UNIVERSITY OF BERN

BACHELOR THESIS

Indoor positioning using Raspberry Pi with UWB

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Declaration of Authorship

I, Mischa WENGER, declare that this thesis titled, "Indoor positioning using Raspberry Pi with UWB" and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed:

Date:

"Thanks to my solid academic training, today I can write hundreds of words on virtually any topic without possessing a shred of information, which is how I got a good job in journalism."

Dave Barry

UNIVERSITY OF BERN

Abstract

Faculty Name
Institute of Computer Science

Bachelor of Science in Computer Science

Indoor positioning using Raspberry Pi with UWB

by Mischa WENGER

The Thesis Abstract is written here (and usually kept to just this page). The page is kept centered vertically so can expand into the blank space above the title too…

Acknowledgements

The acknowledgments and the people to thank go here, don't forget to include your project advisor…

Contents

List of Figures

List of Tables

List of Abbreviations

ACK	**ACK**nowledgement
GPS	**G**lobal **P**ositioning **S**ystem
IMU	**I**nertial **M**easurement **U**nits
IoT	**I**nternet **o**f **T**hings
M2M	**M**achine **2**(to) **M**achine
RTT	**R**ound **T**rip **T**ime
RSSI	**R**eceived **S**ignal **S**trengh **I**ndication
SDS-TWR	**S**ymmetrical **D**ouble **S**ided - **T**wo **W**ay **R**anging
TDOA	**T**ime **D**ifference **O**f **A**rrival
ToF	**T**ime **o**f **F**light
TWR	**T**wo **W**ay **R**anging
UWB	**U**ltra **W**ide**B**and

Physical Constants

Speed of Light $c_0 = 2.997\,924\,58 \times 10^8\,\mathrm{m\,s^{-1}}$ (exact)

List of Symbols

a	distance	m
P	power	W ($\mathrm{J\,s^{-1}}$)
ω	angular frequency	rad

For/Dedicated to/To my…

Chapter 1

Introduction

1.1 Motivation

In the last twenty years, the number of mobile devices in use has tremendously increased. In the first quater of 2018 more than 380 Million smartphones have been sold worldwide *Gartner Gartner Says Worldwide Sales of Smartphones Returned to Growth in First Quarter of 2018*. However, in the past few years, not only smartphones have been sold, but also a new market of mobile gadgets and connected devices, summed up as Internet of Things, has evolved. In 2017, more than 20 Billion devices were connected to the internet. Forecasts predict 30 Billion devices in 2020 and already more than 70 Billion in 2025. *Statista Internet of Things - number of connected devices worldwide 2015-2025*

This increase in mobile computing has also increased the demand of accurate real-time positioning systems, which led to an active research mainly in indoor positioning system technologies, as there are established solutions for outdoor positioning.

1.1.1 Indoor difficulties vs Outdoor

For outdoor applications, primarily the Global Positioning System (GPS) is in use. For indoor application in the other hand, GPS has limitations that make it almost useless. Due to the environmental conditions indoors, with heavy walls armoured with steel and other distractions, additional signal loss is encountered which makes it hard to detect and decode GPS signals. Kerem Ozsoy and Tekin, 2013 In addition, higher buildings in the neighborhood can reflect transmitted signals, which leads to false position estimations. As GPS is mainy applied as 2D positioning system, it will not provide 3D indoor information such as the current floor level For this purposes we are forced to use alternative technologies that provide even higher accurracy indoors than GPS would achieve outdoors. There are many different approaches to do indoor positioning, which made it an attractive and active research field.

1.1.2 Important Applications

There are various possible use cases for devices that track their indoor position. These use cases can be grouped into two groups. In the one hand applications for pedestrians with a smartphone and in the other hand real machine to machine (M2M) applications.

Some examples for Smartphones:

Location of person in need For emergency services every second counts to get to the position of persons in need. An accurate positioning system that indicates additional information such as the floor level could save lifes.

Security Guards Real time tracking of security guards on their patrol. A security system can check autonomous if all security guards are on the right tracks.

