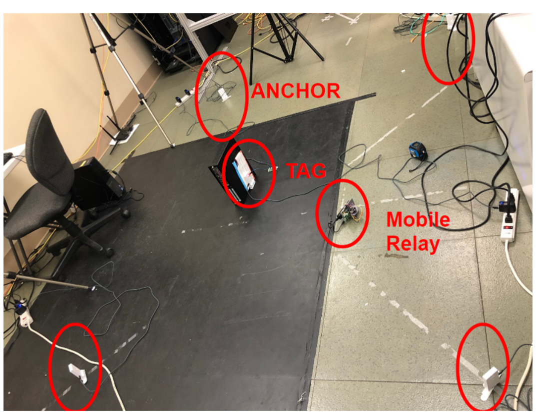

Figure 7: Real deployment of our experiment environment

6 RESULT & EVALUATION

With the restriction of time and building access, we only did one set of experiments with the above experiment environment. Because there is only one experiment result, the result does not have a statistical significance and cannot prove our system's real effectiveness. We want to use the result to prove the concept of our systems. In future work, we can do more experiments to get statistically significant results and prove our system's effectiveness. We summarize our result in table 1

Method	Coordinate(m)	Error(cm)
GT	(1.22, 1.22)	(0, 0)
B	(1.23, 0.98)	(+1, -24)
LUMR	**(1.18, 1.19)**	**(-4, -3)**
MRAMA	(0.96, 0.18)	(-26, -104)
MRAMA'	(1.27,1.13)	(+4, -9)

Table 1: Experiment Result(GT: ground truth; B: Baseline; LUMR: Laser-UWB mobile relay system; MRAMA: Mobile Relay as Mobile Anchor system, MRAMA': Mobile Relay as Mobile Anchor system(remove NLOS anchors)

Measurement	Ground Truth	Result	Error
UWB	(0.79, 0.56)(m)	(0.77, 0.54)(m)	(-2, -2)(cm)
D	74.5 cm	74.0 cm	-0.5 cm
O	28.76 degree	27.57 degree	-1.19 degree

Table 2: Measurement Results for Laser-UWB mobile relay(UWB: UWB localization result of the mobile relay; D: distance between the mobile relay and the target; O: the orientation of the mobile relay)

The experiment environment setting is shown in figure 6 and 7. The ground truth coordinate of the tag is (1.22 m, 1.22 m). The baseline method is to directly use the four anchors to locate the tag with the provided algorithm and Android application. The result is (1.23 m, 0.98m). The metal blocks the signal's directed path from the anchor to the target, so the signal will take a longer path to arrive at the tag from the anchor. The tag will think the longer path's distance is the real distance between itself and the anchor, so the output distance from the NLOS anchor will be longer than the real distance. The trilateration algorithm takes the wrong data in so that the output coordinate will have a large error.

The result we get from Laser-UWB mobile relay system is (1.18m, 1.19m). The error is less than 5 cm in both the x and y-axis. We are not surprised when we get this result. In this method, we fuse three measurement results to get the target coordinate. The three measurements are (1) UWB localization results of the mobile relay. (2) distance between the mobile relay and the target (3) the orientation of the mobile relay. We compare each measurement's ground truth and the measurement result and summarize the result in table 2. We can find that each measurement error is small, so it is no wonder the fused coordinate will be very accurate.

The result of Mobile Relay as Mobile Anchor system is (0.96m, 0.18m), which is far worse than other methods. We exam the embedded trilateration algorithm and find the algorithm will choose four distances (we don't know the choosing rule) to calculate the coordinate. In our case, the algorithm chooses the distance between the tag and two LOS anchors, our mobile relay(also a LOS anchor) and an NLOS anchor to calculate the coordinate. The input from the NLOS anchor influences the final result a lot. To get a good result, we need to detect the LOS anchors and only use the LOS anchors' distance results to calculate the coordinate. We manually turn off the two NLOS anchors as if we can detect NLOS anchors and get another result that we name it MRAMA' in table 1. The new result is (1.27, 1.13), which has sub decimeter error as advertised. Here we assume we can detect the NLOS anchor. In future work, we will develop a system or algorithm to detect NLOS anchors automatically.

In summary, though we only have one experiment result, we show our Laser-UWB mobile relay system can almost automatically localize the static target with high accuracy. The Mobile Relay as Mobile Anchor system currently has some limitations, but we will try to solve them in future work.

7 LIMITATION & FUTURE WORK

[Use of commercial UWB development kit]

In this work, we directly use the commercial UWB system and the embedded algorithm. The system only supports the two-way ranging distance. We cannot use this development kit to build some innovative algorithms from scratch. In the future, we can develop our UWB system and design our algorithms.

[Assume the UWB system exists]

We assume there is a UWB system, or we need to install such a system in the environment where we want to deploy sensors. Though this assumption is not true today, we believe in the near future that the UWB indoor location system will be a standard for buildings as many mobile device manufacturers have embedded UWB chips in their devices.

[Bulky and extra hardware]

Our system needs extra hardware such as the mobile relay and goggles. In the future, we can leverage the existed hardware such as the UWB chip and the camera in our mobile phone to rebuild this measurement system. In the future, after you deploy some sensors for your smart home, you can use your phone to locate each sensor directly. With that location information, you can (1) upgrade your smart home system with the location based context to get more advanced services (2) automatically label the sensor's location into your home floor plan to help you manage and visualize each sensor more straightforwardly and intuitively.

[Short of experiment result]

We only have one experiment result in a 2D scenario. In future work, we will do more experiments in both 2D and 3D scenarios to give statistically meaningful proof of our systems' effectiveness.

8 CONCLUSION

In this report, based on the UWB indoor localization technique, we propose two systems to automatically measure the coordinate of static targets in a complex indoor environment. We build prototypes for both systems and test their accuracy. Our Laser-UWB mobile relay system can localize the target with errors in the x and y-axis less than five cms. After selecting the right anchors, our Mobile Relay as Mobile Anchor system has an error which is less than ten cms in both axes. We learned the limitations and possibilities of current commercial UWB indoor positioning systems. In the future, we hope to see more interesting and practical systems based on UWB techniques.

9 ACKNOWLEDGEMENT

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