Real Time Localization of Assets in Hospitals using Quuppa Indoor Positioning Technology

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by

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Abstract

Indoor positioning is becoming a hot topic in public areas that are used by large numbers of people. Finding people and assets in buildings has become more difficult because of the complexity and scale of today's public space. On the subject of locating assets in the hospital the following use case is defined for this project. Positioning and localization of assets in a hospital is useful to do for several reasons. Loss and theft of equipment takes a large expense of the hospital's budget. When it is possible to have the position of a device in real time, a system could be developed that locates the assets through the hospital building.

The main goal of this project is to develop a model for an indoor positioning system for localization of assets in a hospital. The indoor positioning technology developed by Quuppa forms the basis for this. Their indoor positioning solution consists of Bluetooth powered tags measured by monitors on the ceiling (*locators*). The hospital that is going to be involved in this project is the Rijnstate hospital, located in Arnhem. They provided the input necessary to define the requirements for the use case. Based on the requirements from the use case and the specifications of the positioning system six test cases were defined for analysis of the test data and development of the localization model.

This MSc thesis describes a scientific approach to investigate the subject of indoor localization by performing data acquisition, processing and analysis of indoor position data. In order to localize the assets indoors, a map matching method is developed that takes into account several factors such as geometrical influences, characteristics of the positioning system and obstructions in the indoor environment. For matching the position data to a real world location, several location types are developed by subdividing the floor plan into location clusters.

The research has shown that a sub-meter accuracy level can be achieved for locations that are within the high-resolution range of the *locator*. The performance for positioning at the smallest cluster levels can only be achieved when having a dense distribution of *locators*. Test cases that were defined for specific situations related to the hospital case show successful localization for the majority of the test data. A correction model for making coordinate adjustments of the position estimates is described based on the reliability of the data from the test cases.

Keywords: Indoor positioning technology, asset tracking, Bluetooth Low Energy, Angle of Arrival, indoor localization, map matching

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List of abbreviations

AoA	Angle of Arrival
AoI	Area of Interest
AP	Access Point
BLE	Bluetooth Low Energy
BT	Bluetooth
CSV	Comma-Separated Values
GPS	Global Positioning System
HAIP	High Accuracy Indoor Positioning
Hz	Hertz
IDW	Inverse Distance Weighting
IPS	Indoor Positioning System
ISM	Industrial, Scientific and Medical bandwidth
IV	Intravenous
JSON	JavaScript Object Notation
LoS	Line of Sight
PoC	Proof of Concept
PoE	Power over Ethernet
QPE	Quuppa Positioning Engine
QSP	Quuppa Site Planner
RFID	Radio-frequency Identification
RT	Real Time
SD	Standard Deviation
WiFi	Wireless Fidelity

Contents

1

Introduction

This master thesis is written for the graduation project Geo2000 of the master Geomatics at the Faculty of Architecture from Delft University of Technology. This graduation project was done within an internship project at CGI, an ICT consultancy company in Rotterdam. The research is about defining a method for localization of assets in an indoor environment. In order to a use case is described and a number of tests are performed using an indoor positioning system. The output is analysed to assess the performance of the system. CGI is a company interested in making innovative systems, e.g. indoor positioning, available on a large scale for all kinds of clients. They partnered with a Finnish company, called Quuppa, which provided the hardware necessary for setting up the indoor positioning service. This system was tested in a small-scale office environment at CGI's office in Rotterdam.

Indoor positioning is becoming a hot topic in public areas that are used by large numbers of people. The main goal of the project is to develop a model for a working indoor positioning system for tracking assets in hospitals. The indoor positioning technology developed by Quuppa forms the basis for this. The hospital that is involved in this project is the Rijnstate hospital, located in Arnhem. They provide the input necessary to define the requirements for the use case. A number of large hospitals in the Netherlands is already using indoor positioning applications implemented in a service for their customers or the staff. For example, a company called Logis.P developed an app for the Leiden University Medical Centrum (LUMC) that enables the user to be guided to the location of his or her appointment and navigate to a subsequent appointment [21]. Movin, a small software developing company from Zwolle, came up with a similar application for the Utrecht Medical Center (UMC) and the Amsterdam Medical Center (AMC). Like Quuppa, their systems use Bluetooth Low Energy (BLE) technology, which has a major advantage over other wireless communication techniques, e.g. WiFi [11]. A case study of these applications was not possible because there was no documentation available at this time.

The structure of this document is as follows. In section 1, an introduction of the different elements of this project is given and the research questions and methodology for the research are defined. In section 2 a description of the use case and a review of the used positioning technology is given. An extensive overview of the theoretical background is given for several subjects that are important for understanding of the research part. Section 3 describes the setup of the demo system in the test facility at CGI. In section 4, the tests are described for the processing and analysis part as well as a definition and description of the localization model. Section 5 includes the answers to the research questions and recommendations for further research. Appendix A contains the datasets of the tests.

1.1. Problem statement

The problems that patients, staff and visitors experience in a hospital building day in day out are twofold. On the one hand these issues can be seen from the hospital's (management) point of view. Finding people and assets in buildings is becoming harder because of the complexity and scale of today's public space. The equipment used in hospitals is often lost or not at the location where it should be. Hospitals solve this problem now by buying more equipment than necessary to make sure that there is always a device of any type available. As the management is responsible for the optimization of user satisfaction and cost efficiency they are interested in a system that helps solving those issues.

On the other hand, this problem can be viewed from a client's perspective. The patients coming to the hospital for treatment or people coming to visit will benefit from a system that makes the experience less stressful. It can be very difficult to navigate yourself through buildings such as airports, train stations, schools and universities, libraries and hospitals. Hospitals are often seen as unfriendly environments where people do not feel comfortable, which makes way finding more difficult [35]. The focus of this research will be on the hospital's point of view. In a hospital, the different types of assets (e.g. IV pumps, AED's, wheelchairs, beds) in combination with the architectural layout of the building make it an interesting case for implementing an indoor positioning system.

Indoor positioning is a technology that is becoming more and more common in public- and office buildings. The indoor positions of objects and people can be used for localization and tracking. Tracking is the process of repeated positioning of a moving object or person over time [22]. Using GPS technology for positioning outdoors has proven to be a reliable for use in navigation applications. As GPS is not an option for indoor positioning, other wireless technologies like Bluetooth (BT), RFID and WiFi come to mind that return a higher accuracy for indoor localization. A lot of buildings have a WiFi system installed that has good coverage of the areas where people are most of the time. It is possible to set up comparable networks using other technologies like BT or BLE, which is used in this case.

1.1.1. Scientific relevance

Although some hospitals have already implemented an indoor navigation system, the technology and applications of indoor way finding are still relatively new. End-to-end navigation solutions should consist of applications for both outdoors and indoors as the complexity of modern buildings requires a system that also covers the indoor environment. The elements of (indoor) navigation are positioning, localization and routing. This project focusses on positioning and localization in an indoor environment. Within the scope of this project, defined by the use case and the positioning technology, it is more than relevant to build on the existing developments and explore the possibilities of the positioning technology of Quuppa's for localization of assets. From a scientific point of view, the relevance of this research is to find the best possible way to apply positioning technology to localize assets in a hospital. The elements of the project are shown in Figure 1. The use case and the positioning technology define the scope of the research. A third element is the technical background knowledge, which provides the theoretical background for the tests and analysis. These three elements are described in section 2.

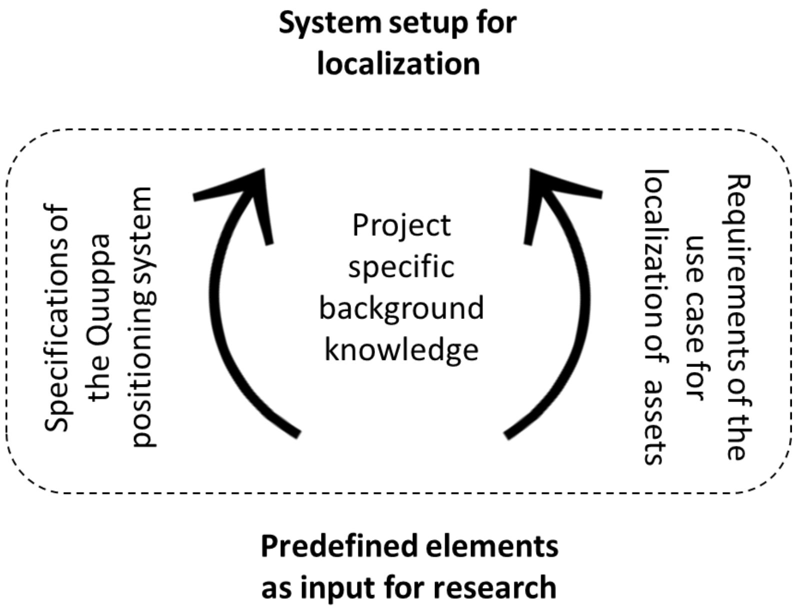


Figure 1: Definition of input elements based the requirements for indoor localization

1.1.2. Positioning and localization

The positioning system can return the x and y coordinates in 2D, and x, y and z coordinates in 3D, of the position of an asset or person in a coordinate system. However, without any information about the environment, the position is useless for systems and human beings to understand. [22] defines positioning, as: "Positioning is the general term for determination of a position of an object or a person". It is particularly used to emphasize that the target object has been moved to a new location". Adding semantics to the position of the object to be able to pin point it at a specific place and exclude all other places, is called localization. Localization is defined as: "…localization is mainly associated with rough estimation of location" [22]. Both these terms are relevant within this research and form the basic structure of the methodology for testing.

1.2. Research questions

1.2.1. Main research question

The subject of the research is to measure the performance of the Quuppa indoor positioning system when it is used for indoor localization of assets. The performance can be defined as the degree to which the expectations of positioning meet the outcome of the tests. In order to measure the performance of the positioning system a number of parameters are specified. The specifications of the Quuppa system and the requirements of the use case can be used to define the technical and operational parameters of the system. The technical and operational parameters are defined in section 4.1.1. The conclusion of the research will be to what extent the technical and operational requirements meet the requirements set in the use case. Based on this, the main research question can be formulated as follows:

"Does the technical and operational positioning performance of Quuppa technology meet the localisation requirements for asset tracking in a hospital environment?"

To be able to answer the main question, 6 sub questions are defined below.

1.2.2. Sub research questions

The sub-questions are formulated in such a way that the main research question can be answered in a structured way. In order to answer the sub-questions, a number of parameters are defined to measure the performance of the system. The use case contains the requirements coming from the application field, to be able to compare it to the findings of the tests.

1. *What are the possibilities and limitations of the Quuppa system?*

The possibilities and limitations of the Quuppa system can largely be derived from the specifications of the system. These specifications will be compared to the requirements of the use case. When a certain specification is better than required for the use case it is defined as a possibility. On the other hand, a poor specification puts a limitation on the use case. This way, assumptions can be made about the expectations of the performance.

2. *What are the technical and operational performance parameters and how can they be measured?*

The technical performance parameters are defined based on literature and on the tag (meta)data of the returned positions provided by the Quuppa system. The operational performance parameters are not explicitly available through the output of the Quuppa system.

3. *What is the performance of the system based on the technical parameters?*

In contrast to the first sub-question the performance is indicated by the results from the tests that were carried out. For every parameter an acceptable range will be set and this will be compared to the results from the tests. Getting on-the-fly values for the technical parameters, e.g. accuracy, is a subject for research.

4. *What is the performance of the system based on the operational parameters?*

The parameters for the operational performance are selected based on aspects that affect the results of the positioning from external sources. In particular, the architecture of the building is of interest. Also the influence of shape and material of obstructive parts is investigated.

5. *How can the results of the test and analyses be put into a model for localization of assets using Quuppa technology?*

Based on the outcome of the map matching, together with the analyses of the technical and operational performance, a localization model for using Quuppa technology to perform indoor localization is described.

1.3. Methodology

In this section the methodology and steps of the project in general and the research are described into detail. The input of the research is the Quuppa technology and the use case for localization of assets in hospitals. The output in Figure 1 consists of the requirements and knowledge needed to define a model for indoor localization using the Quuppa system. In Figure 2 the components of the project are visualised. The project consists of five phases which can be subdivided into tasks that generate the output necessary to proceed to the next phase. In the first phase the scope and structure of the research are defined. The second phase is about providing case input and a theoretical background. The third phase consists of the installation of the system and definition of the test setup. Tests are carried out and analysis is done in the fourth phase to assess the configuration and performance of the system setup. If the results are satisfying, the current configuration can be used for further steps. If not, the parameters and settings are reviewed and redefined to adjust the output in the right way. Analyses are carried out in order to describe a method for localization of assets in a hospital. In the fifth phase conclusions are drawn in order to answer the research questions and recommendations for future research are given.

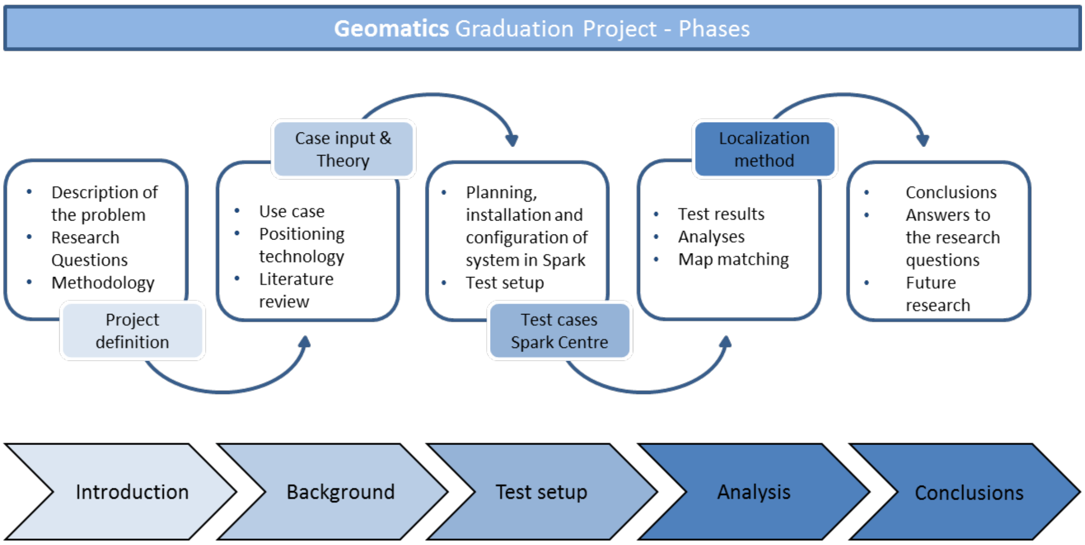


Figure 2: Flow chart of project methodology

1.3.1. Introduction

- Getting to know and try out Quuppa system at Spark Center
- Organise meeting with the hospital for use case input
- Define research questions
- Methodology

The test set up at the CGI office will help to test these aspects 'in the field'. As the method and technology of positioning are predefined, the focus of the research will be mainly on configuration of the hospital system and using the location data to make localization of the assets possible. The next step is about defining the use cases and determining the requirements. An important aspect of the project is to sit together with the client (hospital management) to get input and feedback on the requirements and the application. Results from this meeting can be used to test the system specifically on aspects that are of importance to asset tracking. Also the research questions are formulated, which consist of a main question and 5 sub research questions covering both the Quuppa technology and the use case. Finally, the methodology for the project in general and the research are described in detail.

1.3.2. Background

- Review of Quuppa technology
- Definition of the use case
- Definition of the requirements
- Literature review and case studies

First the characteristics of the positioning system provided by Quuppa are described. Based on the input of the hospital management the use case is defined for localization of assets in hospitals. Both the review of the positioning system and the use case define the requirements for the test cases. A literature study is carried out to explain the technical background and show existing applications of the Quuppa system. In order to define the configuration parameters in section 4.1.1, a good understanding of the system is important. The accuracy and precision of the system are considered the most important aspects.

1.3.3. Test setup

- Description of installation of the Quuppa system
- Description of the test setup
- Definition of the tests cases

In this part the installation and configuration of the Quuppa system in the Spark Center is described. The test setups are defined based on the specifications of the system in order to use the Quuppa technology for acquisition of the position data. Six test cases are defined to measure the reliability of localization based on the position output of the Quuppa system. These test cases are based on the requirements described in the use case in section 2.2. The test cases are used as input for the map matching scenario's described in Figure 4.

1.3.4. Data processing and analysis

- Definition of parameters
- Collecting and processing tag positions
- Data analyses
- Definition of locations and map matching
- Description of a model for indoor localization

The next step is the testing of the system set up. This is carried out at the Spark Center at CGI's office in Rotterdam, since a full test setup in (a part of) the hospital is not possible within the time frame of this project. Section 4.1 covers the positioning part of the research. First a number of parameters are defined for analysis of the position data. Figure 3 gives an overview of the steps taken from data processing to development of the model. To retrieve a dataset of indoor positions, the tag positions are collected for known coordinates in a grid in the local reference system. For each grid point the x and y coordinates are averaged and the standard deviation is calculated to create a dataset of average position measurements. Based on the resulting dataset analyses for positioning are performed. Section 4.2 covers the localization part of the research. Location types are defined in order to perform map matching using the positioning data. After this step the reliability of the test cases is determined to define specific correction methods for successful localization.

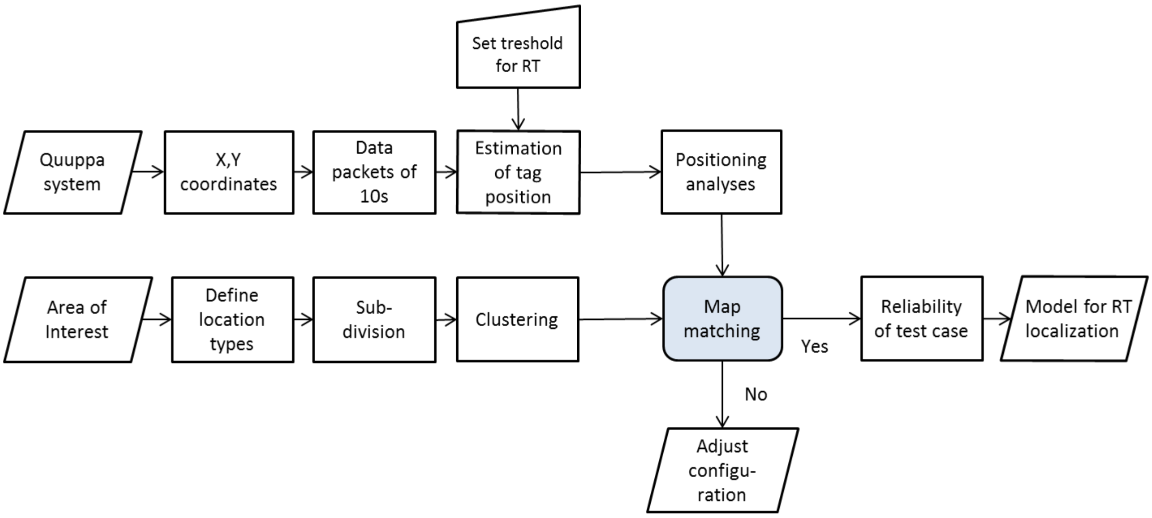
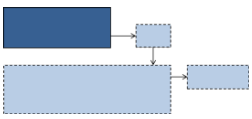


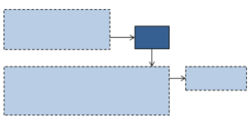
Figure 3: Flow chart of research part for positioning (upper path) and localization (lower path)

The technical and operational parameters defined in section 4.1.1 are used to measure the performance of the positioning system. Figure 4 shows a matrix for map matching based on the location types and the scenarios for the statistical analyses results. In order to perform map matching (sub)location types are defined based on the floor plan to be able to assign the positions to places that human beings can easily understand. The elements A, B and C are defined in section 4.2.1. A definition of the scenarios is given in section 2.3.4. The next step is to assign the positions to the locations and check the reliability of the locations in different test cases. The results of measuring the performance of the positioning system can be used to optimize the matching process. A more detailed description of the research methodology is given below.



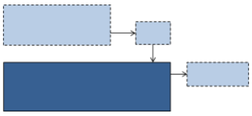
Step 1: Collection of the data

To determine the positions in a way that the real x, y coordinates are known, the tags are placed on the crossings of a 1x1 grid. The cell size of the grid is determined based on the quality of the positioning solution that is used. The grid positions on the floorplan of the Spark Center are measured along the x and y axis for different time spans. A total of three tests are carried out to test different configurations of the system, tags and tracking plane during office hours. The tracking plane is the indoor area where the positioning can take place. The tags are reconfigured to a transmit rate best fitting the use case. For every group of measurements per grid point the average (mean and median) is calculated as well as the standard deviation (SD). A more detailed description of the individual tests is given in section 3.4.



Step 2: Data analyses

A number of parameters are defined to analyse the results of the tests. These parameters are based on the requirements for the use case and the data that is available from the Quuppa system. This analysis covers the positioning part of the test. Conclusions are drawn to provide an input for a model for indoor localization based on the Quuppa positioning system. The conclusions of the analyses are used to define the map matching methods in step 3.