Museum guidance Tourists visiting a museum could easily be guided through the museum with customized location based information.

Examples for Machine to machine (M2M):

Logistic An autonomous storage system can find articles in a big storehouse according to the exact position of the carrier vehicle. Numerous vehicles can be in use at the same time.

Cleaning An autonomous cleaning machine keeps track of its position, such that the floor can efficiently be cleaned.

Indoor post roboter An autonomous roboter can collect letters in the building and bring them to the internal post office.

1.2 Idea

For an object in space, there are several basic ideas to keep track of its current location. We can define a starting position and keep track of every move the device registers. E.g. every visitor in the museum starts at the entrance and will then walk through the building. Alternatively the object can be tracked by defining at least three triangulation points and periodically measure the distance from these points to the device. There are various ways to measure this distance, some with higher and some with lower accuracy.

1.2.1 Ranging Positioning System with different Inputs

Our idea was to not only use one of the mentioned approaches, but to combine them to in one alorithm. We would use a range positoning system combined with motion detection of the device and even integrate environmental restrictions, given by floor topologies like walls. By combining different methods we hope to compensate measurement errors and thus minimize the overall errors.

1.3 Contributions

In this thesis we present a real-time indoor positioning system on Raspberry Pi based on a particle filter implementation in smartphones, developed in previous works of the University of Bern. Neto, 2018 We adapted the inputs of the particle filter to range-based localization using ultra wideband (UWB) instead of Wi-Fi and added motions measured by inertial measurement units (IMU) of the target. We expound results of our experiments, where we tested different variants of our implementation and other algorithms in a real test scenario and compared the accuracy of the estimated position.

Our main contributions are:

- We implemented a real-time localization system on raspberry pi using UWB and IMU sensors.
- We created an extensive test scenario, where we placed several anchor nodes in a real building and collected data on complex indoor trajectories.

- We compared the results of our implementation to the results of an UWB based localization system provided by Uniset Company.

1.4 Overview

Our work compounds of five remaining chapters: Section 2 provides the theoretical background and related work. Chapter 3 presents the theoretical system design and chapter 4 more specifically explains our system implementation and the test bed. The evaluation of our experiments can be found in section 5. Finally the sixth part concludes the work, where our findings are summarized.

Chapter 2

Theoretical Background and Related Work

In this section we explain the different types of range measuring in range-based localization systems. For comparison reasons, we shortly introduce variants of received signal strength indication (RSSI), which is the mostly used indoor localization technique. We then briefly explain two slightly less common methods, which were used in our system - two way ranging (TWR) and time difference of arrival (TDOA). We also include some background theory about our implementation and the particle filter.
These are the main parts of this section:
First a short overview of range based localization with the mean principles of RSSI, TWR and TDOA as well as the concept of triangulation/trilateration and the weighting process. Second we present background information about ultra wideband (UWB) and finally information about the particle filter is given.

2.1 Range based localization

Range based localization systems are depending on an infrastructure in the area of the localization:

- **Target Node (TAG)** which is the device that is localized.
- **Anchor Nodes (AN)** that are placed on carefully chosen points in the building, to encounter the best coverage of the whole area.

FIGURE 2.1: A simple ranging process.

As shown in figure 2.1, a simplified localization system work as follows: Either the TAG, the anchor or both of them collect data used for localization. The data can be a signal strength, a round trip time or IMU measurement. In a processing unit - on the TAG or on a seperate server - the data is processed and converted into a distance. This is repeated for every anchor node. The last step contains trilateration of the position using the ranges of every AN to the TAG.

In this abridged scenario, some difficulties are left out. Full indoor localization systems are more complex, as they use ingenious algorithms to improve the accuracy of the estimated ranges or improve the system by adding weighting to deal with incorrect range measures.