Step 3: Definition of the locations and map matching

Another aspect of (indoor) localization is knowing where the object or person is in the real world. For the hospital case, described in section 2.2, it is more relevant to localize the asset at a location on the map that is easy to understand for human beings instead of showing the x, y position in the local coordinate system. Typically, the type of building (e.g. airport, hospital, university, shopping mall, train station) is determinant for the lay out of the floor plan and the arrangement of interior elements [15]. However, the elements describing the boundaries of (sub)locations share common attributes such as height, surface area and materials.

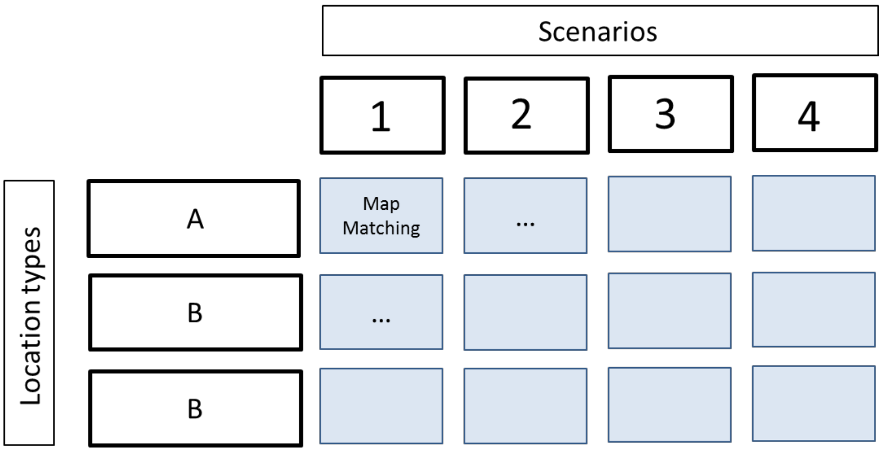
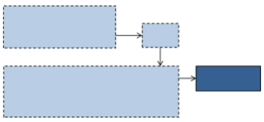


Figure 4: Map matching matrix based the input from the location types and scenarios for reliability



Step 4: Definition of method for indoor localization

The locations that were defined are matched to the processed positioning data gathered during testing. The main goal of this step, after processing and definition of the subdivision of the floor plan is to locate the tag on a specific location with the highest possible probability. In Figure 4, a matrix for determination of the success of the localization method is shown. In addition to a standard intersection of the position and the location, three components of improving localization are proposed. The method for map matching is explained in section 4.2.2. For defining the localization model, six test cases are analysed based on their performance for localization. The map matching methods are used for suggesting corrections for localization. The steps for analysis of the test cases and definition of the localization model are given below. The first three steps are described in section 4.2.3 and the last step is described in section 4.2.4.

- The type of asset and its corresponding location is used to assess the reliability of the case
- A matching scenario is determined for each test case.
- The scenario determines the performance of localization
- Based on the PA a correction method is described
    - Models for localization are defined based on the reliability of the position measurement
    - Map matching methods are used for correction

1.3.5. Conclusions

- Conclusions from the analyses
- Answering the research questions
- Provide recommendations for further research

Finally, all the steps of the research should be documented in the thesis report. The research questions are answered based on the used technology, the use case, results and analyses from the research. From the conclusions of this research a generic method for localization using Quuppa indoor positioning technology and determining an optimum constellation of the Quuppa system is described. Some recommendations for improvement of the proposed method and test setup are given.

2

Background

In this section the background information that is needed to define the test cases is given. First the positioning technology and hardware, provided by Quuppa, is reviewed. Secondly, the use case is described to provide a framework for the testing of the positioning system. Additionally, a literature review is done to explain some of the technical aspects of the used technology and the data processing method before carrying out the tests and doing the analyses of the data.

2.1. Review of Quuppa technology

Quuppa was founded in 2012 as a company focusing on indoor positioning technology. The company developed a system called High Accuracy Indoor Positioning (HAIP). This system is able to locate people or assets in an indoor environment making use of the Angle of Arrival (AoA) principle based on Bluetooth Low Energy (BLE) technology. Quuppa claims that the system can measure a location in real time based on the following specifications [29].

2.1.1. Specifications of the indoor positioning system

- Up to sub-meter accuracy (between 10m and 10cm)
- Real-time data (between 1min and 100ms latency)
- Transmit rate of 1-100 Hz
- No interference (operates within ISM band)
- BLE tags and devices are supported

For the first three specifications, the different values belong to predefined software licenses. The 'basic' license offers the minimum specifications and the 'ultra' license offers maximum specifications of the system. Because of the latency of 1min, the basic license cannot be used for real time positioning. The specifications of the demo system used in this research are similar to the 'ultra' license package. Depending on the system setup and the application, the system returns an accuracy op to 10cm. The latency, which is the delay in the measuring of the tag's position and the output of the position estimate, is adjustable up to 100ms. Transmit rate or update is adjustable up to 100 broadcasts per second. The settings for the transmit rate mainly depend on the velocity of the objects that are being positioned. Based on these specifications, the system is expected to perform sufficiently within the requirements of the use case. However, tests need to be carried out to assess the performance of the system in a real life environment. The specifications described here are used for setting up the test cases in section 3.5.

2.1.2. Positioning principle

The positioning principle integrated in the Quuppa technology is Angle of Arrival (AoA). This method determines the position of a tag by measuring the azimuth angle and the elevation angle relative to the *locator*. The elevation angle is the angle with respect to the normal (z axis). The azimuth angle is the angle rotating around the normal. The range of the *locator* is cone shaped and has two predefined levels of accuracy for positioning. The inner cone can return a highly accurate position of both the azimuth and elevation angle. The outer cone can only return an accurate position in the azimuth direction and show some dispersion of the elevation angle. A third range is only suitable for detection of the tag's signal and cannot be used for positioning. More detailed information about the method and the difference between estimation of the position in 2D and 3D is given in section 2.3.2.

2.1.3. Possible system setups

The system set up of Quuppa's High Accuracy Location System (HAIP) consists of multiple components. The *locators* attached to the ceiling detect the *tags* or *BLE sensors/devices* around them. The information about their position is send to the Quuppa Positioning Engine (QPE), which is installed on an Apple Mac Mini. The Mac Mini also contains a local version of the Quuppa Customer Portal, which contains a planner and deployment tool and a DHCP server to assign an IP addresses to each *locator*. The dashboard of the QPE can also be accessed through a URL on other PC's on the same network.

Four set ups are presented that return different levels of accuracy for localization indoors. The first setup is the most accurate and uses a tag for Bluetooth connectivity. This configuration is able to send signals between the tags and *locators* in both directions. The second setup uses BLE devices, which emulate a tag. The specifications of this system are similar to the first one mentioned except the signal only travels from the device to the *locator*. The third setup uses iBeacons to localize the BLE devices that are in the neighbourhood of a *locator*. As the iBeacon configuration does return a proximity variable instead of x and y coordinates, this system is not suitable for high scale applications. A fourth setup presented by Quuppa uses BLE sensors for remote sensing purposes. This way all kind of sensor data can be gathered if a BLE device is connected to it. Examples of sensor data can be heart rate, compass, humidity and temperature. The set up used in this project is the first one described above.

2.1.4. Radio signal

The bandwidth defined as the ISM band (frequencies reserved for industrial, scientific and medical purposes) is reserved for these purposes other than telecommunications [32]. BLE radio signals use the ISM band of the radio spectrum. This band contains the frequencies between 2,400 GHz and 2,483 GHz. Quuppa claims that there is no interference between their positioning system and other wireless systems like WiFi, which operates in the same bandwidth. To avoid any interference, the HAIP system can be configured to use proprietary channels at the band edges (frequencies 2.401 and 2.481 GHz). A test of detecting possible interference was done by measuring the data velocity over the access points (AP) of a WiFi system. The data velocity did not change indeed after the Quuppa system was active.

As the strength of the radio signal decreases when moving further away from the *locator*, different range levels for positioning can be defined. Assuming that the coverage of the *locator* is represented by a cone shaped geometry, three sizes can be distinguished. Positions measured in the inner, high-resolution, cone can be quite accurate based on measurements of just one *locator*. The range of this level covers a 2m radius when the *locator* height is 3m and the tracking plane is set to 1m. In the middle, low-resolution, cone only the angle in the azimuthal direction is accurate. This range level is between 2 and 7m in the situation described before. The third outer cone is not suitable for positioning, but it can still detect the presence of tags. This area covers up to a 30-50m radius from the center of the *locator*. The area in relation to the floor plan where the tags can be positioned by the system is called the '*tracking area*'.

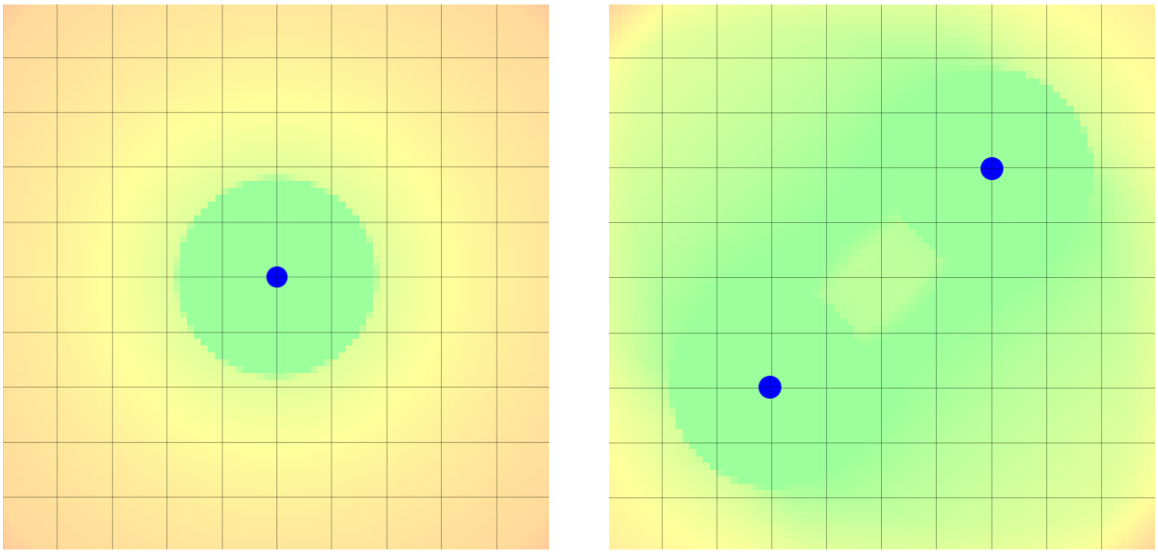


Figure 5: Range levels of one *locator* (l) and two adjacent *locators* (r)

In Figure 5 a visualization of the range levels for positioning are shown. These images are rendered by the Quuppa Site Planner (QSP) software based on the ranges, height of the *locator* and the size of the *tracking area*. The heat map on the left shows the coverage of one *locator* in a virtual room of 10m x 10m. The high-resolution range covers up to a 2m radius around the *locator* at a height of 3,55m when the *tracking area* is set to 1m (pocket height). Adding a second *locator* to the room improves the coverage by more than 100%. The corners and the area between two *locators* return lower signal coverage. The effect of improved coverage towards the corners where no *locator* is placed is called the Fresnel zone (F. Belloni, personal communication, September 4, 2015). This effect describes an alternation of half- and double signal strength regions in between two receivers [40].

A side view of the coverage of the radio signal in the 2D situation is shown in Figure 6. Due to the cone shaped area of the antenna, the coverage decreases when the tag is at a larger z value. The green area indicated the positioning range of the *locator*. In this area, the system can return x, y (,z) coordinates for each tag. Tags that are in the red area of the coverage field cannot be positioned accurately. However, detection of the tag is still possible to a certain extent (maximum of 50 meter radius in open space). The height of the *locator* is the main variable for the coverage, assuming that the tags remain at the same height. Generally, placing the *locators* at a larger z value improves the area of the coverage field. However, ceiling height and possible obstructing objects on the ceiling are restrictive factors.

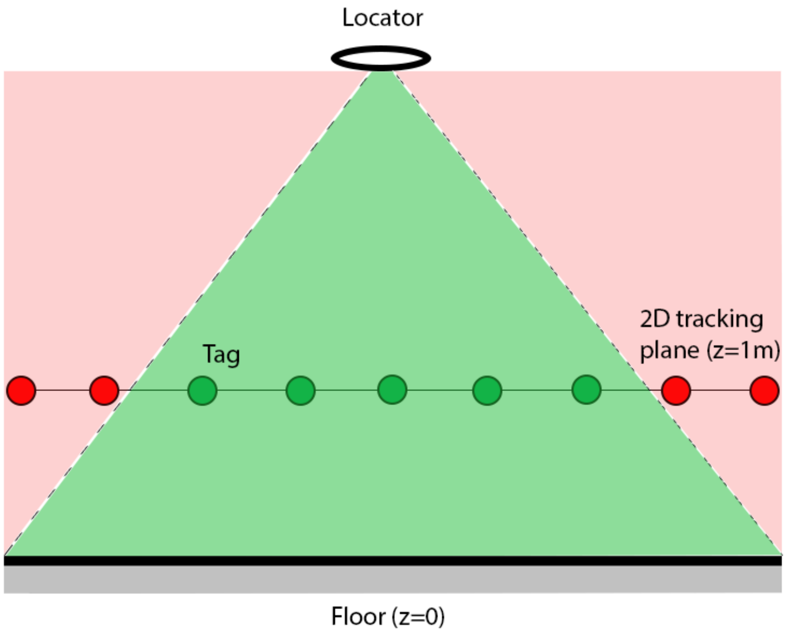


Figure 6: Side view of covered area (green) and uncovered area (red)

2.1.5. Reflections and obstructions

Positioning in the indoor environment is influenced by reflections of the radio signals. This phenomenon is also called multipath. Compared to outside positioning, the effects of reflections of the radio signal from transmitter to the reader are probably worse in the indoor environment. Furniture, room dividers and material of walls can have a large impact on the behaviour of radio signals. In the Spark Center, where a demo setup of the system is installed for testing, the TV screens and metal walls in particular can cause reflections of the signal. Reflections can also exist because of objects that are placed within a 1 meter radius from the *locator*. For this reason, this area around a *locator* needs to be free of obstructions to avoid uncovered areas and disturbance in the radio signal.

2.1.6. Application fields

Different positioning set ups of Quuppa have been implemented in several application fields. For example, sports, retail and health care are three of the areas where the (indoor) positioning technology of Quuppa is being used. An interesting use case for indoor positioning in hospitals is patient or asset tracking to trigger events based on the location of a person or asset. Other applications can be found in the field of safety and security of patients and staff and also equipment. The case studies in section give an example of how the Quuppa technology can be applied in practice.

2.1.7. Quuppa output parameters

In this section two parameters that are returned by the Quuppa system with every position estimate are further explained. An extensive overview of all Quuppa parameter can be found in the Appendix. One of the variables that are returned with every position estimate is the *positionAccuracy*. This is a distance value in meters which describes the estimated accuracy of the position fix. It is represented by the radius of a circle in 2D tracking mode and of a sphere in 3D mode (F. Belloni, personal communication, July 12, 2015). The PA parameter can be regarded as a quality indication of the measurement and is not an accuracy value according to the definition in section 0. The PA can be described as an approximation of the covariance matrix, which is an estimate of the error distribution along the main axis x and y. In general, the covariance matrix is an ellipsoid, which is approximated into a circle or a sphere by the position accuracy value, centred at the estimated position. In section 2.3.4 the covariance matrix is explained in more detail. The position accuracy variable of the output field of the QPE API should be seen as estimates of variance (i.e. error dispersion) and not as a bias (i.e. error distance). The covariance matrix is not used for statistical analyses in this research. Calculation of the dispersion of the measurements for each of the positions is done using the standard deviation based on the returned positions during testing.

2.1.8. Case studies

Asset tracking Quuppa HAIP in Retail (U-Hopper)
An indoor positioning system for asset tracking has been developed by an Italian company called U-hopper. The system tracks and analyses the tags attached to shopping carts and baskets in real-time to gain insight in the behaviour of customers in retail and grocery stores. The requirements for this system are full coverage of the floorplan by the wireless signal and an accuracy of the returned position of 20 cm. The parameters U-hopper set as requirements for the implementation of the HAIP technology are scalability, accuracy, reliability, and coverage.

The scalability of the system is important when applying the technology commercially, as the size and lay out of the stores differs from client to client. Compared to the use of WiFi technology for positioning, the HAIP system has a major advantage. Positioning with WiFi is dependent on a radio map containing RSSI values that need to be updated regularly and changes when an AP is added or the plan is modified. The HAIP system is built on BLE and AoA as a positioning method, which is better scalable.

In general the accuracy of a WiFi based indoor positioning system is 5-20m where a BLE based system can get down to 0.1m [29]. For asset tracking of larger objects in an indoor environment it might not be necessary to have data with sub meter accuracy. In a retail environment the data is used to find out in which specific products the customer is interested. In this case there is a need for a very high accuracy. The level of accuracy is therefore dependent on the application, which does not favour one system over the other. The other three parameters, accuracy, precision and coverage are both influenced by a lot of different variables. For example, the reliability or robustness of the system depends on the hardware and doesn't influence the application field much. The coverage is mainly depending on the number of *locators* that are installed. In general, the larger area that can be covered by one device, the cheaper the system will be because less *locators* are needed.

In Figure 7, the areas marked in red show the locations that are used most and the blue areas represent the locations that are not often used by the people visiting the store. In the case of asset tracking in hospitals it would be more useful to link the red areas to specific rooms and display the tag numbers for that specific location.

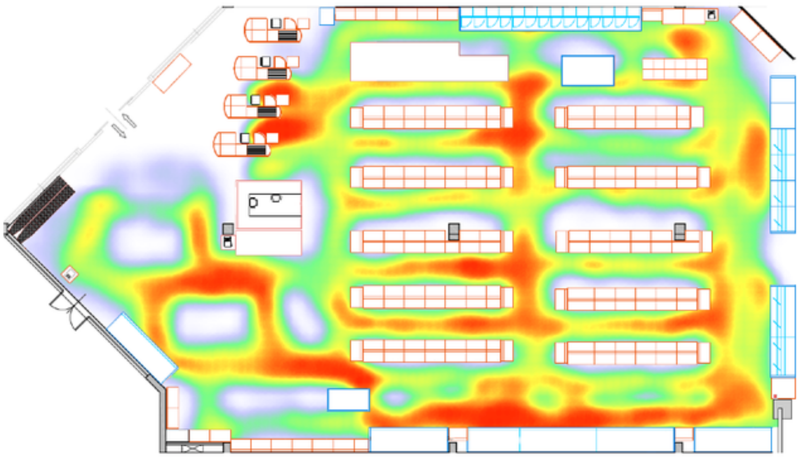


Figure 7: Heat map of most used area in a retail store [27]

Quuppa partnership with General Sensing
General Sensing is an USA/Hong Kong based business that specializes in wireless sensor system for health care applications. Within the partnership with Quuppa they developed two applications for hospital environments. The first one is called MedSense Look [24], which keeps track of the time medical staff needs to spend on a patient together with patient waiting times and (real time) staffing levels. An example of the 'Look' application and hand hygiene compliance is shown in Figure 8.

Figure 8: MedSense Look (l) and MedSense Clear (r) [28]

The other application is called MedSense Clear [23] monitors the hand hygiene compliance of the staff. The staff members carry a custom badge with a sensor, which detects Beacons that are placed around the hospital. When they enter a certain area where they should wash their hands before taking care of a patient, an alert is send to the badge to remind them. When the staff member enters the 'base area' the data stored on the badge is send to the central database, which gives the management insight in the compliance data.

2.2. Use case: Asset tracking in hospitals

CGI collaborates with the Rijnstate hospital in Arnhem to implement asset tracking in (a part of) their building in Arnhem. A meeting with Alinda Blauw, Innovation Manager, brought to light the issues the hospital staff is struggling with during their daily routine. On the subject of locating assets in the hospital a use case is defined for this project. Localizing assets in a hospital is useful to do for several reasons. Loss and theft of equipment takes a large expense of the hospital's budget. When it is possible to have the position of the piece of equipment in real time, a system could be developed that tracks the assets through the hospital building. Examples of assets that may be useful to be tracked are: IV stands, wheelchairs, AED's, medication, ventilators, ultrasound, IT equipment etc.

Figure 9: IV pump that is used in Rijnstate hospital (Carefusion 2015)

In consultation with the hospital, IV pumps are selected to describe the routine and bottlenecks of this asset for the use case. In Figure 9 the pump that is used in the Rijnstate hospital is shown. IV pumps are used to automatically give medicine and fluids to a patient. The pumps can be attached to a mobile or a fixed IV stand. When an IV pump is needed, the staff puts in a request at the central supply room. The request is registered in the 'Ultimo' system, which keeps track of the status of the pumps. When the pump is shipped to the department that made the request, the ID of the pump is assigned to that specific department. The pumps are picked up by a nurse or delivered to the department by a staff member of facility management. This process is shown in Figure 10.

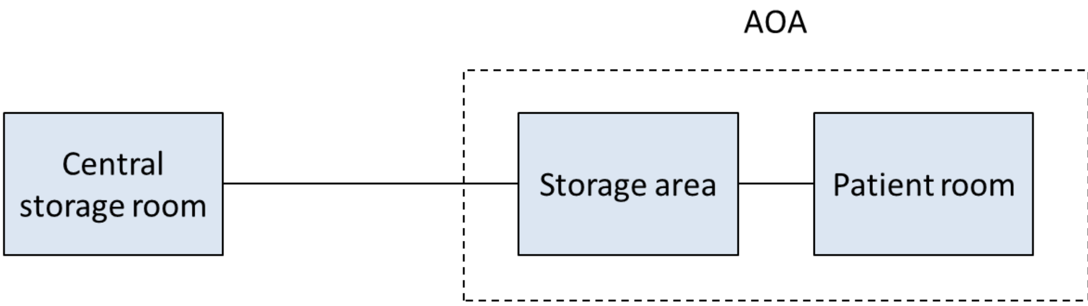


Figure 10: Process of pump distribution in the Rijnstate hospital

The area in a room where the object is, that needs to be positioned according to the use case, is called the Area of Interest (AoI). The AoI for the use case is the Acute Opname Afdeling (AOA), which is distributed over 3 wings at the fourth floor of the building. Used pumps are placed at the storage area, a central location on the ward, to be returned to the supply room in order to get cleaned and stored for next use. A staff member of the facility management makes a round through the hospital twice a day to collect the used pumps from the wards. Back in the supply room the pumps are scanned and become available for re-use. The following situations can occur regarding transport and use of the IV pumps. An IV pump is requested but none are available at the central supply. The supplier would like to know where used pumps are located in order to fill the stock. Another situation occurs when a pump is taken from another department and not returned afterwards. In both situations the issue is that there are no pumps available at the ward or at the supply room. The supplier needs to have information about the location of the used pumps so they can be cleaned and are ready for re-use. In Figure 11 the breakdown of the hospital use case is shown.

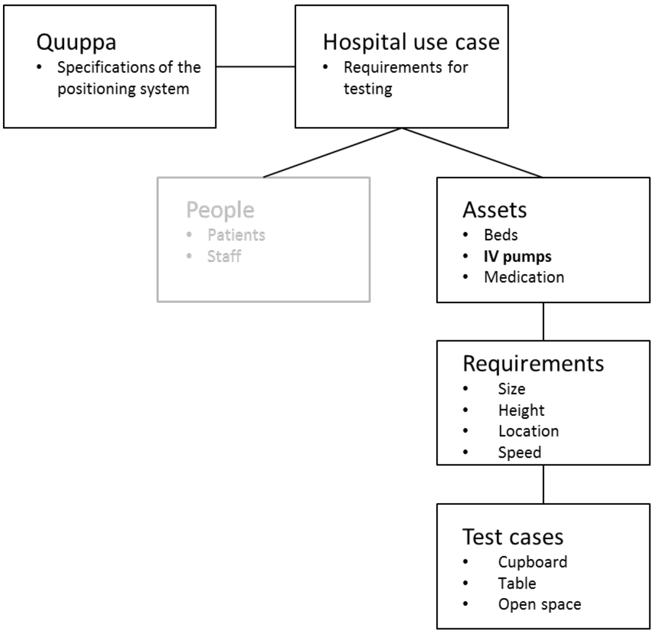


Figure 11: Break down schedule of the use case

2.2.1. Context of the use case

The problem statement described in 1.1 can be summarized to three general topics. These topics provide the context of the use case for making the location a medical equipment and people available to the staff and management. The topics are described below.

Quality

- Improve the quality of care by better-informed decision making.
- Monitor the compliance of (medical) procedures by staff and patients.
- More time for patient care instead of wasting time looking for the right equipment.

Safety

- Any system architecture should prevent violation of the privacy of staff, patients and visitors when tracking people or assets related to people.
- Improve safety of patients and staff by providing information about the whereabouts of essential medical equipment and patients.
- Improve maintenance compliance by having a RT inventory

Efficiency

- The system should be set up and be operational within the budget of the hospital regarding time-, capital-, maintenance- and space costs [22].
- Reduce equipment and maintenance costs because it is not necessary anymore of buying medical equipment in abundance.
- A localization system should improve the current distribution system of medical equipment.

2.2.2. Requirements for test case

Based on the input from the hospital management, a number of properties are defined for locating assets and people. The values of these properties are used as requirements for the test cases. In Table 1 the requirements for the tests are shown. The size is an indication of the longest side in a 2D plane of the item to be localized. For instance, the dimensions of the IV pump shown in Figure 9 are 148mm x 225mm x 148mm (lxbxh) [8]. The corresponding height of the object is 1,5m when it is attached to an IV stand or a bed. In order to measure the performance of localization, three locations commonly present in a hospital building, are defined. The locations approximately cover the entire space on the floor plan were an asset theoretically can be localized. The last property for the use case requirements is the movement of the object represented by 'Velocity'. Assets tend to stay in the same place for a large amount of time, while people move around from one location to another.

For asset management in hospitals the location is only needed when the object is static or has been moved. Knowing the location of a moving object is of less importance because it covers only a small part of the time. The locations for the test case are a cupboard, used for localization around the border of a room. A table, for localizing smaller objects such as medication. And open space, to measure the localization of large movable objects, e.g. beds, and people. In consultation with the hospital management, the characteristics of the IV pumps are used as input for further testing and analyses. The definition of the test cases is described in section 3.5.1.

Table 1: Requirements for localization in the hospital based on the properties assets and people

		Size [m]	**Height [m]**	**Location**			**Velocity**
				Cupboard	*Table*	*Open space*	
Assets	*Beds*	2	0,8	no	no	yes	no
	IV pumps	**0,2**	**1,5**	**yes**	**yes**	**yes**	**no**
	Medication	0,1	NA	yes	yes	no	no
People	*Patients*	0,5	1,2	no	no	yes	yes
	Staff	0,5	1,2	no	no	yes	yes

2.2.3. Simulation of hospital case in Spark Center

As the testing cannot be done in the hospital itself, the data from the Spark Center test setup will be used for the analyses. For the use case it is important to have similar data compared to when the testing would have been carried out in the hospital. For this reason, a simulation of the routine of the assets described in the use case was performed in the Spark Center. A number of test cases are defined to use the position data collected in the Spark Center as input to measure the performance of localization in the hospital. A more extensive description of the test setup is given in section 3.5. In Appendix B a description of a Proof of Concept for the implementing the Quuppa system in a part of the Rijnstate hospital in Arnhem is given.

2.3. Literature review

In this section Bluetooth technology, the Angle of Arrival positioning method and the trilateration method for determining the *locator* orientation are discussed to clarify the technology used within the Quuppa system. Next to this some background knowledge for better understanding of the parameters for statistical analysis is given. A method for indoor asset tracking is reviewed to provide a framework for setting up an indoor positioning system for localizing objects. Finally, a number of (spatial) analyses methods are suggested to provide input for analysing the data.

2.3.1. Bluetooth Low Energy

Bluetooth Low Energy (BLE) or Bluetooth Smart is developed from the classic Bluetooth technology. The main innovation is the lower power consumption of the devices, which last for over a year without recharging. The use of small coin-cell batteries reduces the dimensions of BLE enabled devices. Dual-mode chips enable older devices to work while having the benefits of the new technology. The implementation of BLE in the Quuppa tags uses single-mode chips. Adaptive frequency hopping in the 2.4 GHz ISM-band minimizes interference between wireless systems, which improves the opportunities for BLE applications for indoor use.

The range of BLE spans up to 60m, where the classic BT was limited to a 10m range. This makes the technology more useful for applications indoors [6]. However, in indoor environments the signal-strength is affected by many factors (multi-path effects, reflection effects, etc.) [4]. The Internet of Things (IoT) also benefits from the innovation of BLE, which makes the use of BT for connections between devices more applicable for everyday objects [7]. Also medical equipment, such as heart-rat monitors and IV pumps can be integrated in an IoT system to communicate with mobile devices operated by medical staff or the patient itself.

2.3.2. Angle of Arrival

Position coordinates determined by using an AoA method, based on the direction of incidence (ϕ,θ), can be obtained by the use of directionally sensitive antennas [5]. The Quuppa *locators* contain a directional antenna that is cone-shaped. If measurements are taken by at least two *locators*, the position can be determined by an intersection of lines [22]. In this case, the 3D position, i.e. x, y and z coordinates, can be derived from the measurements. In 2D a single *locator* is sufficient to measure the position. The AoA-based positioning accuracy degrades with increasing distance between the tag and the *locator* because of the increasing linear change for every difference in degrees of the angle at the *locator* [36]. In Figure 12 the angular parameters for measuring the positions are shown.

Indoor positioning is more challenging compared to outdoor (for example using GPS), because of the smaller, closed spaces in buildings. This causes the signal between the transmitter and the receiver to be blocked by walls and ceilings. The main challenge for positioning in an indoor environment is identifying the multipath arrival of the received signal [36]. This phenomenon can influence the direction of the signal sent by the tag to the *locator* and thus the position that is calculated for this tag. The availability of the signal of the wireless system (e.g. BT) is not optimal in every part of the building. The performance of the indoor positioning system depends on different technical and architectural aspects that are explained in 4.1.1.

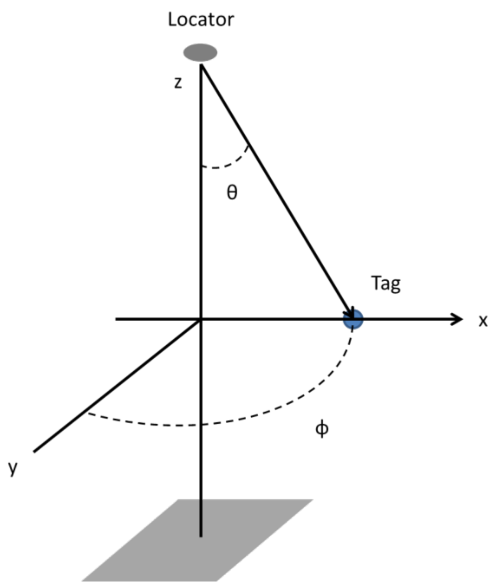


Figure 12: Angles (θ,ϕ) measured by *locator* to estimate the tag position in the 2D plane

Positioning in 2D

In Figure 13, the 2D tracking plane is shown in blue, which represents the pre-set object height when the system is configured to track in 2D. When a single *locator* detects a tag, the system can only return the 2D position of a tag. The height component, represented by a 2D plane with value h, is known beforehand and fixed for all measurements. For each tag the X and Y position is returned. For measuring a position in 3D, the system needs at least 2 *locators*. To optimize the availability of the signal there should be no obstruction of the *locator* within a one-meter radius from the *locator*. Having an obstacle within this distance can result in a propagation of the uncovered area towards the floor.

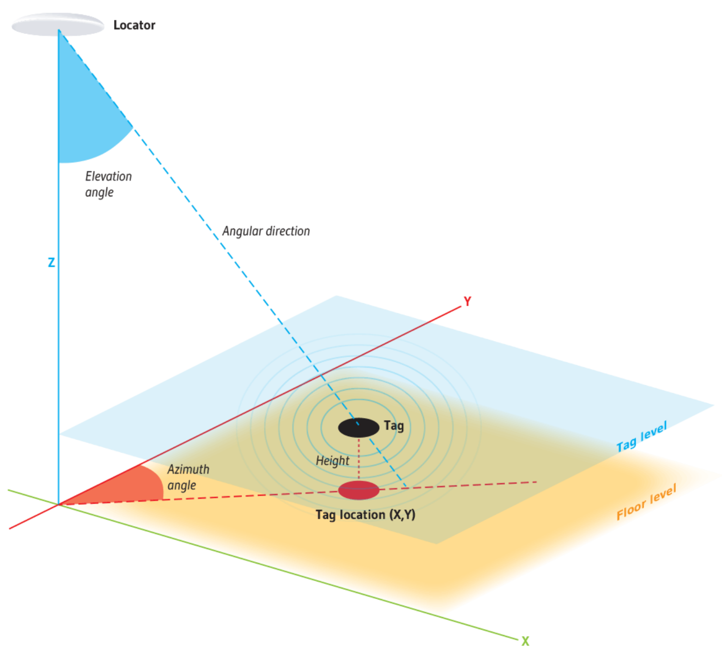


Figure 13: Tracking plane (blue) for 2D positioning (Quuppa, 2015)

Positioning in 3D

Two or more *locators* can return the position in 3D, by measuring the X, Y and Z value at every position. In 3D mode, compared to 2D, both the azimuth- and the elevation angle can be estimated more accurately because the uncertainty field becomes smaller. As the tag position is measured by two *locators*, the intersection point of the measurements can also return a Z value, for the height of the tag. In the situation where a tag is seen by two *locators* that make a 180 degree angle with the tag, the position estimate is less accurate. This is explained in the next section.

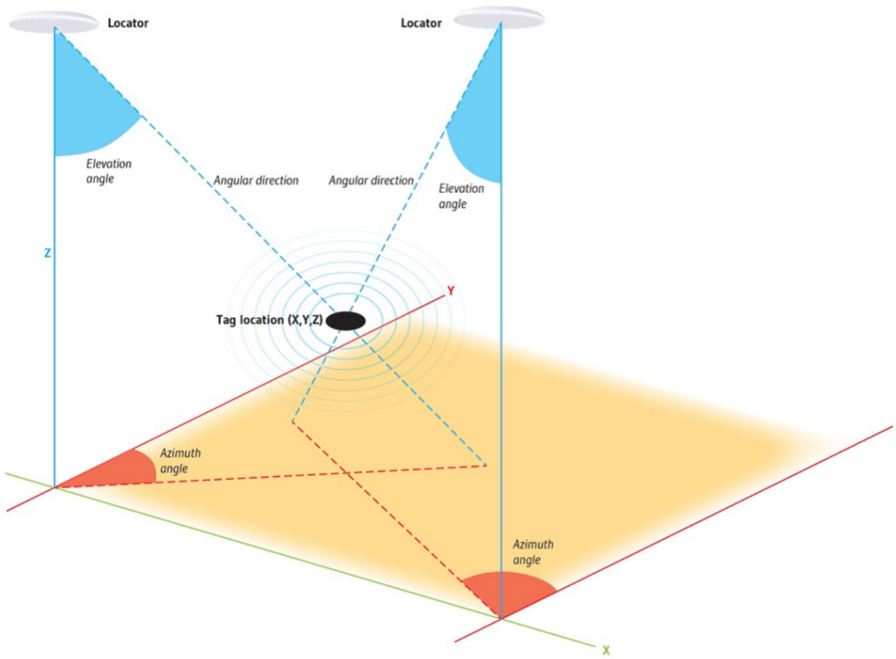


Figure 14: Angle of Arrival 3D positioning principle (Quuppa 2015)

Dilution of Precision

Dilution of Precision (DOP) is a geometric phenomenon that affects the accuracy of each individual measurement. This is a term mostly associated with satellite constellations however it is also applicable to other positioning systems using radio signals. The DOP value represents the geometric effect on the relationship between the measurement error and the positioning determination error [9]. When measuring the horizontal coordinates (x and y), each measurement contains a certain error represented by the range circles, i.e. the measurement error. For estimation of the position by combining two or more range circles of different reader nodes (*locators*), the uncertainty grows. This influences the positioning error negatively.

To compute the DOP value for a certain constellation, the SD of the pseudo range measurement error plus the residual model error [16]. The pseudo range measurements are the measurements of the position of the transmitter that are taken without taking into account the DoP error. The residual model error is determined by least squares approximation. Knowing this SD, the different DOP values (Geometrical /Horizontal/Vertical) can be calculated based on the appropriate variances. DOP values below 7 are considered to have a good confidence level. Values above 20 indicate a measurement is too inaccurate and can only give a rough estimate of the position [19].

$$GDOP = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2}$$

$$HDOP = \sqrt{\sigma_x^2 + \sigma_y^2}$$

$$VDOP = \sqrt{\sigma_Z^2}$$

In Figure 15 the difference in the positioning error for two configurations of the readers are shown. A small uncertainty field occurs when the reader nodes are far away from each other and the angle to the Line of Sight (LoS) from reader to transmitter is relatively large (a). When this angle is small (b), the uncertainty field is larger, which increases the positioning determination error.

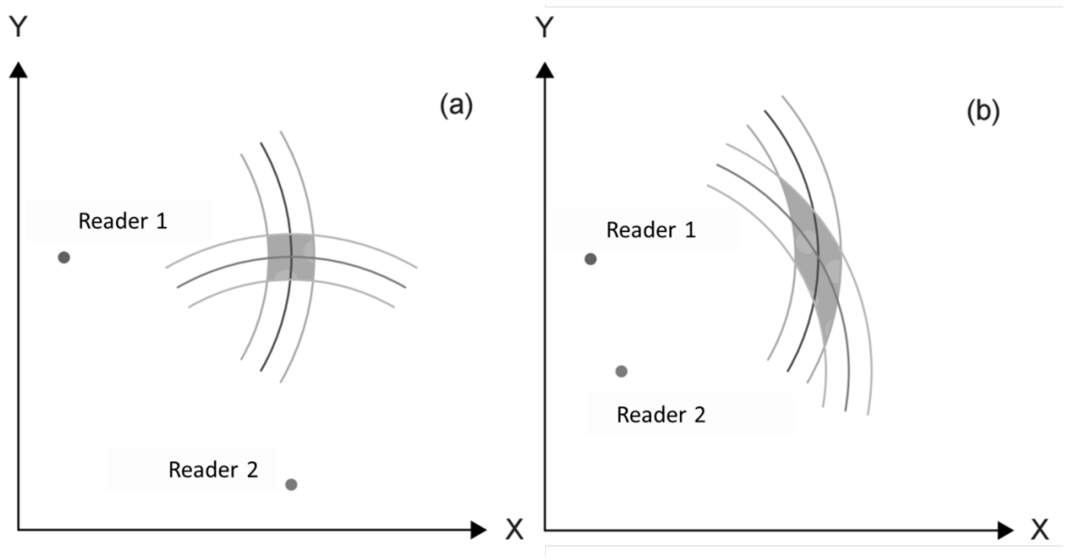


Figure 15: Configuration of reader nodes influences the field of uncertainty

In the configuration of the *locators* of the Quuppa system, a third example of an enlarged uncertainty field can be described. A stated before, the positioning error grows when the angle between the LoS of two measurements is small. This is also the case when the reader nodes are located opposite to each other. Figure 16 shows that the performance of the system is lower in the area between two *locators*. This is because the intersection point of the virtual lines based on the azimuth angle is relatively large and therefore more difficult to define. The individual measurements of this angle are relatively precise. However, for a small change in the azimuth angle the change in the estimated position between the two *locators* is rather large.

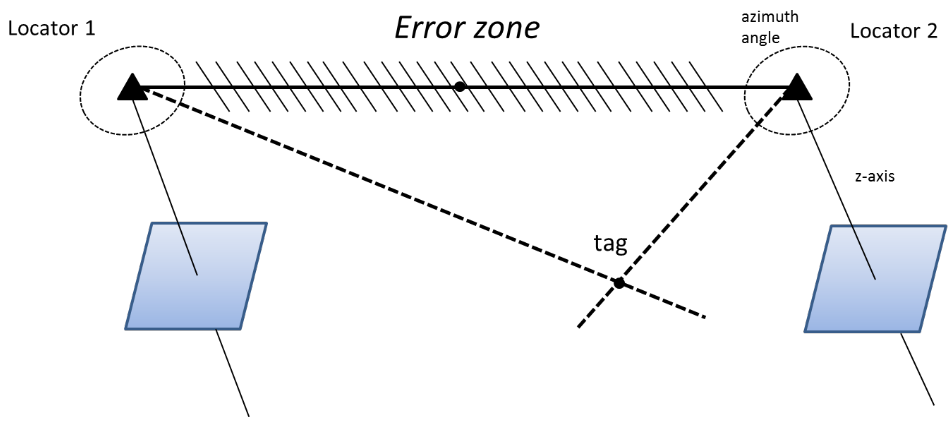


Figure 16: Error prone area between two *locators*

2.3.3. Trilateration

To determine the X, Y and Z coordinates of a mobile position, a method called trilateration can be used. In 2D this is done by measuring the horizontal distance from the mobile position to a number of fixed points (with a minimum of three). The intersection of three virtual circles defines the unknown position of the fourth point. In 3D the coordinates are found at the intersection of three sphere surfaces given the centres and radii of the three spheres [10]. The formula for calculation of the 3D coordinates in shown below. For 2D, the formula contains only the x and y term.

$$r_k = \sqrt{(x_k - x)^2 + (y_k - y)^2 + (z_k - z)^2}$$

where:

- (x_k, y_k, z_k) are the known coordinates of the fixed points
- $k = 1,2,3$
- (x, y, z) are the coordinates of the mobile point

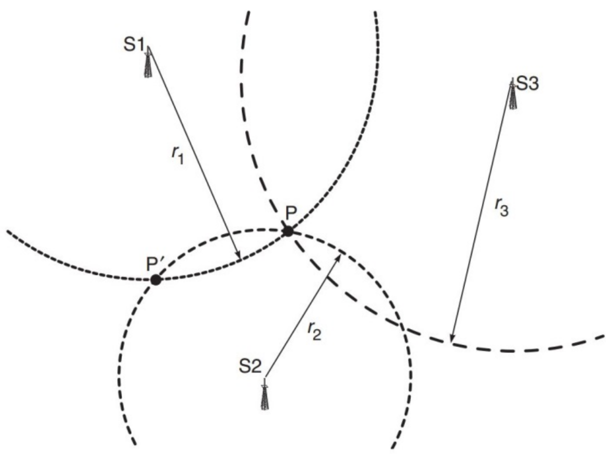


Figure 17: Trilateration in 2D used to determine *locator* coordinates [25]

To determine the mobile position, the equation has to be solved for every circle around a fixed point with radius *r*. In Figure 17 the intersection of the circles around the fixed points (S), with radius *r*, are shown. In practice, an intersection point is rare. An intersection area adds some uncertainty to the resulting coordinates which should be taken into account. Trilateration as a positioning method is implemented into the *locator* configuration tool of the QSP to determine the x and y coordinates of the installed *locators*.