2.1.1 Received signal strength indication

As already mentioned, many indoor positioning algorithms use received signal strength indiacation to calculate distances to the anchor nodes. Mainly because RSSI can be applied to almost every type of transmitted signal thus RSSI uses the universal theory of free-space path loss. The following formula describes the relation between the received signal strength and the distance to the transmitter. *Computernetze Vorlesungsunterlagen Uebertragungsmedien*.

$$P_r = P_t(\lambda/4\pi r)^2$$

P_r - received signal strength
P_t - transmitted signal strength
λ - wavelength
r - radius (distance from transmitter to receiver)

However, this formula is restricted to free-space. There are several different kind of distractions that can affect the accuracy of the measurements in an indoor environment. For example the following occurences:

- Multi-path propagation
- Reflections
- Diffraction
- Doppler effect
- etc.

Signal strength can often be obtained from the transmitter hardware as a discrete number. The higher the number, the stronger the signal. This discretization reflects another source of errors.

2.1.2 Round trip time: Two way ranging, time difference of arrival

Gathering round trip times (RTT) is a second method to get distance estimations. For accurate RTT results the hardware of transmitter and receiver, as well as the operating firmware are very important. For the presented two RTT-measuring communication techniques, the key characteristics are either a quick responding time or extremely well synchronized TAG and AN.

Operating in two way ranging (TWR) mode, the TAG sends a message to the ANs and registers the exact time of sending. As soon as the message arrives at its destination, the firmware of the AN instantly captures another timestamp. In an acknowledgement (ACK) message, the timestamp of reception and a timestamp of sending the response is transmitted. When this message arrives at the TAG, again a timestamp is registered. With the equation below, the time of flight can now be evaluated *SewioTWR UWB Technology - Two way ranging*. To achieve higher accuracy,

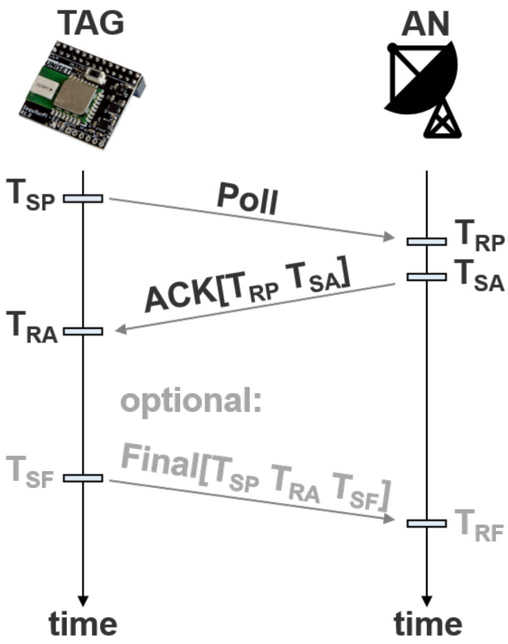

FIGURE 2.2: Illustration of TWR and SDS-TWR communication

the communication can be extended with a final message containing the timestamps of the requester. This is called symmetrical double-sided two-way ranging (SDS-TWR) *Wikipedia Symmetrical double-sided two-way ranging* and is indicated as optional in Figure 2.2.

Time of flight for TWR:

$$ToF = [(T_{RA} - T_{SP}) - (T_{SA} - T_{RP})]/2$$

Time of flight for SDS-TWR:

$$ToF = [(T_{RA} - T_{SP}) - (T_{SA} - T_{RP}) + (T_{RF} - T_{SA}) - (T_{SF} - T_{RA})]/4$$

ToF - Time of flight
T_{SP} - sending of poll timestamp
T_{RP}- reception of poll timestamp
T_{SA} - sending of ACK timestamp
T_{RA} - reception of ACK timestamp
T_{SF} - sending of final timestamp
T_{RF} - reception of final timestamp

For simplicity reasons normally ranging systems are designed such that the TAG gets the final message of the TWR communication, as the TWR is done with several ANs. In this case the requested information - the distances to every AN - is already on one device and can be further processed. However, the TWR has not necessarily to be inizialized by the TAG - the receiver and the sender can easily be exchanged. When for example the computational power of the TAG is limited or the application runs on a separate server, we can imagine some benefits to trigger the TWR in the ANs and forward the collected data direclty to the server.