2.3.4. Covariance matrix

Before explaining the theory and application of the covariance matrix for this research, some terms need to be defined. When measuring a point, in this case x, y coordinates, the results are distributed around the mean value. If the data is normally distributed, the spread in the measurements is described by the *variance* (σ^2). The "N-1" part in the formula below refers to the total number of observations subtracted by 1, because only a subpart of the total population is taken. The variance only represents the spread of the data in the direction along the x and y axis. With only the variance of a group of measurements the correlation between the x and y values cannot be explained [33].

$$Variance = \frac{1}{N-1}\sum_{i=1}^{N}(x_i - \mu)^2$$

$$SD = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \mu)^2}$$

Another term that needs explanation is the standard deviation (SD). The SD is the square root of the variance, which represents the average deviation of each data point to the mean [33]. For each axis the SD in the x- and in the y direction can be calculated. Where the variance only captures the axis-aligned spread, the diagonal spread of the data points can be computed by the covariance [34]. This results in a 2x2 matrix in the case of 2D coordinates. For each data point in the group of measurements, the covariance matrix (Σ) is:

$$\Sigma = \begin{bmatrix} \sigma_{x,x} & \sigma_{x,y} \\ \sigma_{y,x} & \sigma_{y,y} \end{bmatrix}$$

The SD in the x and y direction for both X and Y can be represented by a vector $\vec{v} = (x, y)$ [34]. The vector for the x values has as input $\sigma_{x,x}, \sigma_{x,y}$, the vector for the y values is computed from $\sigma_{y,x}, \sigma_{y,y}$. These vectors can be used to show the direction of the distribution of x and y values of the measured coordinates. The difference in the vectors (size and direction) can be used for assigning the measured position to a predefined (sub)location.

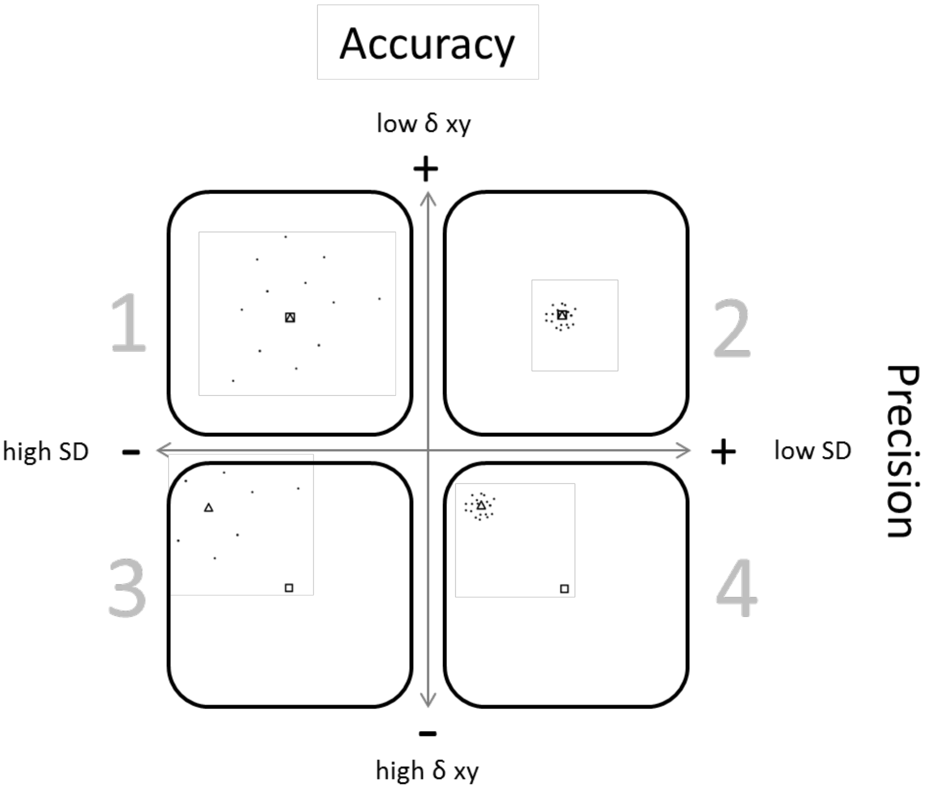


Figure 18: Four scenarios based on the relation between the accuracy and the precision of a position. The real value is indicated by a square shape and the average of the measurements by a triangle.

Use of SD for analyses

The standard deviation (SD) is an indication for the dispersion of the measurements around the average of those measurements. This value can be linked to the real value, i.e. grid point (square). Two other variables involved in determining the reliability of the measurements are accuracy and precision. Accuracy is a measure for the closeness of the measurements to the real value. Precision can be defined as a measure for the spread of the measurements around the real value [3]. In Figure 18 the relation between the precision and accuracy of the measurements is shown. The precision is indicated by the SD and for the accuracy the difference between the measured- and the real position is used. If the precision is high, the SD is low because the measurements have a low dispersion around the average value (triangle). If the precision is low, the dispersion of the measurement is high and the SD will be relatively high. Low accuracy values correspond with a high δ xy and low δ xy values indicate a high accuracy. These four relations are used as the scenarios for map matching in section 4.2.2.

2.3.5. Asset tracking

Definition and relevance

The process of repeated positioning of a moving object or person over time is called tracking. Object tracking can also be denoted as asset tracking [22]. The specific need for tracking of assets comes from a fundamental difference between people and objects. People can locate themselves to a certain extent because they are able to talk and communicate with others. Objects can only be identified at a location through a positioning system. When the location of the object is known, the object will be able to communicate its whereabouts and (real time) status.

Issues regarding tracking in hospitals

Hospitals use a lot of (medical) equipment that is needed to provide their services. Because of the unpredictable service demand and the complex infrastructure of hospitals, quickly locating the critical assets has been one of the perpetual problems in the healthcare service industry [18]. A system that will solve this problem needs to deal with the complexity of the building lay out and processes in a hospital environment. In this respect, the setup of the positioning system and the characteristics of the objects to be located are crucial.

Characteristics of the assets

The location of medical equipment can change arbitrarily and continuously. In order to provide the staff members of the hospital with a tool they can use to locate this equipment, the real time location and information of the assets needs to be returned by the positioning system. The characteristics of the assets which make it difficult to identify and track objects in real time are common usage by different departments and locating the assets in various local storages [26].

Set up of the tracking system

All positioning systems need a reader and a transponder (tag) to locate an object. The placement and coverage field of the wireless network connectors, which is needed for indoor positioning, is crucial for the performance of the tracking system [26]. To solve the difficulties mentioned in the previous paragraph, the positioning system needs to shorten the tracking time and increase the accuracy of positioning and identifying [20]. An optimized placement of the readers throughout the hospital will decrease the search time for critical assets and fewer staff will be needed to perform equipment round-ups [26].

Proposed optimization method

In [26] some variables that can be used to indicate the need for coverage by the positioning system at every square within a pre-set grid are described. The proposed method was designed for a tracking system that uses RFID technology. The variables give an indication of the criticality index (c_i) for a specific type of asset for the performance of every demand square.

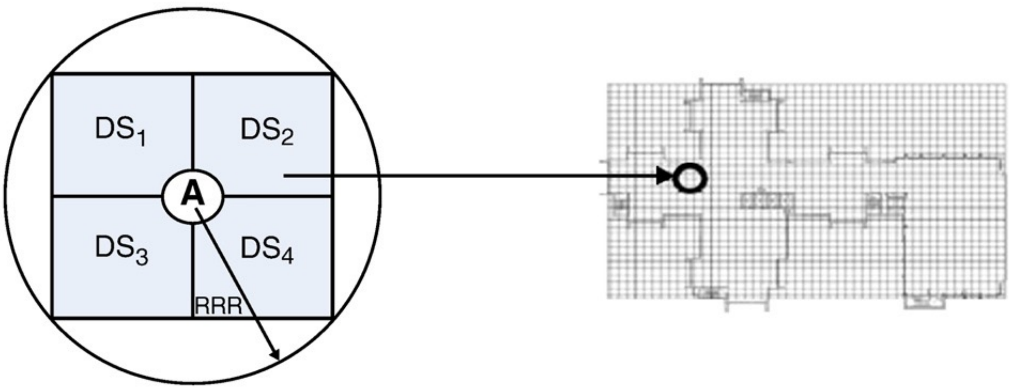


Figure 19: Coverage of reader node in relation to demand squares [26]

The formula of the index and the required variables are:

$$c_i = \sum_{k=1}^{L} f_{ki} * (d_t)_{ki} * s_k$$

where:

s_k = Severity: The level of importance in case of an emergency on a 5 point Likert-scale [31].
F_{ki} = Frequency: number of times asset passes a certain demand square in a day.
d_t = Dwell time: average time that an asset spends in a demand square during 1 day.

The formula for the coverage (A) of the floorplan including all demand squares, which are covered by the reader located in A, is:

$$A = c1 + c2 + c3 + \ldots$$

These two formulas can be used in two different ways. On the one hand, to evaluate the placement of the readers, a certain threshold for A could be set and when a reader scores below that value a new location should be found. On the other hand, it is possible to determine the best location for the reader by calculating the highest A value based on the c values within the range of the reader. To calculate the best location the following formula is used:

$$\text{Max } w_1\left(\sum_{i=1}^{n} c_i * y_i\right) - w_2\left(\sum_{i=1}^{n}\left(\sum_{j\in N_i} x_j\right) - y_i\right)$$

where:

n = total number of demand squares
c_i = criticality index of a demand square i
y_i = binary value: 1: in range of at least 1 node, 0: otherwise
x_j = 1: located at reader node j, 0: otherwise
N_i = set of reader nodes that can cover demand square i

2.3.6. Methods for (spatial) analysis

Geofencing
Geofences can be used to put spatial restrictions on a certain asset or to locate an asset at a user defined location instead of returning just x and y coordinates. An alert is send to the management when an asset leaves or enters a predefined area. In practice this means when the asset passes a specific *locator* outside the specified area. ESRI's Geotrigger service can be used to implement this tool.

Heat map
A heat map shows the differences of a parameter for each location on the map within a certain time frame. For example, when tracking people, it might be useful to show what places on a map are visited more than other, i.e. have a higher intensity. For analysis purposes of the system setup a heat map can be created of the PA parameter of the returned position. This variable is returned by the Quuppa system for every measured position of a tag.

Flagging
Flagging of an asset means that certain information about the asset can be changed based on the location or the status of the asset. Flagging can be done manually by wirelessly connecting to a

reader (mostly RFID) or automatically when the location of the asset corresponds with the type of usage. In the case of the IV pumps, a status can be assigned to each asset by the employee using a custom tag or based on the location using the location data. The status can be changed from “clean” to “dirty” in the case of an IV pump. Flagging is not possible within the tools provided by Quuppa. However, it can be implemented in a custom made application connected to a database.

Counting

When the stock is isolated and the *locator* is strategically placed it is possible to count the assets that are passing this specific *locator*. A detection of the asset by a *locator* means that the asset is taken out of the stock and that the stock needs to be filled.

3

Test setup Spark Center

In this part the criteria and design decisions of the test set up at the Spark Innovation Center, will be discussed. Five *locators* will be placed at the test facility. The purpose of the demo system setup is to return the location of people and assets and show this on a display in the Spark Center. The setup of the demo system consists of the following phases: planning, Installation and configuration. The test location is a demo center in CGI's office in Rotterdam where clients and personnel are introduced to new technology and software developed by CGI. This room is an open space divided into three main parts, i.e. Play Zone, Business Zone, and Theatre. Impressions of these zones are shown in Figure 20. The main goal of this research is localization of objects in a hospital using the Quuppa positioning system. After installation of the system at the test facility tests are carried out to collect a dataset of position measurements. The general test setup and specific test cases related to the hospital use case are discussed from section 3.4 onwards.

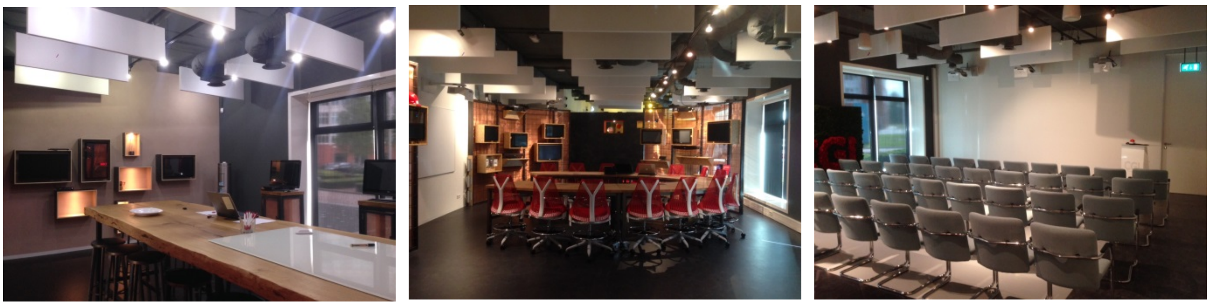


Figure 20: Impressions of different areas in the test facility: Play Zone (l), Business Zone (m) and Theatre (r)

3.1. Planning phase

The main requirement of the setup of the system is to cover the area were the activity takes place. This is shown in Figure 21. A plan of the three zones is shown in Figure 22 The walking area is situated along the midline of the Spark Center. The areas along both of the walls (outside/hallway) do not accommodate any important functions. Only in the Play Zone some desktops and a cupboard are situated near the borders of the plan. The QSP describes three types of areas which provide guidelines for installation and configuration, i.e. open, semi-confined and confined [29]. The type that best fits the Spark Center is *confined* as this is described as: Any indoor space with many interior elements, concrete walls/floors, e.g. logistic hub, hospital. In the Spark Center the system is used to show the position of visitors, carrying a tag on their visitor key card, on a screen. The focus of this research is on localization of assets. However, both of these applications were taken into account for choosing the positions of the *locators*.

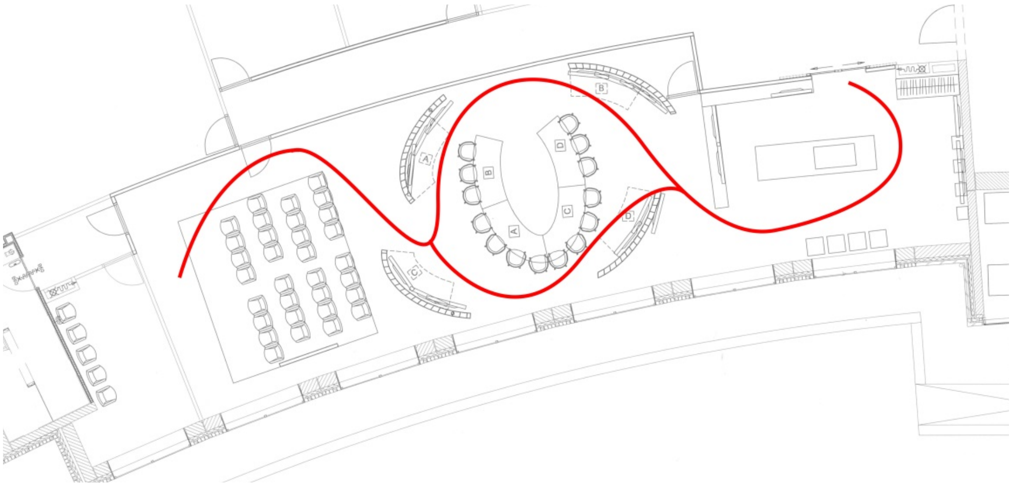


Figure 21: Traffic area of the Spark Center

The reason for placing the *locators* around the midline comes from the characteristics of the positioning method and technology. This can be explained by comparing it to positioning using WiFi AP's. Since WiFi positioning is based on estimation of the distance from the reader to the transmitter, the position is calculated by finding the intersection of circles with a certain radius. For this method a configuration where the readers are placed alongside the boundaries of the area of interest gives the best results. In the case of the Quuppa system, which uses BLE technology and AoA as a positioning method, the setup should be different. For this reason, the *locators* of the Quuppa system are placed in the middle of the AoI.

AoA estimates the position of a tag based on two angles that are measured by each *locator*. This means that when the tag is close to the *locator*, the estimation can be very accurate. Further away the uncertainty in the measurements grows, also because of the decrease in signal strength. For this reason the *locators* should be placed in the middle of the area of interest, which can be seen in Figure 24. This setup returns the best coverage of the parts of the floorplan that are mostly used by visitors. If the *locators* are placed too close to the edges of the room, a large part of the signal will be blocked or outside the area of interest. Some interior elements may block the signal of the *locators*. These elements are marked blue in Figure 23.

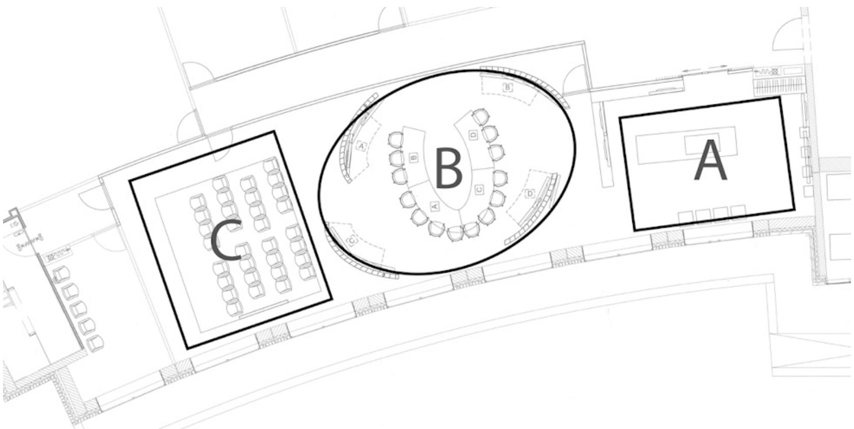


Figure 22: Different areas in the Spark Center, i.e. Play zone (A), Business zone (B) and Theatre (C).

The installation of the *locators* in the vertical direction depends on two factors. Mounting the *locators* directly to the ceiling will cause blockage of the signal by the ventilations units, acoustic screens and lighting rails. The second factor is the coverage area of the *locator*. As this area is cone-shaped, the coverage will be less when the *locator* is installed closer to the floor. This results in a trade-off between having a smaller coverage area without obstruction or a larger coverage area that might be partly blocked by obstacles.

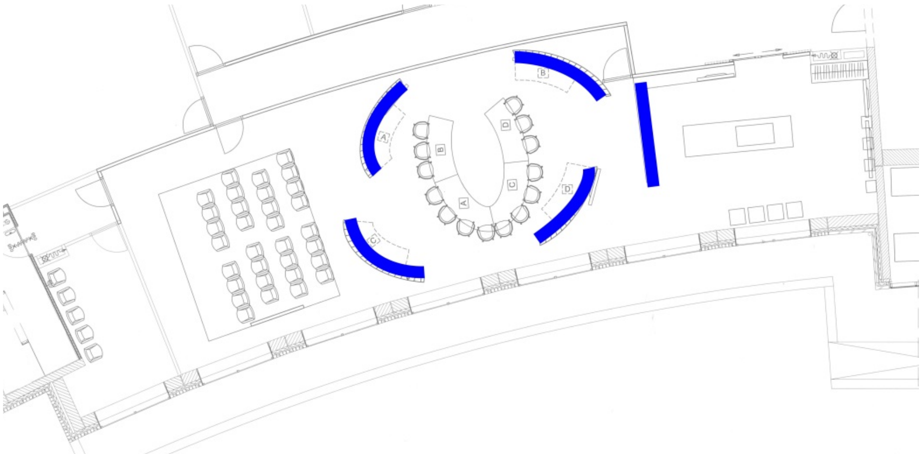


Figure 23: Interior elements possibly blocking the radio signals

Because of the restrictions to the hardware in the demo package provided by Quuppa (including only 5 *locators*) and the requirement to have full coverage of the floorplan of the Spark Center, the *locators* are mounted directly to the ceiling. The range has a conical angle of 100 degrees. Installing multiple *locators* will improve the covered area of the *locator* by 5 degrees in each direction (conical angle of 110 degrees). The default height of the tags is set at 90 cm (for positioning in 2D). The configuration of the *locators* is shown in Figure 24. As mentioned before, all *locators* are connected to a switch by Ethernet cables. These cables need to be guided along some objects on the ceiling. In most cases there is a cable tray nearby. The switch will be placed in the center of the room to keep the cabling as short as possible. In this case this is the storage room next to the office area.

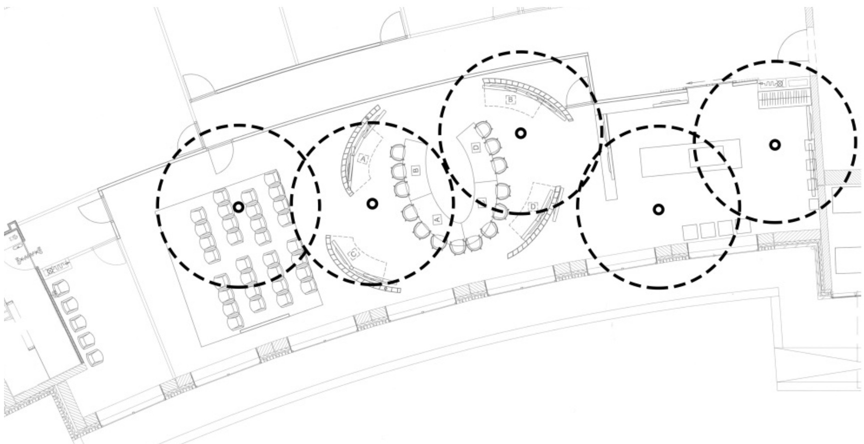


Figure 24: Range of the individual *locators* on the floor based on the conical angle

***Locator* 1**

- Location: At the right side of the Play zone
- Installation: Mounting plate attached to a PVC tube using tie wraps and ceiling board for stability Coverage: Entrance, Demo corner, Table
- Height: 3550 mm
- Possible blocking objects: Table

***Locator* 2**

- Location: At the left side of the Play zone
- Installation: Mounting plate attached to a PVC tube using tie wraps and ceiling board for stability
- Coverage: Lobby: 'Wall of Fame', Table and the area between lobby and office.
- Height: 3530 mm
- Possible blocking objects: A ventilation box, the partition wall, table

***Locator* 3**

- Location: Right side of the business zone
- Installation: Mounting plate attached to a PVC tube using tie wraps and ceiling board for stability Coverage: Area between lobby and office (between the curved screens) and the east side of the office.
- Height: 3530 mm
- Possible blocking objects: The curved screens consist of a metal structure and a metal netting which may block and/or reflect the signal because the structure is very dense.

***Locator* 4**

- Location: Left side of the business zone
- Installation: Mounting plate attached to a PVC tube using tie wraps and ceiling board for stability
- Coverage: The left side of the office and the area between the office and the theatre.
- Height: 3540 mm
- Possible blocking objects: The curved screens consist of a metal structure and a metal netting which may block the signal because the structure is very dense. Also some of the ventilation boxes and shafts can block the signal.

***Locator* 5**

- Location: Over the Theatre area towards the inner wall
- Installation: Mounting plate attached to a PVC tube using tie wraps and ceiling board for stability
- Coverage: The larger part of the seating area and the passageway between the theatre and the office.
- Height: 3560 mm
- Possible blocking objects: The curved screens may block the signal coming from the theatre. However, *locator* IV covers the area behind the screens.

3.2. Installation of the hardware

The hardware components of the demo system are 5 *locators*, 1 focusing *locator* (used for configuration), 1 Mac Mini (Site planner tool, server), 20 tags and a Power over Ethernet switch (PoE) and Ethernet cables. In Table 2, an overview of some important number with respect to the installation and configuration are shown.

Table 2: Facts and figures of the pilot installation in the Spark Center.

Spark Innovation Center	
Dimensions [lxb]	24 x 6.5
Space [m2]	156
Number of *locators*	5
Ethernet cable [m]	60
Coverage QSP (=good)	90%

3.3. Configuration of *locators* and tags

After installation of the hardware, configuration of the *locators* is needed. To configure the *locators* to be able to operate in 'tracking/deployment' mode and track the tags, the following steps have to be taken. A sixth *locator*, called the focussing *locator*, acts as a 'master' device to configure the installed, focussed *locators* on the ceiling. First a background map has to be loaded and georeferenced. For analyses purposes and to best fit the tracking environment, the coordinate reference system is set to RD, because it uses the unit 'meter'. The origin of the local coordinate system is placed in the lower left corner of the Spark Center in order to have mostly positive (>0) results for the coordinate measurements. The X and Y axis of the local coordinate system are shown in Figure 25 (red lines).

To find the x, y and z coordinates of the *locators*, the trilateration method is used (see section 2.3.3). For each *locator* a minimum of three tie points were chosen. The tie points (tri xx) for all five *locators* (L00x) are shown in Figure 25. Before measuring the orientation of the *locators*, each *locator* has to get a unique ID by identifying them using the identification wizard built into the Quuppa Site Planning tool. The white polygon in the floor plan defines the 2D *tracking area* based on the tracking plane. The *tracking area* defines the location where tags can be positioned by the system. Positioning outside this area is not possible. Tags outside this area are snapped to the boundary of the *tracking area*. This property can be used to avoid wrong localization results in rooms that are adjacent.

The next step is to determine the orientation of the *locators*. The three directions that need to be measures are tilt/elevation (angular displacement in the X and Y direction) and the azimuth (rotation around the Z axis). All *locators* are equipped with an accelerometer that measures the attitude and relative movements of the *locator*. The focusing *locator* must be placed in at least two different locations on the local X and Y axis of the floor plan. The error of the measured orientation, in degrees, should be 1 or lower. In the case of this test setup all orientation errors were between 0.2° and 0.7°, which is considered good.

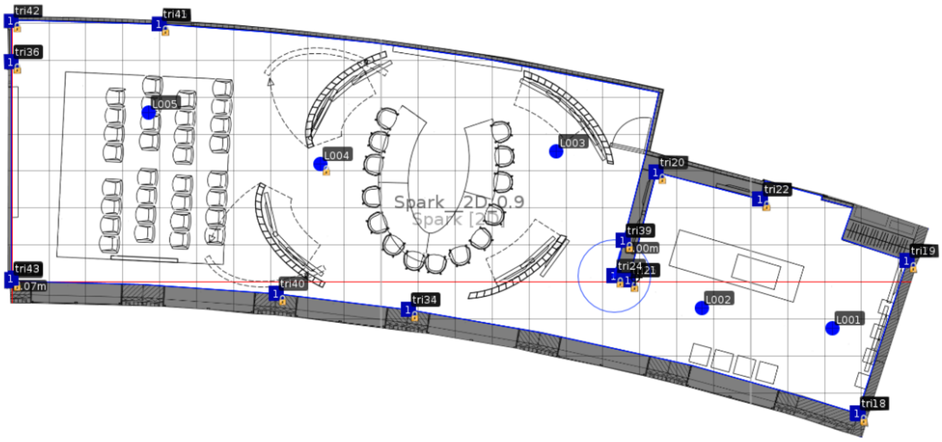


Figure 25: Trilateration (tie) points used for determining the X, Y, Z position of the *locators*

The Site Planner has a built in feature that shows the coverage of the *locator* network. As mentioned before, the coverage and accuracy of the returned location improve, when two or more *locators* can determine the position. Figure 26 shows the coverage of the system setup in the Spark Center where five *locators* were installed. This coverage is based on a 2D tracking plane with a pre-set Z value. The majority of the floor plan returns good coverage which makes it suitable for high-resolution positioning. On the left site of the floor plan the coverage of the *locators* is worse compared to the rest of the room. This is partly due to the fact that on this side only 1 *locator* was installed, so the coverage does not improve around the borders of the *locator*'s range. In the middle of the floorplan, between *locator* 3 and 4, the coverage is also slightly less. This is due to a geometric phenomenon discussed in section 2.3.2. In these areas low-resolution positioning is still possible.

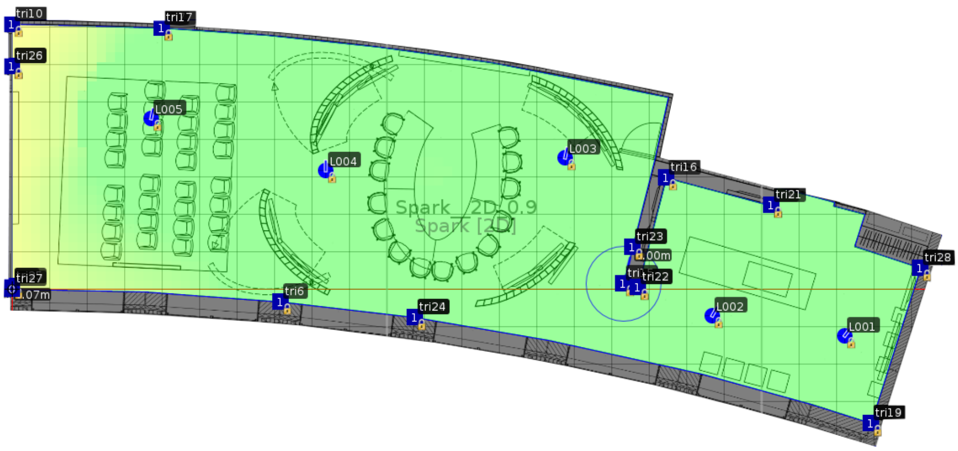


Figure 26: Coverage of the *locators* in the 2D tracking plane

The last step is the configuration of the tags. The tags that come with the Quuppa system are active tags that send out a signal, which is picked up by the *locators*. A custom configuration can be applied where the properties of each tag can be adjusted. The program can configure different 'states' of the tag. In Figure 27, the configuration tool is shown. The state 'triggered' is used when the tag is active (e.g. moving), and the transmit rate is for example 2.0 Hz. When the tag does not move for a certain amount of time, e.g. 5 minutes, the state changes to 'default' and the transmit rate slow down to 0.5 Hz.

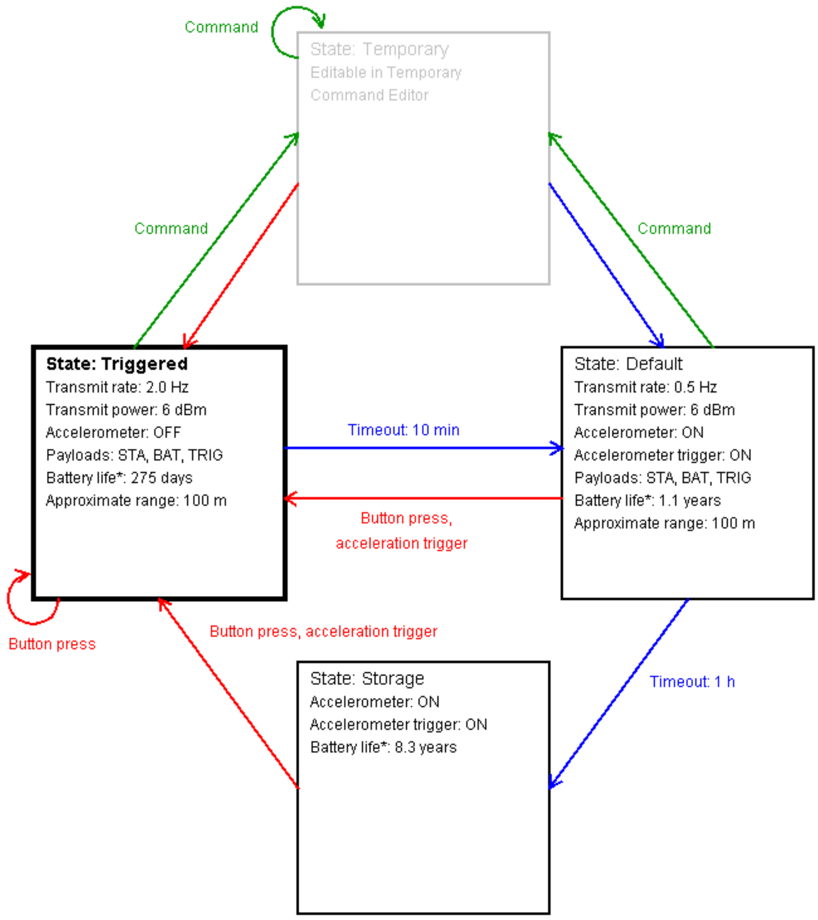


Figure 27: Diagram of tag configuration for testing

The positions of the active tags can be requested from the Quuppa server. A typical request contains the following information:

http://10.16.5.201:8080/qpe/getHAIPLocation?version=2&maxAge=30000&humanReadable=true&tag=001830ed43dd

Where '*tag'* specifies the tag ID's that need to be in the response and '*maxAge'* [ms] returns the last location of the tag within the time set. The response can be formatted in JSON or CSV format. Below an example of the returned locations in JSON format is shown. In this response a covariance matrix is given, along with the tag ID, the returned position and the accuracy of the position. To analyse and visualise the accuracy of the test set up, a heat map can be constructed of the tag position data of the Spark Center [30]. Below, the output of the request 'getHAIPLocation' is shown in JSON format.

The response output of the system consists of three types of information. The parameters *´areaId´*, *´areaName´*, *´color´*, *´id´*, *´name´* and *´version´* return information about the tags and the *tracking area*. The parameters ´position´ and ´smoothedPosition´ contain the x, y and z coordinates for the measured position of the tag. The ´covarianceMatrix´ and ´positionAccuracy´ parameters provide information about the quality of the position estimate.

```
{
  "responseTS": 1437655660069,
  "tags": [{
    "areaId": "0001",
    "areaName": "Spark",
    "color": "#FF0000",
    "coordinateSystemId": "0001",
    "coordinateSystemName": null,
    "covarianceMatrix": [
      0.12,
      -0.02,
      -0.02,
      0.2
    ],
    "id": "001830ed43dd",
    "name": "visitor_05",
    "position": [
      21.34,
      0.8,
      0.85
    ],
    "positionAccuracy": 0.2,
    "positionTS": 1437655659614,
    "smoothedPosition": [
      21.35,
      0.8,
      0.85
    ],
    "zones": []
  }],
  "version": "2.0"
}
```


Figure 28: Custom output of Quuppa parameters for the tests in JSON format

3.4. Test setup

3.4.1. Test 1

The first test was carried out to measure the positions of known points on a predefined grid. The *tracking area* was set to the boundaries of the Spark Center, which defines the area where the tags can be positioned. The tags were placed on the floor to use the range of the *locators* to its full extent. Data packets of approximately 100kb were collected in order to receive the same number of measurements for all grid points.

3.4.2. Test 2

For the second test, the boundaries of the *tracking area* were removed, which made it possible for the tag to be positioned outside the floor plan of the Spark Center. This was done to check for outliers and to identify large positioning errors. Also the z value was changed 0,8m to have more representative measurements for the use case of asset tracking. Placing the tags at this height would also avoid most of the line of sight obstructions because of the furniture. Setting the Z value to 0 during the first test resulted in some large positioning errors and tags not being seen by the *locators* at all. In the second test, tags were placed on bar stools to have a fixed and elevated height for all measurements. The setup during test 2 is shown in Figure 29. In contrast to the first test the positions were measured for different time spans independent of each other. For every row of x values, the positions were measured for respectively 10, 30 and 60 seconds. This was done to check for differences in how the data is built up over time. The result of this analysis is an indication of the possibilities for real time positioning which is discussed in section 0.

Figure 29: Example of the setup for test 2 and test 3

3.4.3. Test 3

The third test was carried out to collect the quality parameters that Quuppa adds to the output data. These parameters can be used to make a comparison to the statistical analyses done based on the coordinate values. Another reason is to find out whether the quality parameter can be used as an instant analytical value to adjust, correct or exclude the data from a localization application. This test was divided into three parts. First the grid points of the Play zone are measured again, this time by logging the coordinates and quality parameters.

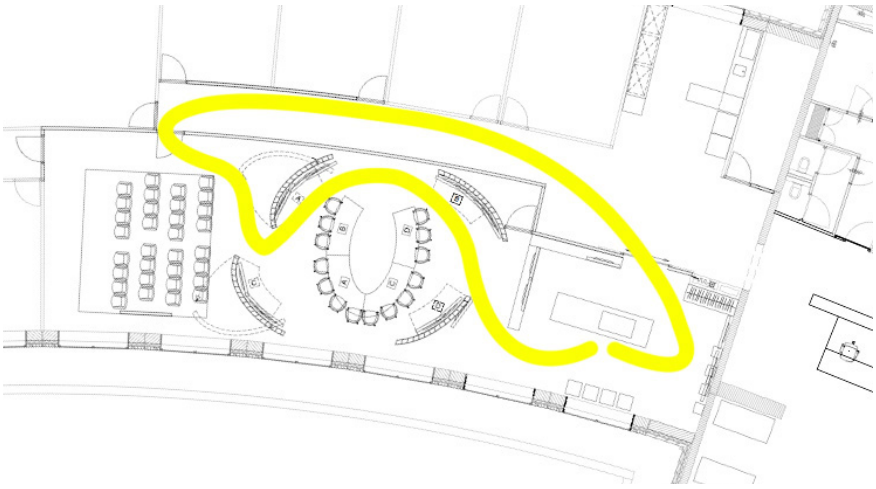


Figure 30: Path followed by the tag outside the *tracking area* along the inner wall

The second part was to check the influence of the tag itself on the output of the system. This was done by using the same tag to measure the points of row 22. The third part consisted of a test where area outside the Spark Center is measured in order to check the coverage of the signal outside the '*tracking area*' of the *locators*. This data was collected from both the area inside and outside the building adjacent to the Spark Center. Instead of placing the tags on grid points and measure the static positions, someone walked along a predefined path. The path along the inner wall is shown in Figure 30. The path along the outer along the outer wall and the parking lot is shown in Figure 31.

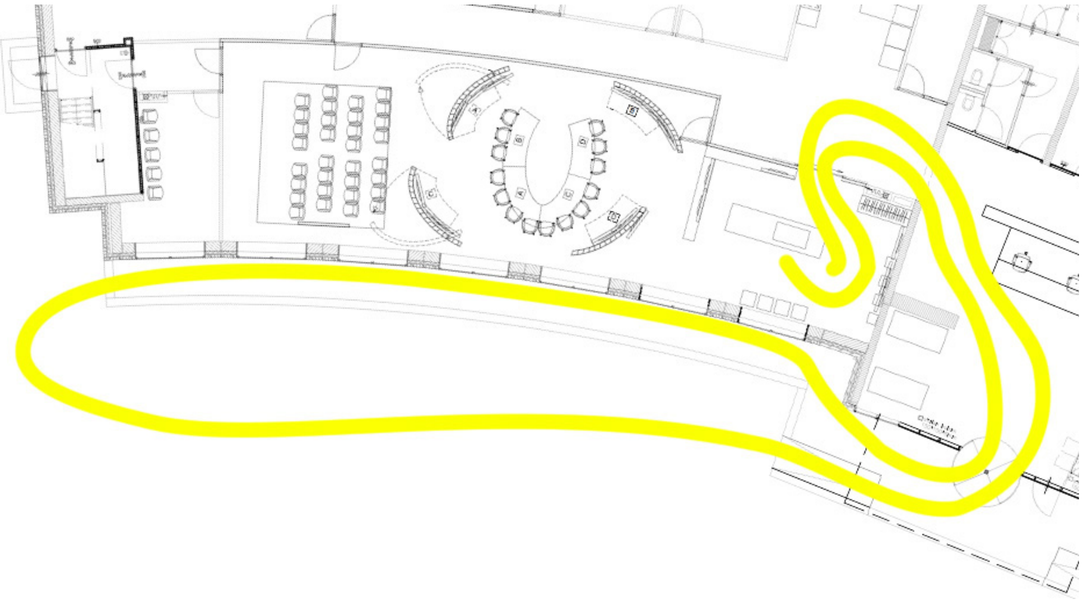


Figure 31: Path followed by the tag outside the *tracking area* along the outer wall

3.5. Test cases for Spark Center

The topic for research is localization of IV pumps in a hospital. Based on the input from the use case, a number of requirements, i.e. height, size, location and velocity, are defined in section 2.2.2. These requirements are used to define case specific tests using (parts of) the position data. For the test setup the characteristics of an IV pump are used as input, which is shown in Figure 32. An IV pump remains in the same place, e.g. storage room and patient's room, most of the time and is fixed to an IV stand or a patient's bed. This implies that, during measuring of the positions, the tags can remain in the same place (static) instead of being moved across the room (dynamic). The height of 0,8m is chosen arbitrarily to be able to perform the tests in the most efficient way possible. Based on the information about the routine and characteristics of the IV pumps, a number of test cases are defined.

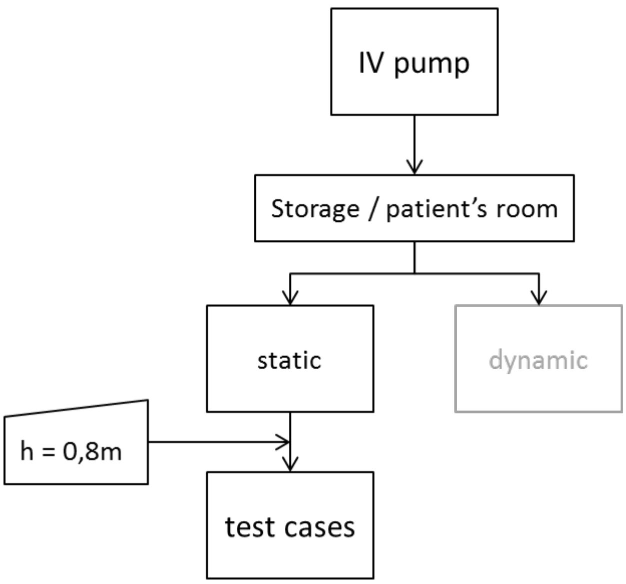


Figure 32: Input from requirements of the hospital use case for definition of the test cases

In Figure 33 the matrix for analysis of the test cases is shown. Six cases are defined based on possible locations of the IV pumps. For the Rijnstate hospital those locations are the storage room, from where the pumps are distributed and the patient's rooms on the wards. The dashed areas I to VI describe a specific subset of the data that complies with the requirements the horizontal and vertical direction of the matrix. The size and shape of these two rooms correspond to part A and B in the Spark Center. These areas are best covered by the Quuppa system (see Figure 24). The Play Zone (A) is used to simulate the storage room. The AoI is situated along the borders of the room, which makes it possible to simulate the storage of IV pumps in the cupboards. The Business Zone (B) is used as the test area for the patient's room. The area size corresponds to a single patient's room in the hospital.