While TWR does not need further synchronization between the devices, time difference of arrival (TDOA) requires a very precise synchronization of the anchor nodes. This is normally done by specifying a master node per three to five anchors. For bigger scenarios often multiple dedicated masters will send clock synchronizations every once in a while, such that every AN gets at least one sync package. It occurs as well that an anchor holds two differently synchronized times. To evaluate the time of flight, a TAG in range will broadcast a blink message. Every AN that receives this blink, will capture a timestamp of the time of arrival (or when holding more than one synctime, capture multiple timestamps). These timestamps are forwarded to the server together with a synch ID and a blink transmitter identity. When a server received at least three timestamps with the same synch ID for a tagret device, it can perform the position and therefore the distance estimation. A huge benefit of TDOA is the fact, that the tag only needs to send one blink message per timeinterval and will not have to communicate with every AN separately, as in TWR. For TWR the overhead grows enourmous with every anchor and every tag that is added. For TDOA hundrets of TAGs can be tracked, whith only proportional overhead growth and much lower energy consumption for the TAG.
Number of messages sent in one iteration:
TWR: $3 * n_t * n_{an}$
TDOA: n_t
Where n_t is the number of TAGs and n_{an} is the number of anchor nodes. *SewioTDOA UWB Technology - Time difference of arrival*

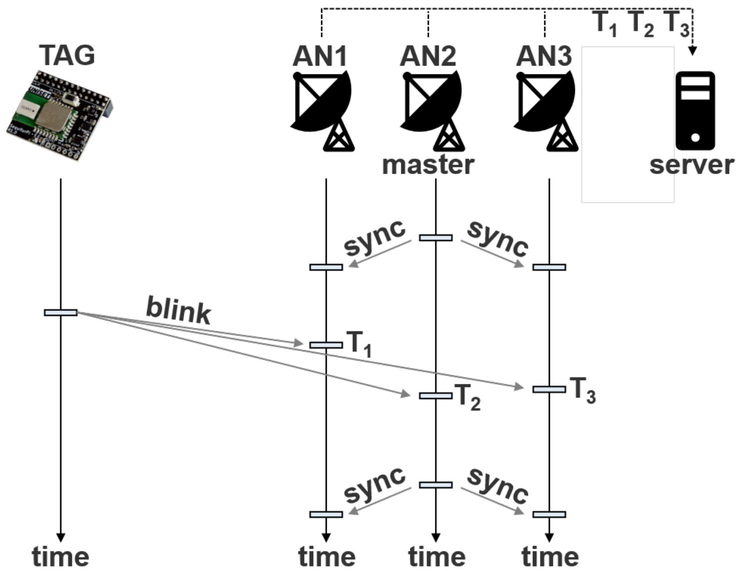

FIGURE 2.3: Typical Setup for Time Difference of Arrival communication

For both methods the same calculations to convert the ToF to the related distance can be applied. We assume that radio signals travel almost with speed of light, so we just multiply the ToF with speed of light (c_0).

$$distance = ToF * c_0$$

ToF - Time of flight
c_0 - Speed of Light = $2.997\,924\,58 \times 10^8\,\mathrm{m\,s^{-1}}$ (exact)

2.1.3 Triangulation and Trilateration

Triagulation and trilateration use the mathematical concepts of triangles to find unknown lengths. Triangulation was already mentioned by the greek mathematician Thales, who used this concept for finding out the height of ancient egypt pyramids. Kerner, 2017 It was also used for cartography purposes, where angles between fixed points were measured and heights and distances could be calculated. Although trilateration and triangulation use the same mathematical triangle concept, they have one defined difference: We call it triangulation, when angles to anchor positions are measured, otherwise - when distances to anchors are measured - it's called trilateration. As it was easier to measure angles than distances in the past, triangulation was more often used. With modern electronic devices, it is more common to determine distances, rather than angles.