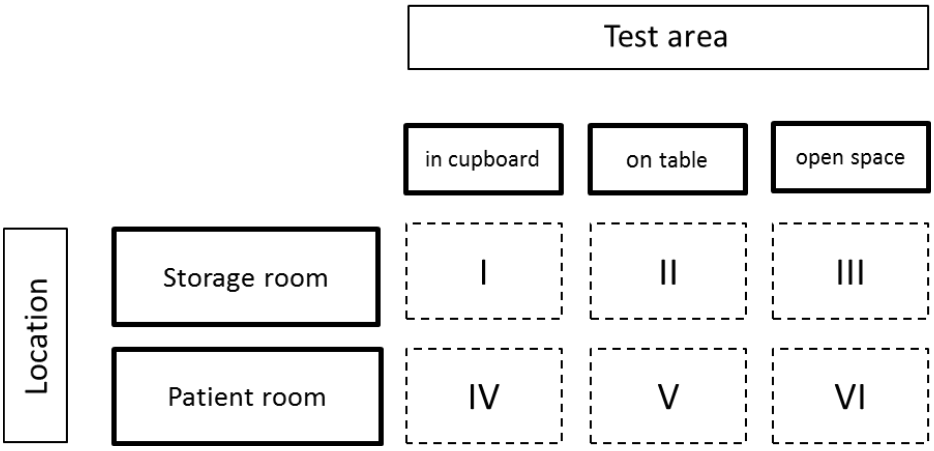


Figure 33: Matrix for test cases to be carries out in the Spark Center

For every test case the reliability of the measurements is calculated and map matching is performed. One of four scenarios shown in Figure 4 is selected for each of the six test cases. These scenarios, based on the accuracy and precision of the position estimates, are defined in section 2.3.4. The reliability of the location is indicated by the amount of measurements that are located correctly based on the situation described in the test case. Map matching of a position measurement can either be correct or incorrect. For correct localization of the points that would be wrongly assigned to a location, the reliability value can be used. Based on the reliability, a model for correcting the coordinates of the point measurement is described. This model uses the methods for map matching that are described in section 4.2.2.

3.5.1. Description of the test cases

Specific locations in the environment are used for defining the test cases based on the characteristics of the object to be localized. According to [1] the "context varies according to application constraints, taking into account (…) the interfaces to interact with". For each of the standard locations of the IV pumps, i.e. the storage room and a patient's room, three test areas are defined. These three test areas have different characteristics and cover different parts of the floor plan of both rooms. The first category is represented by a cupboard. This object is generally placed against a wall, which corresponds with localization of a tag at the borders of a room. The second category is localization on a table. This represents all situations across the floor plan where the tag is situated on an object with a Z value larger than 0. The third category covers all other situations where a tag is located in open space. Open space can be defined as the part of the floor plan where no obstacles are placed and objects and people can move around freely. Analysis of the test cases is described in section 4.2.3.

4

Data processing and analysis

In this section a description of the steps that were taken to test the setup of the system is given. This section consists of two main parts. Section 4.1 covers the positioning part and section 4.2 covers the localization part. In the first subsection the parameters for analysis are defined. The second subsection describes the processing of the data. In the third subsection, the results of the tests are analysed. For localization, the first subsection describes the location types that are defined and matches the positions to these locations. The second subsection shows the results of matching the positions to the location types. In the third and fourth subsection the test cases are analysed and a model for localization is described.

4.1. Positioning

4.1.1. Parameters for research

A total of sixteen parameters that can be used to assess indoor positioning systems are defined by [22], which are shown in Figure 34. These user requirements can be subdivided into parameters for the technical and for the operational requirements. Accuracy, coverage and update rate can be selected for the technical parameters. The other technical parameters are chosen based on the output available from the Quuppa system. The requirement groups for this research are defined based on the scope of this project and the background of the author. All the requirements important for this case are explained below.

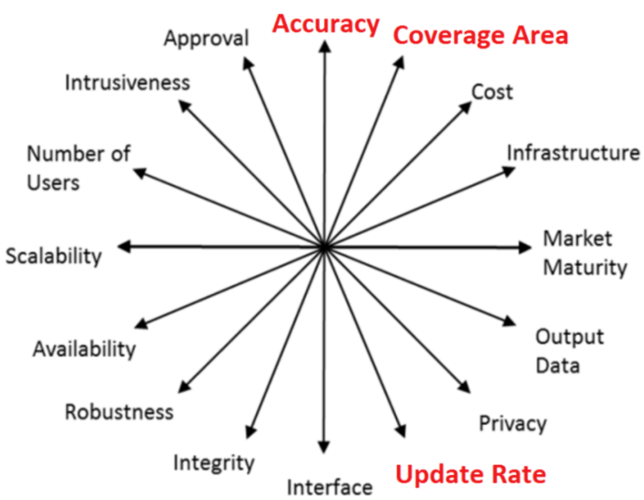


Figure 34: (Non-technical) user requirements (Mautz, 2012)

Technical parameters

- To gain optimum performance of the system under all circumstances within the scope of the use case
- The Quuppa system should be used for indoor positioning in RT
- Define a custom system setup for asset tracking in hospitals

Accuracy
The accuracy of the measurements is the first parameter for the reliability of the position estimate. Reliability is a measure for the consistency of data [12]. In this case the reliability of a position can be described by the accuracy and precision of the measurements. The precision of the measurement can be an indication of the accuracy for future measurements. The Joint Committee for Guides in Metrology (JCGM) defines accuracy as: “the closeness of agreement between a measured quantity value and a true quantity value of a measurand” [22]. This definition implies that two values need to be known in order to determine the accuracy parameter: 1: the position of the asset according to the positioning system and 2: the actual location of the asset in the real world. Because of the involvement of people, the level for localization can be done on a relatively large scale, i.e. (sub)room level.

Precision
Precision is the second parameter for the reliability of the position estimate. The precision is an indication of the dispersion of the measurements around the mean value. Where the accuracy covers a single measurement, the precision is a variable referring to a group of measurements. An indication of this parameter can be given by the SD of the measurements, which is discussed into more detail in section 0. For reliable position estimates both the accuracy and precision are expected to be high. Unreliable results are likely to show bad values for accuracy and precision. These two parameters are important to measure the coverage of the system.

Coverage
This parameter is defined by [22] as the spatial extension where system performance must be guaranteed by a positioning system. The coverage can be described as a scalable parameter in this case. The coverage area can be increased easily by adding hardware. A condition for the scalability of the system is that the coverage is not affected by a loss of accuracy. For this use case, the coverage needs to be sufficient in the areas where the assets remain static for a longer amount of time. The areas (e.g. hallways, elevators) where the assets move from one location to another do not need to have a sufficient coverage of the system.

Latency
The latency parameter is a measure of the time between the data collection and the moment that this data is made available to the user. This time period is mainly depending on the software of the positioning system. The required value for this use case is real time (RT), because medical equipment needs to be available immediately when an emergency situation occurs. The possibilities for RT and the corresponding time span are described in more detail in section 4.1.3. The relation of latency and update rate is of interest for the assessment of the possibility of RT positioning.

Update Rate
The update rate is the frequency with which the positions are calculated by the system [22]. This

parameter has a correlation with the latency because there is no need to have a higher update rate than the amount of time it takes for the system to provide the data to the user. There a three types of measurement rates (a, b and c) defined below. For this use case, the periodic type (a) can be configured in more than one way. For example, when the device is moving the update rate is higher compared to when the device is static (e.g. in a patient room or in the storage room). In this case, an update rate of respectively 5Hz and 2Hz should be sufficient.

a) periodic: regular update, specified in an interval (unit e.g. (Hz))
b) on request: triggered by the user or by a remote device.
c) on event: measurement update initiated by the local device when a specific event occurs

Operational parameters

- A custom setup should make the system work optimally in a generic environment. For subdivision of the floor plan, architectural shape and setup should be taken into account as well as the used materials for walls, floors and other building parts.
- It should be possible to locate an asset at a predefined scale level taking into account the architectural shape and setup.

The operational requirements are the second part of the research. Regarding the setup of the *locators*, alternatives for placing the devices are suggested. However, within the scope and time limits of this project it is not possible to perform tests with different *locator* constellations. The main research of this project will evolve around finding the best way to localize an asset at a (sub)location of the floor plan. The methodology for defining the location models and the analyses of the different localization methods can be found in section 4.2.1 and 4.2.2.

4.1.2. Data processing

Table 3: Comparison of test setup 1, 2 and 3

	Test 1	Test 2	Test 3
Z value [m]	0	0,8	0,8
Transmit rate [Hz]	2	5	5
Latency [s]	0,1	0,1	0,1
Logging	CSV	CSV	JSON
Time span [s]	± 60	10/30/60	1/5/10
Tracking area	Spark	no	Spark/no

The first test of measuring the tag positions in the test environment was carried out on 28th of July 2015. The second test on 17th of August 2015. And a third test was done on 4th of September 2015. During all three tests the tags were placed on a 1 x 1 meter grid for each x value (x=1, 2, 3…) in the local coordinate system. The characteristics of both test setups are shown below. The test grid structure is shown in Figure 35. For tests 1 and 2 all points in the image are used. For the third test only the points in marked green are measured. The red triangles indicate the positions of the *locators*. The processed data of the 10s set of the second test is added in Appendix A2.

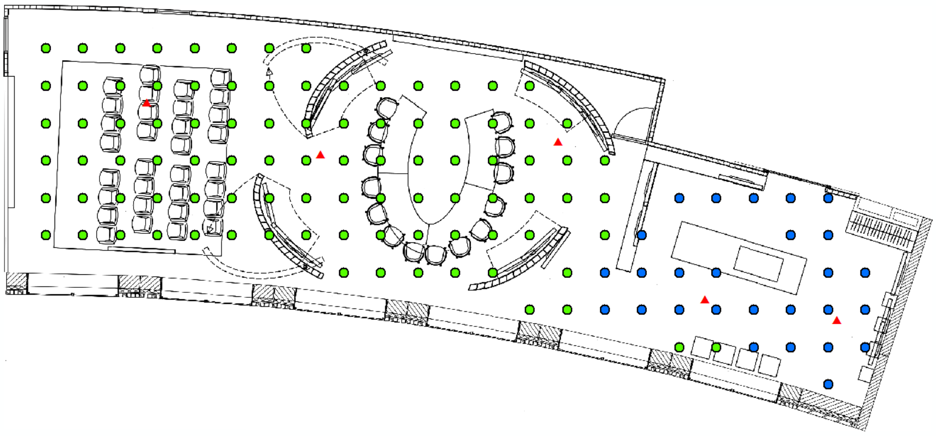


Figure 35: Grid points of test 1 and 2 (all) and the grid points of test 3 (blue)

In this section the general steps for processing of the output data are described. Calculation of the mean, median and SD of the measurements in order to use the data in the analyses are part of this. The data structure of the retrieved positions is a CSV or JSON file for all measurements per x coordinate in the local coordinate system of the Spark Center. This results in 23 separate data files that were merged together to perform analyses on the data. The steps to process the raw data are described below and performed using MS Excel and PostgreSQL.

Add unique measurement ID

The first step is to assign a unique id to every group of measurements of a certain grid point. The only identifier that is included in the Quuppa output data is the tag_id. However, for the tests single tags are used to measure multiple grid points and can therefore not be distinguished anymore. For every row of measured grid points the x value is added as a column to the output file. Next, all files are merged together in one csv containing all measurements. Reviewing the dataset from the previous step shows a large number of duplicates in the list of measurements.

In this case a duplicate is a logged position with corresponding coordinate estimates, quality, covariance estimate and time stamp. The time stamp is recorded in milliseconds (epoch time) from which can be assumed that the exact same position estimate cannot be measured twice in such a short time span. Therefore, it is most likely that this is a bug in the logging method used. In the data of the second test 7904 of 29480 entries were removed from the dataset. In test_3 230 of 1769 entries were removed. The duplicate position estimates can be caused by either an error in the updating method or in the logging method. The latency of 0,1s makes it impossible for the system to measure the position of a tag twice within 1ms.

A second data file containing the x and y coordinates for every measured grid point was built with the corresponding tag_id. The data of these files was put into a database management system (DBMS) to join the tables on the x value and the tag_id. The resulting table contains the Quuppa output data including the x and y coordinate of the grid points and a unique identifier for every grid point. The data in this file can now be used to calculate the Mean, Median and SD of the position estimates.

Calculate mean of the positions

To find a representative value for every group of measurements, an average value is computed. In addition to the mean, also the median value is calculated to check whether the average may be influenced by outliers. The new dataset of the average values for each grid point measurement is the dataset is shown in Figure 36. The red triangles indicate the position of the *locators*. When the dataset of Figure 35 is merged with the one in Figure 36, the average values that are measured by the positioning system can be assigned to the 'ground truth' data, i.e. the grid points.

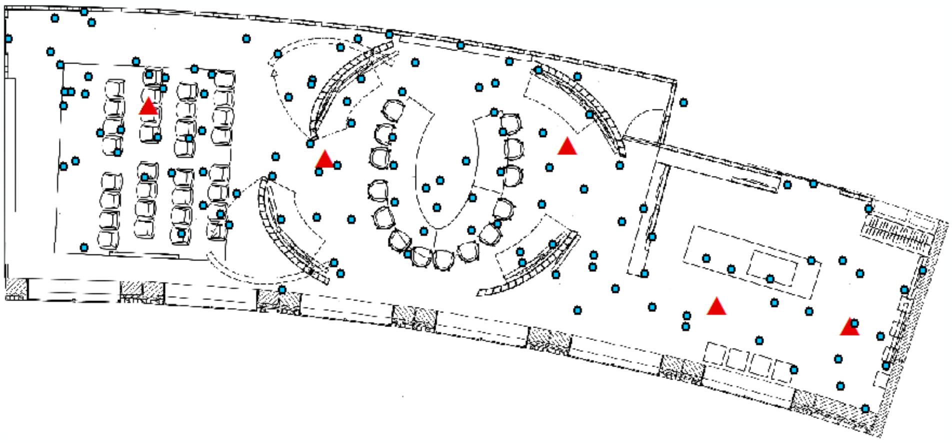


Figure 36: Mean of the measurements per grid point of test 1

In Figure 37 the deviation of the measured points, in relation to the x and y axis of the grid it was based on, is shown. Grid points are indicated by a black triangle; measurement averages are indicated by a red dot. For a number of measurements, the average value is significantly different than the expected value based on the x and y of the grid point. This is visible by the large horizontal lines. This figure was created using the XY to line-tool in ArcMap based on a dataset of both grid x, y and measurement average x, y for every measurement id.

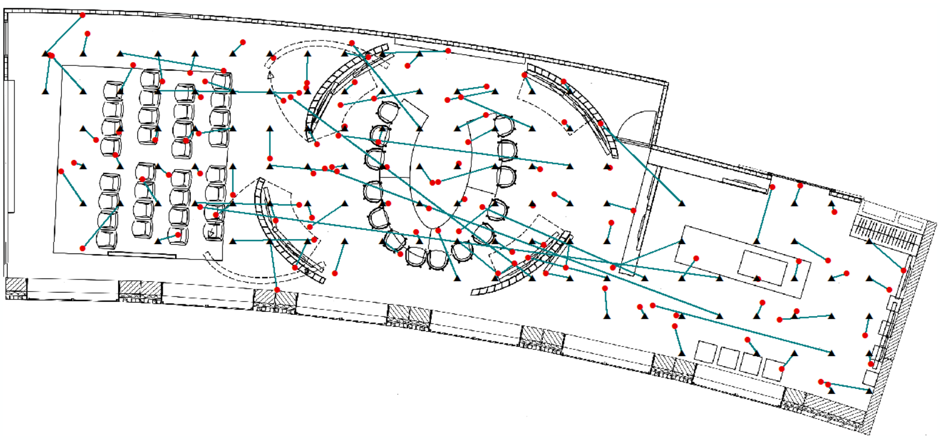


Figure 37: Deviation in measured positions along the x axis of the grid in test 1

Position estimates that differ from the corresponding grid point by a significant amount (alarm limit) can lead to errors in the localization of the asset. The number of wrong position estimates can be a measure for the integrity parameter. To mitigate these errors and be able to correct the position estimate, the integrity parameter can be used for alerting the user through an alarm. Table 4 shows that this partly depends on errors in the positioning system and partly because of error in the data processing. In one case it is due to an insufficient amount of measurements. A processing error means that multiple x, y results were wrongly assigned to the same measurement id, during merging of the measurement data. An environmental error is due to a wrongly calculated position by the positioning system due to influences from the environment as the data shows the same (wrong) location throughout the whole dataset. Statistical analysis of the error values of the retrieved data is done in the next step. Grid points that contain no data at all within the specified time spans (10s/30s/60s) are not taken into account for the analysis part.

Table 4: Errors in data matching between grid point and measurement average for test 1

ID	X_grid	Y_grid	X_avg	Y_avg	Error type
23	4	5	7,8	5	Processing error
64	11	4	9	4,5	Environmental error
79	14	0	10	6,4	Too few measurements
97	17	0	12,7	0	Processing error
104	19	-1	4,9	5,5	Environmental error
105	19	0	4,8	3,7	Environmental error
119	22	-2	17,3	-0,76	Processing error

The same steps were taken to process the data of the second test. In general the measurements show the same results for all three time spans. In Figure 38 the difference between the position of the grid point and the average of the measurements for each point are visualized for the 10s dataset of test 2. In Figure 39, only a single measurement was done for point 1,1 which was positioned about 12m across the floor plan. This is probably due to a number of factors, e.g. reflections, dilution of precision and low-resolution coverage of the *locator.* The 60s dataset in Figure 40 is similar to the 10s dataset. For this reason the 10s dataset is used for further processing and analyses. To find the sources of the errors in the data of the second test, the structure of the 10s dataset was analysed. In contrast to the first test only two error types were identified. All error measurements were taken along the border of the *tracking area*. In the case of an environmental error the deviation is probably caused by reflection or DoP. For the other measurement errors there were significantly less entries in the output data. This might be due to low coverage of the grid point by the system.

Table 5: Errors in data matching between grid point and measurement average for test 2_10

ID	X_grid	Y_grid	X_avg	Y_avg	Error type
4	1	4	-0,8	4,8	Too few measurements
8	2	2	2,3	-6,5	Environmental error
13,25	3,5	1	-	-	Environmental error
37	7	1	4,8	-2,1	Too few measurements
43	8	1	8,7	-5,8	Too few measurements
74	13	1	10,8	-3,5	Environmental error
93	16	2	16	2,9	Too few measurements
100, 104, 107, 111	18-21	2	-	-	Environmental error

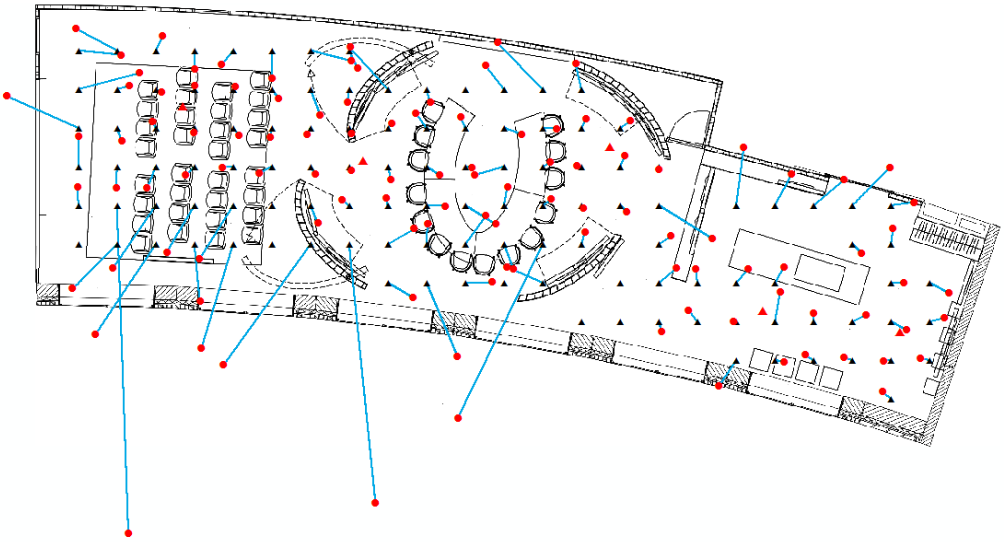


Figure 38: Difference between grid point and averaged measurement per point ID in 10s data of test 2

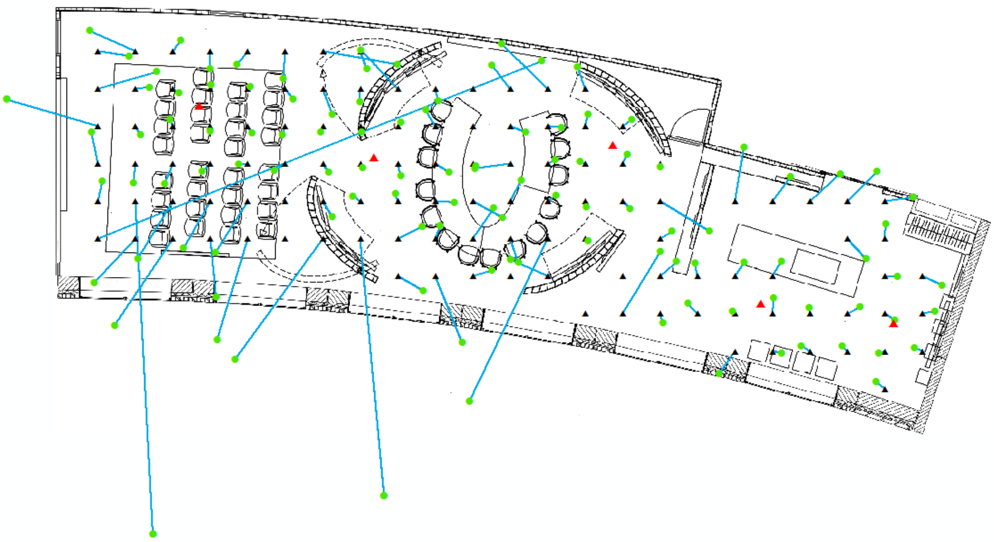


Figure 39: Difference between grid point and averaged measurement per point ID in 30s data of test 2

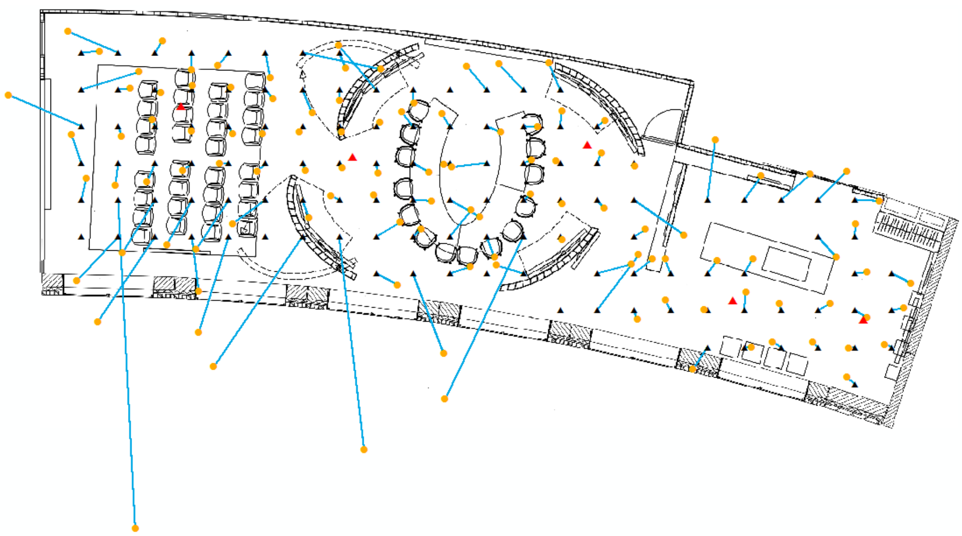


Figure 40: Difference between grid point and averaged measurement per point ID in 60s data of test 2

Calculate median of the positions

Because the dispersion of the points in the dataset differs throughout the map and per test, it is hard to determine the cause of these measurement uncertainties. As the dataset contains a lot of measurements for every grid point, also the median is calculated to make a comparison to the results of the calculation of the average. Calculating the mean value takes every measurement into account with equal weight. The influence of outliers, when calculating the median of the measurements, is mitigated by having a large number of more or less the same results. It is assumed that the latter is the case with these test results as the outliers are probably a result of incidental influences of the environment on the radio signals used for positioning. Calculation of the median is done using an IF-statement together with the MEDIAN formula built into MS Excel. The first term in the IF-statement checks whether the id (unique for all data collected at a grid point) of the measurement is the same and then calculates the median for this group of measurements based on the x and y values.

1. Group by measurement id
2. “=MEDIAN(IF(A:A=A6;I:I;""))”

Comparison of mean and median

In order to find out what the best calculation method is for determining the average of the measurements, the sum of the mean and median values with respect to their corresponding grid point is calculated. In Table 6 these values are shown for both methods. The comparison shows no significant differences between the two methods. In fact, the distances for the median method are slightly higher. The difference in the x values for the mean and median method in the 10s dataset is caused by a single wrongly calculated grid point (off by 10,81m). The results show no improvement when the grid point is measured for a longer period of time. Although the outliers should have less influence on the mean when more (accurate) data points are taken into account.

Table 6: Sum of x and y values of averaged measurements and grid point in meters

	10s	30s	60s
Mean			
X values	45,47	48,27	48,86
Y values	69,94	71,13	69,47
Median			
X values	56,05	48,66	50,25
Y values	70,45	71,78	72,98

The summed values also show a correlation between x and y values. In all three time spans the deviation in the x direction is around 50m, where the deviation in the y direction is around 70m. This could indicate a system error in the positioning system that adds a bias for x and y to all measurements. The same can be concluded from the differences based on the individual values. An explanation could be that that the error in the measurements is not caused by one or a few outliers in the data. It is more likely that a wrong position was logged for a longer time during testing. The 30s dataset shows the least difference between median and mean. The mean values are used in further analyses of the measurement data.

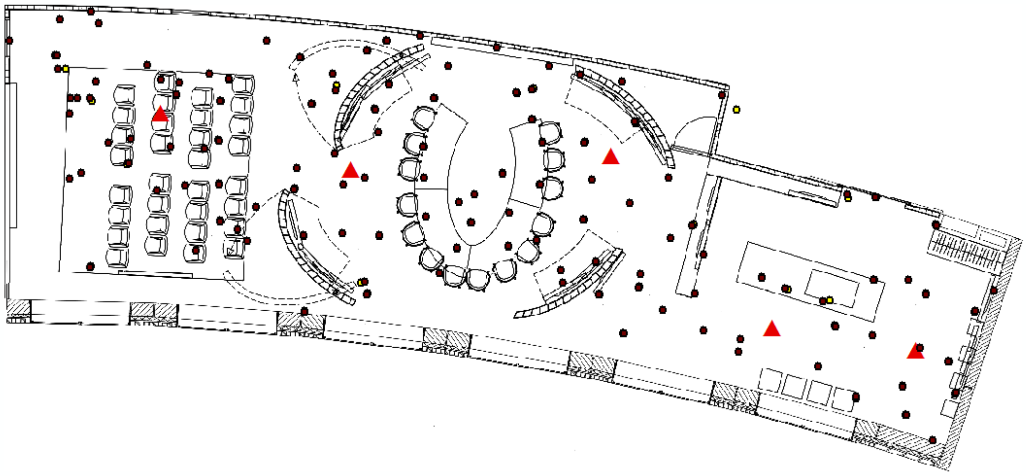


Figure 41: Comparison of mean and median values of measurements

The positions containing both median and mean values for the 10s dataset is shown in Figure 41. For nearly all measured grid points the values are about the same. The mean and median values for the points that are marked with a red circle differ significantly.

Calculate Standard Deviation of the positions

The SD gives an indication of the dispersion of the measurements collected for each grid point. The SD of the x and y values (SD_x/SD_y) is calculated separately in order to determine the error vector SD_{xy}. Both calculation steps are described below:

Step1: Calculate SDx and SDy: Using STDEV.S() formula in MS Excel which is based on the formula for calculation of the SD in 2.3.4. This formula takes the measurements to calculate the standard deviation of the sample:

Step2: Determine SDxy: SDxy can be calculated by squaring the SDx and SDy value and take the square root of the sum of these values carried out using MS Excel:

=SQRT((SDx^2)+(SDy^2))

Where:

SDx = the SD of the x values
SDy = the SD of the y values

Now, the SDxy can be used as an indication of the dispersion of the measurements around the mean value. As stated before, the SD is a measure for the distribution of the points around their mean value. In addition to this, the distance between the real value (grid point) and the estimate x, y position is relevant. To show the relation between the measured point and the real value, two other variables are needed, i.e. accuracy and precision. As shown in Figure 18, there are four scenarios' that can occur when taking into account all variables mentioned before. These cases show that there is no correlation between the value of the SD and the distance from the measurement to the real value. Therefore, a badly estimated position does not necessarily have a high SD, and vice versa. In the case that localization of the tag is likely to go wrong, the situation is as described in the lower half of Figure 18. In Figure 42 the SD of each group of measurements in relation to the distance of the average of the measurements is shown. This gives an indication for the input of map matching matrix. All measurements with a low accuracy can be discarded from the dataset because those positions will inevitably return an unreliable location.

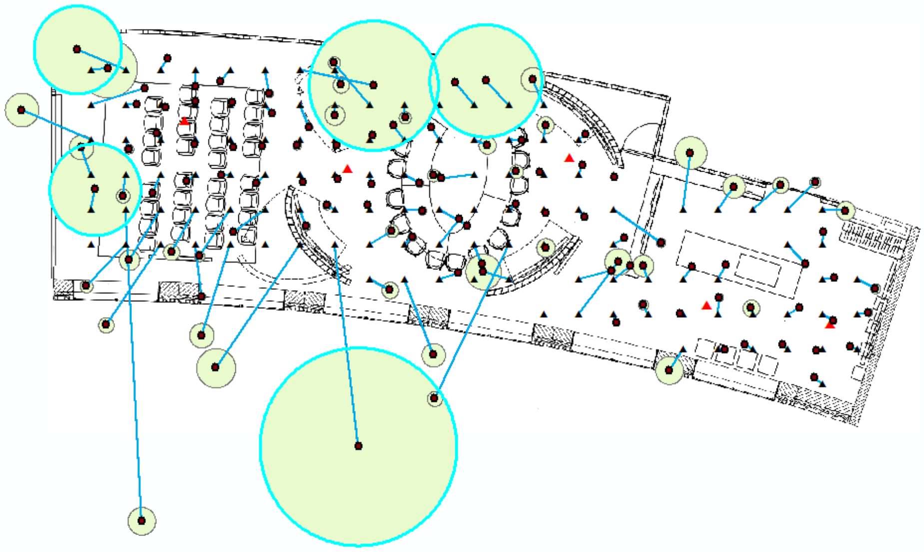


Figure 42: Relation between SD and accuracy of the measurements of test

Usability of the positionAccuracy parameter

The Quuppa parameter *positionAccuracy* (PA) is included in the output of every position estimate (more information on the PA in section 2.1.7). In Figure 43 the values for this parameter are compared with the SD of the measurements. As the PA is an approximation of the covariance matrix, the assumption is that there is a correlation between the PA and the SD of the measurements. However, the PA and the SD show no correlation, even for highly accurate measurement results. In general, the SD and PA are higher when the distance between the average measurement and the grid point gets larger. However, there are some exceptions. Where the SD in the right image is quite good for some positions that have a relatively low accuracy, the PA is also high in accordance to the distance between the grid point and the average. Based on this comparison the PA seems to be a better indication of the reliability of the measurement than the SD.

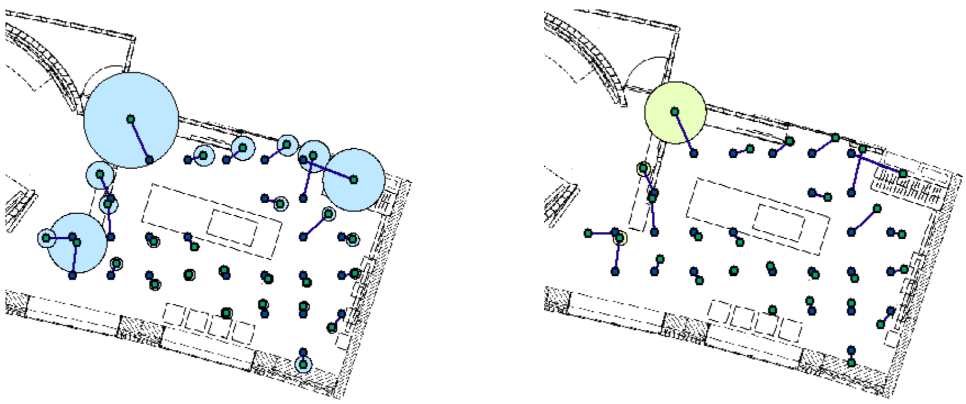


Figure 43: Quuppa parameter "*positionAccuracy*" versus SD values and based on position estimate

When the PA is compared to the accuracy values, which are determined based on the distance between the real value and the measurement average, there are some similarities. The part of the measurements taken outside the high-resolution range of the *locators* return the worst values for both PA and the calculated accuracy. In general, low PA values correspond to high accuracy values and vice versa. However, no relation between individual values for PA and accuracy per point ID can be found. Based on the ranges of the *locator* coverage a division can be made between points having high accuracy and low PA in the inner range and points having low accuracy and high PA in the outer range. This is also shown in Figure 51. The switch points for The PA and accuracy values based on the range are 0,225 and 0,45 respectively. In Table 7 the data points and the switch values are shown for the PA and the accuracy. The average of the *Italic* values is used for setting the switch value for PA and accuracy the ratio of this 'switch-value' is 2 which can be used as an indication for the map matching method in section 4.2.2.

Table 7: Data points for determining the switch value for the *locator* ranges.

	id	**x_grid**	**y_grid**	**PA**	**SD_xy**	**accuracy**
PA	125	21	1	*0,20903*	0,068944	0,423
	128	22	-3	*0,24614*	0,021688	0,289
accuracy	135	23	-2	0,145556	0,031361	*0,423*
	114	19	2	0,299057	0,072041	*0,437*

Summary of data processing

The parameters that were selected for the technical performance are accuracy, precision, coverage, latency and update rate. The first two are used for determining the reliability of the measurements. The latter three parameters are used for analysis of the test data for the positioning performance. A comparison of the mean and median of the position data do not show major differences. For this reason, the mean values are selected for further analysis. The number of returned position measurements per tag differs within the same time span of a test cycle. This is caused by a combination of hardware issues, fluctuations in quality of the radio signal (environmental influences) and the chosen configuration specifications of the system. The second group of concluding remarks can be used as input for the analysis section. The data generally shows two types of position estimates. For the positioning analysis a distinction between 'reliable' and 'unreliable' results is made.

4.1.3. Analysis for positioning

This section covers the analyses for the positioning part of the test. In the topics described below the characteristics of the position measurements returned by the Quuppa system are taken into account.

Coverage

Positioning

The coverage of the floor plan is mainly depending on the placement of the *locators*. Since the dimensions of the virtual cone receiving the radio signals is known, the theoretical coverage can be visualized beforehand. During the second and third test, the 2D tracking plane was set to 0,8m which inevitably results in a smaller coverage area compared to when the tags are positioned on floor level. As mentioned before, the coverage is influenced by many factors such as, obstructions on the ceiling, height of the *locators*, height of the 2D tracking plane and architectural elements. In Figure 44 these factors divide the grid points in well- and badly covered points. This information is used to define areas on the map where reliable localization is expected to be more difficult. Green grid points lie within the high-resolution area and are supposed to return a reliable location. The red points are outside this coverage area and are more likely to show large deviations and localization errors.

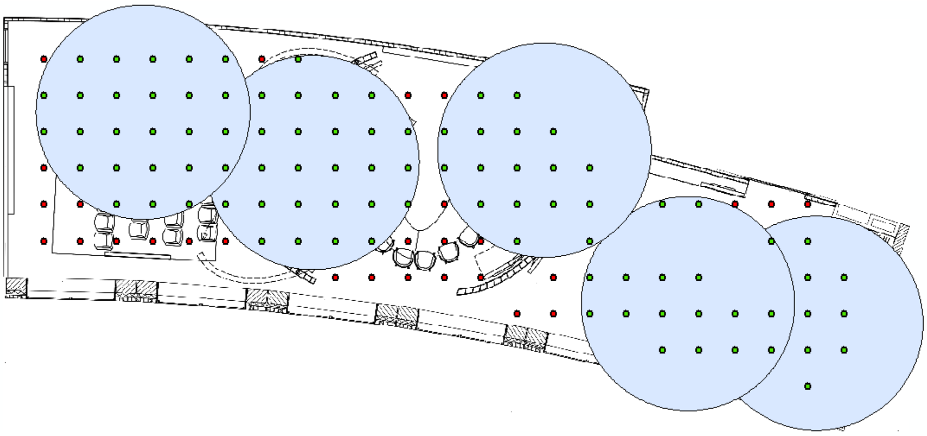


Figure 44: Theoretical coverage of the high-resolution positioning area

Comparing this information to the estimation of the coverage provided by Quuppa (shown in Figure 26) shows two similarities and one difference. The area left of the theatre is badly covered because it is not within reach of *locator* 5. This is also the case between *locator* 3 and 4, which is also visible in the coverage render of Quuppa's. In contrast to the latter estimation, the area on the lower side, close to the outside windows, has low coverage as well. The results of the second test show indeed some large deviations in this area. Low coverage together with reflections of the windows and DoP are the major reasons for errors in this part of the Spark Center. As mentioned before, the coverage is also influenced by obstructions within a 1m radius from the *locator*. For the Spark setup, some *locators* had to be placed close to an obstacle in order to have the right position in the x, y plane with respect to the floor plan and the other *locators*. In Figure 49 the obstacles that block the signal to a particular *locator* are shown. A large part of the range of the second *locator* is blocked by a ventilation box on the ceiling. This influences the quality of the position estimates in the area behind the curved walls, apart from the fact that this area is also in the low resolution range of *locator* 2.

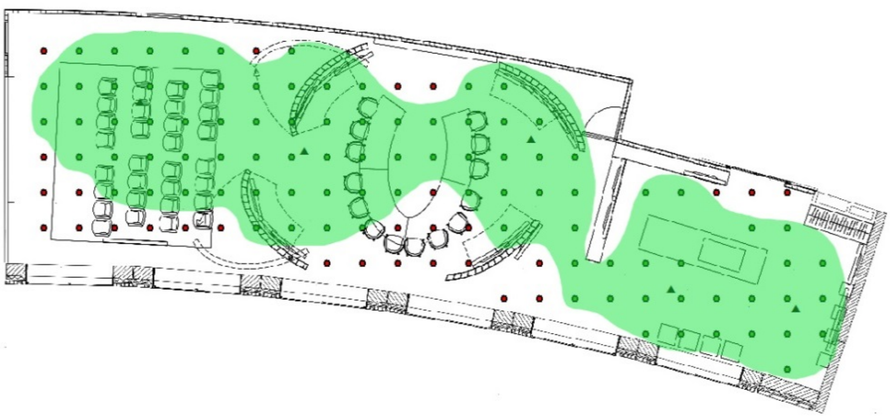


Figure 45: Tags in the green area are expected to return the positions with a high reliability

Detection

Outside the positioning range of the *locators* there is still the possibility for tags to be detected. This was investigated by measuring the x and y coordinates for a two paths outside the *tracking area* in the third test. The dataset of the area outside the Spark Center consists of points positioned in front of the entrances when the doors were opened. No output was returned in the hallways or on the parking lot, which implies that the radio signal of the system does not penetrate through the wall and windows of the Spark Center. Theoretically the system should return data from these locations, as the detection range limit is between 30-50m in open space (F. Belloni, personal communication, September 4, 2015). This range would easily cover the whole left wing of the ground floor, where the Spark Center is located.

In Figure 46 both datasets are visualized. In the left image the points situated just outside the side entrance are influenced by DoP and positioned further away than the actual location. The points inside the *tracking area* follow the exact path of the tag, except for the area between *locator* 2 and 3 where low coverage and reflections influence the accuracy of the position estimates. In the right image, the influence of the building structure is clearly visible as only measurements in front of the (opened) door are returned. The possibilities for detection of a tack outside an enclosed *tracking area* seem to be limited. The influence of specific building materials on the different coverage levels of the system is discussed in 0.