Figure 2.4 shows how trilateration is used for positioning. With the known distance to every AN, a circle with radius of this distance can be drawn around every AN. These circles do only have one common intersection point, that is where the TAG lies. However, this is a theoretical and idealized scenario, where every range can be determined accurately. In real applications, the ranges are not exactly calculated, what leads to the fact that we will not only get a single point for the calculated position, but several points, especially when we use more than three ANs.

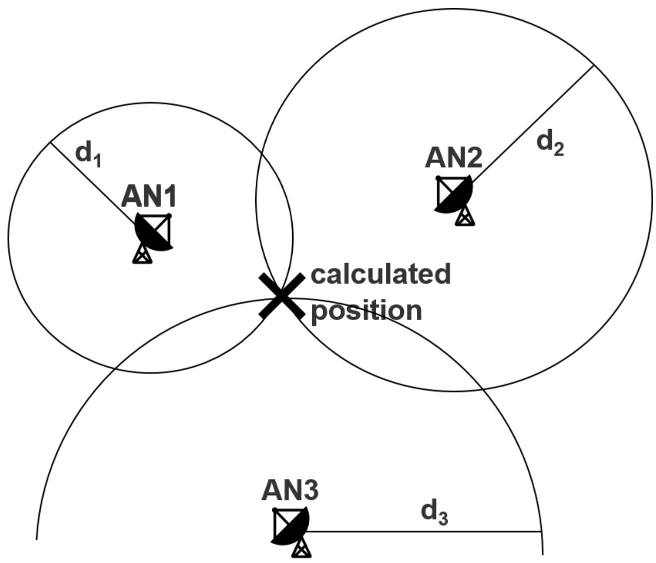

FIGURE 2.4: Graphical illustration of the trilateration concept.

2.2 UWB Theory

Ultra wide-band (UWB) is a radio technology in use for military communication, positioning and collecting sensor data. Unlike other communication technologies, UWB occupies a wide area of frequencies instead of just covering a small frequency spectrum. As showed in figure 2.5, UWB spans over a spectrum of more than 500 MHz that lies within the range of 3.1 GHz and 13.6 GHz. UWB opperates with less

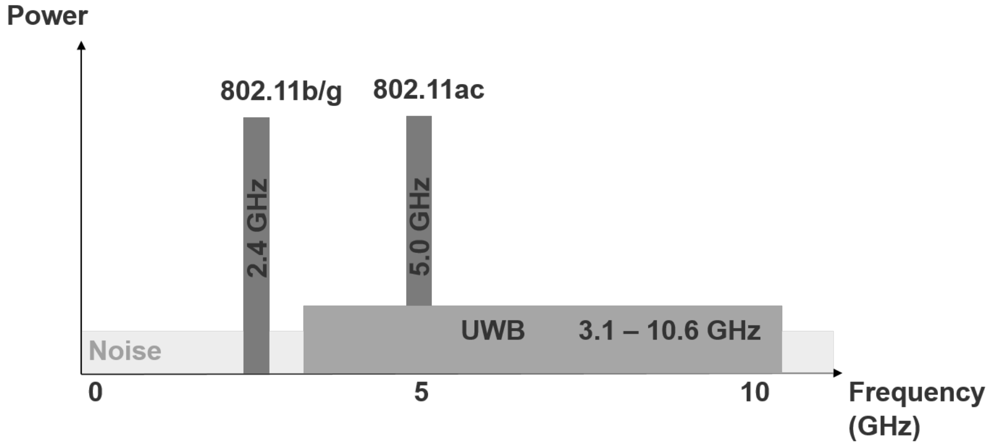

FIGURE 2.5: Comparison of Wi-Fi (802.11) and UWB frequencies.

energy compared to other communication like Wi-Fi. However, the main difference between UWB and conventional radio transmissions is the underlying modulation technique. UWB transmits data by generating short radio energy at specific times instead of varying frequency and phase of sinus waves. In addition to the pulse position, the pulses can carry information either by their polarity, their amplitude or by using orthogonal pulses. A single pulse is kept as short as possible, such that more than 100 Million, sometimes even continuous streams with more than 1 Billion pulses per second are generated. As single pulses can be registered and identified by the receiver, UWB devices are able to determine very exact ToFs such that distance estimations can be done to high resolution. Using the large frequency spectrum, there are even methods to overcome multipath propagation, when at least some frequencies have direct line-of-sight trajectories.

2.3 Particle Filter

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Chapter 3

System design

The given background theory of section 2 was applied for our system design. In the following we present our theoretical system and which aspects of the theory led to system design decisions. We provide a short overview in the first part, following a part where our theoretical setup is introduced. Finally we add our thoughts about algorithms that could be used.

3.1 Overview

As already mentioned in the introduction, our system combines different types of data input to achieve the best position estimation. This leds to a slightly more complicated ranging process than indicated on the simplified illustration in figure 2.1.
We wanted to include not only measurements from one device, but from several different data sources: TAG and AN collect data and send it to the server, where the data is fed into the particle filter. The particle filter spreads particles accoring to TAG movement indication, restricted by the topology read from the floorplan and calculates the position likelihood according to range measurements and again the movement vector. In this phase, trilateration is already done implicitly. With respect to the likelihood, a normalized weight is assigned to each particle. The position estimation corresponds to the weighted sum of all particle positions. An overview of the whole process is illustrated on figure 3.1.

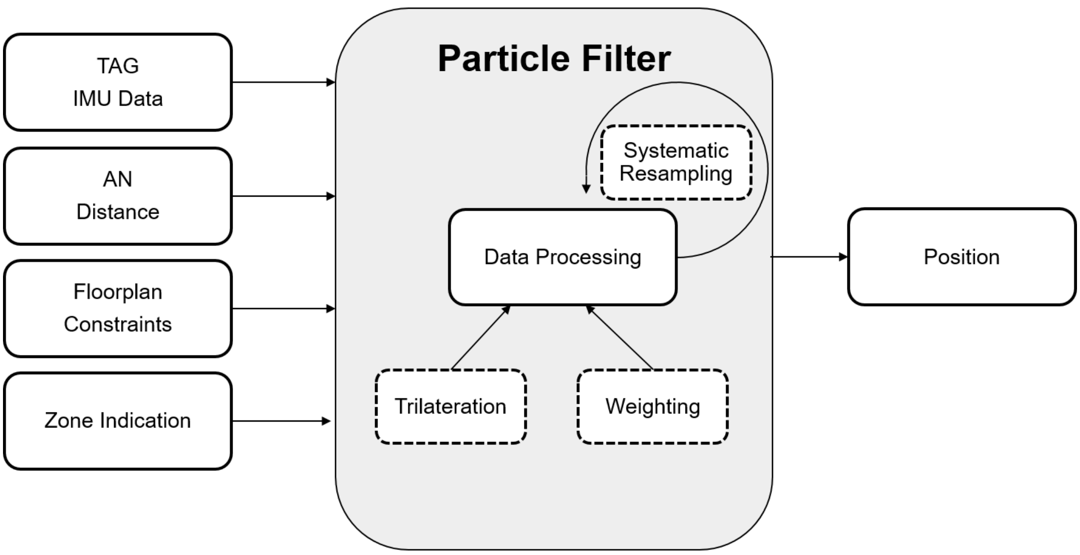

FIGURE 3.1: Overview of the theoretical components in our system.

3.2 Setup

The theoretical design on our system is shown in 3.2, it works as follows: At least three ANs, equipped with UWB technology, are placed in an indoor environment of one floor. Our algorithm runs on a seperate server, where a zoneplan and floorplan of the floor are available. A single TAG is located somewhere on the floor, it is as well equipped with UWB technology, moreover it measures acceleration and magnetic energy with the onboard IMU. The TAG continously collects data from the IMU and contemporary waits for a request from the server. The server periodically requests data via UWB from the TAG. As soon as a request is noticed at the TAG, it performs a range estimation to every AN and sends this data together with the continously collected IMU data to the server. For every estimation period, the server has all the data needed to feed the particle filter.

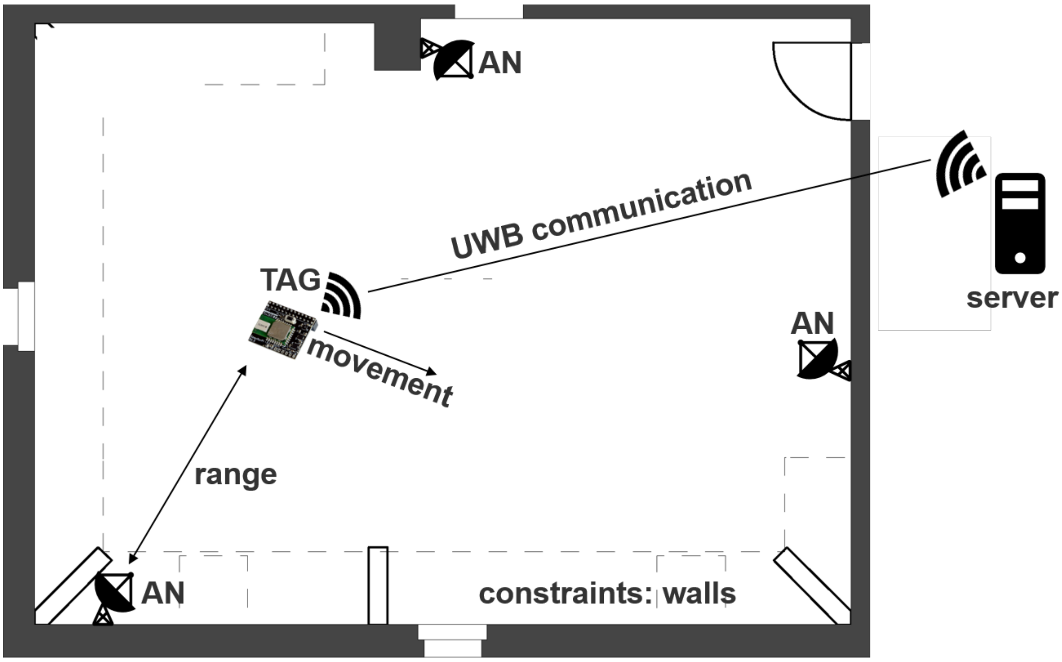

FIGURE 3.2: Overview of the theoretical system design.

3.3 Computations on the server

All computations are done on the seperate server, as we would like to minimize the required computational power and energy consumption of the devices. As already mentioned, the server receives IMU data and range estimations from the nodes. This data, as well as the floorplan constrains, flow into the particle filter. These operations are done on the server:

- Spread the particles and validate new positions with floormap constraints
- Evaluate UWB ranges and IMU measures to assign likelihood
- Calculate weight function and systematically resample (and reposition) particles with low weights
- Sum up weighted positions

In the first part, every particles is moved from its current to a new position. To validate the new position, we check if the direct trajectory between the old and the new location intersects with an impediment. If so, a new position is generated, as the last was not reachable. The second item covers the likelihood of the new position. For every AN, the measured distance is compared to the distance from the new position to the AN. The less these two distances differ, the higher is the assigned liklihood. This is also in effect for the IMU motion, as the difference between the old and the new positon is compared to the measured IMU motion to evaluate the likelihood. In the weighting step, every particle gets weighted by the liklihoods of the previous computations. The weights of all particles are normalized for further processing. The last part is a simple weighted sum of the particles locations.

Appendix A

Frequently Asked Questions

A.1 How do I change the colors of links?

The color of links can be changed to your liking using:
 `\hypersetup{urlcolor=red}`, or
 `\hypersetup{citecolor=green}`, or
 `\hypersetup{allcolor=blue}`.
If you want to completely hide the links, you can use:
 `\hypersetup{allcolors=.}`, or even better:
 `\hypersetup{hidelinks}`.
If you want to have obvious links in the PDF but not the printed text, use:
 `\hypersetup{colorlinks=false}`.

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