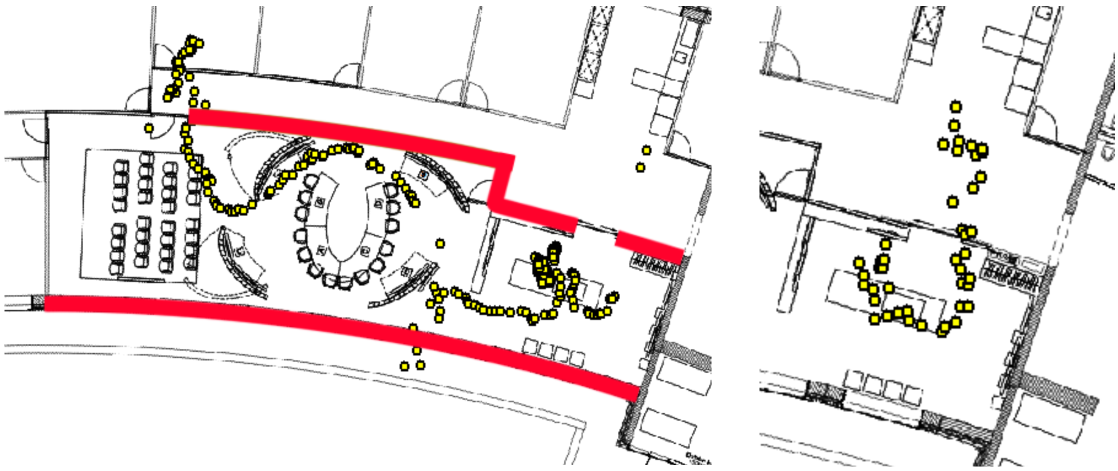


Figure 46: Output data from inside path (l) and outside path (r)

Constellation of the *locators*

Another parameter for the performance of the positioning system is the placement of the *locator* with respect to the area of interest and to the other *locators* around it. The coverage of the floor plan is based on the quality and reliability of the output which is largely influenced by the architectural environment. The constellation parameter is more important for choosing the positions of the *locators* when installing the system. The two key aspects of this parameter are knowledge about the positioning method and information about the use case. Using this particular positioning method (AoA), the area close to the *locator* returns the best performance. Based on the characteristics of the assets, the *locator* should always be placed over the area of interest. Depending on the coverage, influenced by the environment and height of the *locator*, additional *locators* should be installed for full coverage of the floor plan.

A heat map, similar to the one shown in Figure 5, can be constructed based on the constellation of the *locators* together with the known range levels. To each range level a number is assigned and overlapping ranges are added. This information is joined with a dataset of the grid points, which results in a heat map shown in Figure 47. For visualisation, an ArcMap interpolation tool based on Inverse Distance Weighting (IDW) is used to create heat map. This method assigns a high importance to points that are close and a lower importance to points that are further away [14]. In the case of producing a coverage map of the Spark Center, the quality of the range values is supposed to be similar for points within a certain distance from the interpolated point.

The high-resolution range is assigned the number 3, the low-resolution range 2 and the detection zone 1. When this heat map is compared to the coverage render map in Figure 26, this method seems to provide a better result based on the known output of the accuracy and precision parameters. More detailed information about the area of interest and place of large obstacles can be added to construct this heat map. For example, historical accuracy data from the system can be used to get insight in the coverage of the floor plan to detect changes in the values over time. This is a functionality that is not implemented in the QSP coverage render tool.

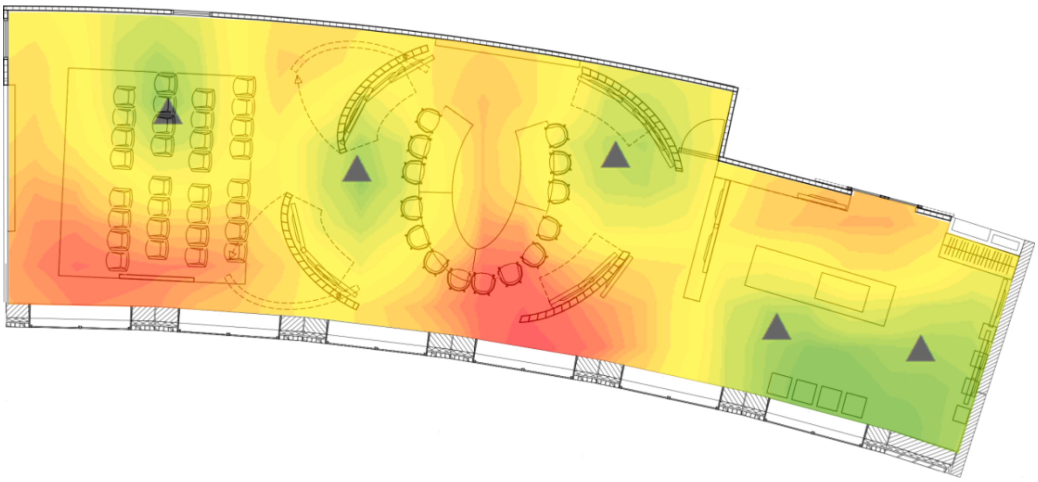


Figure 47: Heat map of the expected output quality of the position estimates based on the range levels of the radio signal

Influence of architecture and building materials

The analysis of the influence of the architectural environment consists of two parts. In the first part the coverage of the signal outside the Spark Center is determined. The purpose of this analysis is to find out to what extent the detection area covers parts of the floor plan that are outside the *tracking area*. The technical parameters of this data were compared to the measurements taken inside the Spark Center taking into account the material and thickness of the walls. Because there are no grid points defined for this test, the only reliability parameter available is the *positionAccuracy*.

The majority of the values of this parameter are higher outside the Spark Center compared to all of the measurements taken inside. A clear transition in the accuracy values is visible around the entrance area, which implies that the glass door and wall block the radio signals to a large extent. The *positionAccuracy* parameter returns unreliable results when the position is calculated outside the positioning range of the system. From this observation can be concluded that line-of-sight between the *locator* and the tag is important for the system to return reliable results.

Table 8: Transparency factor for different building materials

Material type	Transparency factor
Plaster wall	
Wooden frame	**4**
Metal frame	**3**
Closet	2
Glass wall	
No coating	**5**
Reflecting coating	2
Wooden wall	**3**
Brick wall	1
Stone wall	1
Concrete	1
Human being	**3**

The second part shows the influence of obstacles and their material on the measurements. In Figure 48, the positions having a relatively high SD are highlighted in blue. The curved walls are indicated by a red line. These measurements were taken from tags positions near the curved walls in the business zone. These walls consist of a metal frame with metal netting and TV screens mounted on the side facing towards the U-shaped table. The reflections of metals, and also of desktop monitors and TV screens, seem to have a large influence on the accuracy and precision of the measurements. Based on the location of these tags with respect to the *locators* 3 and 4, the points should return reasonably good results. However, the SD of these points is higher than average and some points also have low accuracy.

Close to *locator* 2 and 4 the area within a 1m radius from the *locator* is not obstacle free. In both cases a part of the ventilation installation is blocking the radio signals in a certain direction. For *locator* two, the area behind the lower left curved wall is obstructed. In the other case the lower part of the U-shapes table is obstructed from *locator* 4. Also reflections from the metal surface of these obstacles can have an influence on the coverage of the radio signal in those places. In Table 8 an

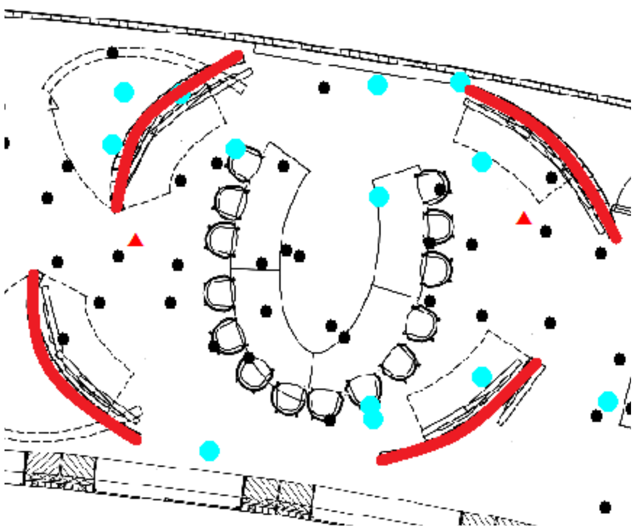


Figure 48: Influence on curved walls on accuracy and precision of the position estimates

overview of the transparency factor for different materials used in constructive building parts is shown. These values are based on information that Quuppa provides for users of the system. The values can be used as an indication of the coverage of the system when there is an obstruction in the line-of-sight between *locator* and tag.

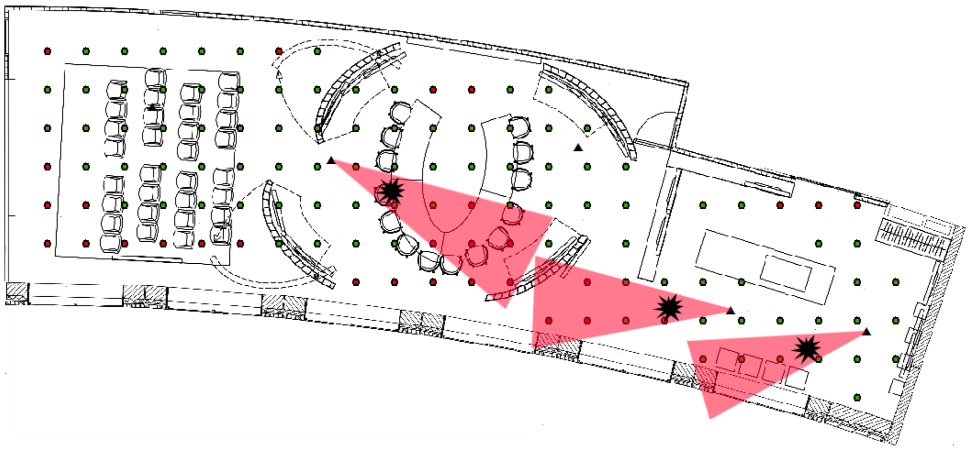


Figure 49: Objects on the ceiling causing obstructions of the radio signal

Real time positioning

The transmit rate highly depends on the latency parameter of the position update. There is no use in having a much higher transmit rate than the time it takes to output an updated position estimate. In the case of RT tracking the transmit rate is highly dependent on the latency. For positioning static assets, the update rate can be much lower than the latency of the system. This can be configured for different states in the Tag configuration tool. However, when positioning assets that move, e.g. if they are picked up by a human being, the transmit rate should be at least 1 measurement per time unit of the latency. For localization of static objects and objects moving at low speed the latency used in the tests is sufficient. In the case of localizing IV pumps in a hospital, a lower latency value is not indicated. For RT positioning of dynamic objects, for example latency and transmit rate are determinative for the minimum time span of measuring the position of an object for reliable positioning.

This part of the data analyses steps shows the possibility of returning the location of the tag in real time. The positioning system should be able to assign the measured tag position to the right location within a reasonable time frame to make it a RT system. The criteria for RT are 1. a correct location in 90% percent of the cases, 2. Based on measurements of the same tag at a certain position over x (10/30/60) seconds time. The update rate, which was defined as a technical parameter in 0, can be used to indicate the possibility for RT positioning. The transmit rate of the data packets containing the x, y position was set to 5 Hz in the 'default state'. The expected number of returned positions can be calculated by multiplying the transmit rate (5 Hz) and the time span of the dataset.

Table 9 shows that the number of tag positions that return the expected amount of data packets is quite low for all three time spans. In the 60s dataset only 31% of the grid points return the position as many times as would be expected from the transmit rate setup. For the other two time spans the percentage of expected returned positions is around 50%. These results indicate that in a large number of cases the position has to be based on fewer measurements than is indicated for RT.

Table 9: Overview of number of returned packets per time span based on the transmit rate

Time span [s]	**10**	**30**	**60**
Expected measurements	50	150	300
Returned measurements			
min	3	1	1
max	97	273	344
mean	57	61	123

Table 10 shows a difference in the results of the mean and the median of the accuracy and SD values. The reason for this is that the majority of the measured points return a reasonably good result for both accuracy and SD. The few points that have a bad accuracy and/or bad SD influence the mean values in a negative manner. In general, the difference in the time span of the test has no major influence on the data. This shows that the reliability of the measurements is not time dependent.

Table 10: Reliability of the datasets based on accuracy and standard deviation

Time span [s]	**10**	**30**	**60**
Accuracy [m]			
min	0,07	0,08	0,08
max	8,48	12,76	8,94
mean	0,82	0,95	0,83
median	0,46	0,44	0,44
Standard Deviation			
min	0,01	0,01	0,02
max	0,91	0,74	1,57
mean	0,09	0,09	0,12
median	0,05	0,05	0,06

Reliability of the location

In order to assign a Confidence Interval (CI) to the measured positions, a threshold needs to be set for the Level of Accuracy (LoA). A confidence interval gives an estimated range of values which is likely to include an unknown population parameter, the estimated range being calculated from a given set of sample data [13]. When a new position is calculated based, the CI can be given based on previous measurements. Different LoA's should be defined for each (sub)location scale. For determining the threshold value, all measurements of the second test in the Spark Center are taken into account. In order to achieve a distinctive output for every grid point, the threshold is set to 0,5m which is half the size of the test grid. In Figure 50 the grid points highlighted in blue are positioned less than 0,5m away from the real value. This result looks similar to the theoretical coverage of the *locators* shown in Figure 45. Generally, the areas within 2-3 m radius around the *locator* return good results. The areas closer to the walls of the Spark Center return less accurate results. In particular, the area around the curved walls show low accuracy results. The visualization of the *positionAccuracy* parameter in Figure 43 also shows lower values for the areas that are within this 2-3m radius from the center of the *locator*. Below a more detailed comparison between the *positionAccuracy* value and the accuracy based on the position data given.

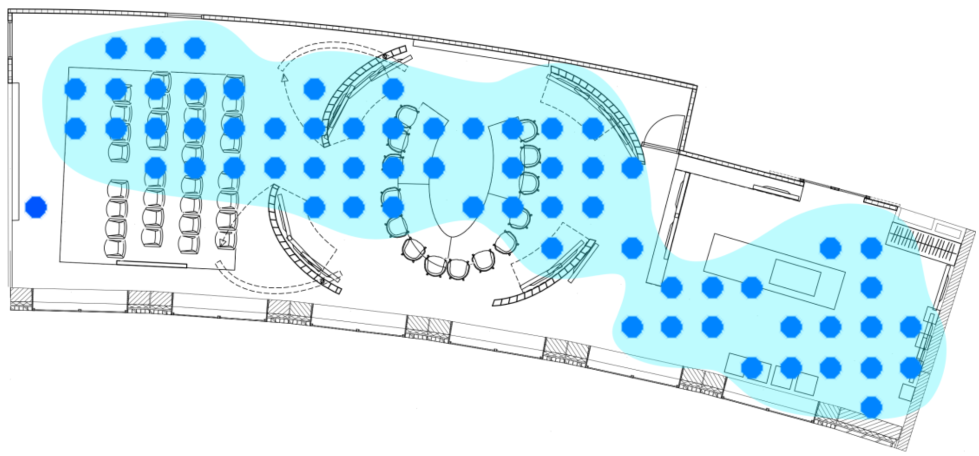


Figure 50: Grid points, in blue, which returned a position estimate with an accuracy value below 0,5m

These two accuracy parameters show similar results for the location of good- and bad position estimates. The dataset of test 3 contains 17 out of 27 measurement positions that have a calculated accuracy value below 0,5m. When the same points are checked for the value of the *positionAccuracy* a threshold of 0,25m is found for the same points (17 out of 27 in total). One point is qualified better by the PA parameter compared to the accuracy value and another point vice versa. As this analysis is based on just 27 measurements and corresponding accuracy values, the threshold of both parameters can differ slightly for larger datasets. The number of measurements taken for each grid point does not differ significantly from the points that have good accuracy values. Seven out of ten points having bad accuracy values are based on 50+ entries. The assumption that the reliability of the measurements does not improve over time, when the calculations are based on more entries, is supported by the outcome of this analysis. Instead of calculating the accuracy and precision of the measurements based on data packets of multiple entries per position, the *positionAccuracy* parameter can be used for on-the-fly computation of the reliability of a single measurement for RT positioning.

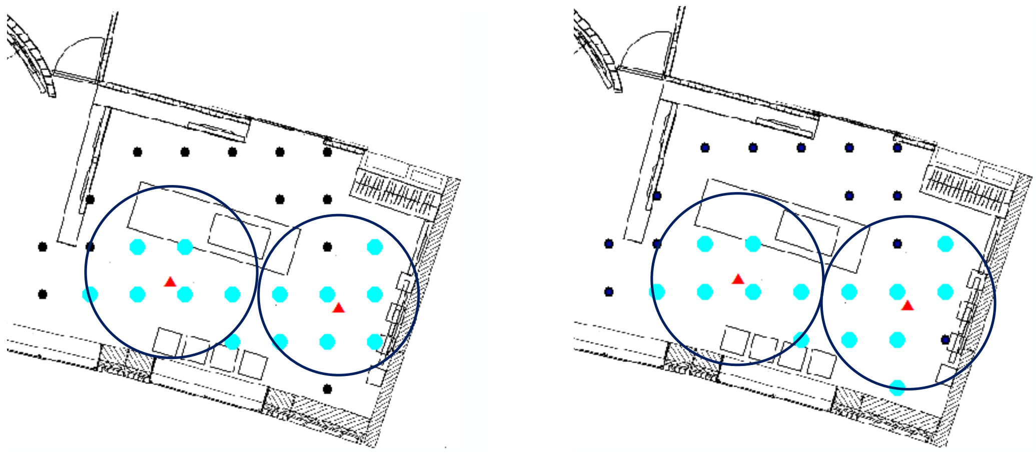


Figure 51: Good *positionAccuracy* values (l) versus good accuracy values (r) for the data of test 3

Based on comparison of the PA and the calculated accuracy no relation between the values of these parameters can be found. When the PA and accuracy values for each position is sorted from low to high, only 44% of the points were less than 2 positions apart in the list. In Figure 51 a comparison is given for the PA and accuracy values for half the dataset. Although these two parameters do not show any relation between the calculated values, the set of points that is considered 'good' is the same (exception is 22,-3/23,-2). The values for both parameters show good values for points close to the *locator* and bad values for points further away. This can also be assumed from the knowledge about the coverage and range.

Summary of data analysis

From the analyses results three main conclusions can be drawn. Firstly, the effect of environmental influences on the performance of the positioning system is significant. When the *tracking area* is defined by structural elements, e.g. interior wall, the coverage of the radio signal outside the *tracking area* is limited. Secondly, the dimension of the range for positioning and detection determines the reliability of the measurements to a large extent. The areas in between two *locators* return positions with lower reliability compared to the areas closer to the *locator*. This has a negative influence on the localization of tags near the boundaries as they are likely to be localized in an adjacent zone when there is no separating element between them. Thirdly, the number of returned positions over time for each measured grid point does not seem to have a significant influence on the reliability of the position. This makes the system suitable for real time positioning. The accuracy parameter seems determinative for the correctness of the position. The *positionAccuracy* parameter is a good estimate for on-the-fly assessment of the quality of a measurement as the values for this parameter show the same structure and results for sub-parts of the dataset.

4.2. Localization

4.2.1. Definition of the location types

To optimize location accuracy of indoor positioning systems, the movement of people and objects and the indoor environment can be taken into account [1]. Previous studies on indoor positioning and indoor way finding have shown that adding semantic information to spatial models can be helpful for tracking and navigation applications [15,38]. Models for localization applications differ because they use other characteristics of the floor plan. Where many models focus on moving people for developing a spatial model, this research looks at the possibility of localizing static objects and the influence of the architectural environment and system setup on the performance of the positioning system. The relevance for localization rather than positioning is described by [39]. "If the context of an environment can be (…) we can describe the environment in natural language". This allows space to be described to users in ways that are familiar to them. According to [38], space partitioning can be done in two ways. The first approach is to use the real boundaries of the subspace (e.g. walls, doors), the other approach is by arbitrarily choosing the boundaries at a more abstract level, e.g. by letting an algorithm decide. The first method lacks capability at a small scale level, however other interior elements as room dividers or large pieces of furniture can be considered for space partitioning. The other method makes a subdivision of the floor area into geometric shapes, which can be either heterogeneous or homogeneous (e.g. square grids, triangles, trapezoids, Voronoi diagrams) [17]. A distinction between fixed structures and moveable entities (e.g. furniture, equipment) is made by [37] to make sure the model is sustainable over time.

The definition of the location types is derived from a subdivision of the floor plan, based on analyses of the floor plans of both the Spark Center and the hospital ward. The elements for division are the primary building structure, which are structural outer and inner walls, the secondary building structure separating larger room and departments and the interior elements, which include screens, room dividers and large pieces of furniture. Three different methods are defined based on these elements, i.e. grid-, zonal - and functional subdivision. The methods are chosen based on their ability to distinguish the different parts of the floor plan to be understood by human beings. The size of the clusters of the chosen method will be determined based on the level of accuracy of the Quuppa and the use case. Based on the data, a sub meter accuracy level can be achieved for most locations. The clusters for all three methods are defined as follows:

- Cluster A: Possibility to make a location estimate on a floor or department level.
- Cluster B: Possibility to make a location estimate on a single room level.
- Cluster C: Possibility to make a location estimate on a sub-room level.

Grid

This option is defined as a reference grid. The size of the grid depends on the scale level and the lay out of the floor plan. The geometric shape of the grid cells will be rectangular by default. When possible, the grid size and shape can be derived from the architectural grid of the floor plan. This might result in an irregular grid. Another option is to define the tracking grid based on the dimensions of the functions or zones. The third option is to use a grid size that is best fitting to the dimensions of the space or room. In Figure 52 the 1x1m grid subdivision is shown.

Table 11: Clustering for grid based method

Cluster	Description	Cell size
A	Different grid cells can distinguish separate rooms or spaces.	5-10m
B	Positioning at sub room level	1-5m
C	Being able to distinguish objects	0.1-1m

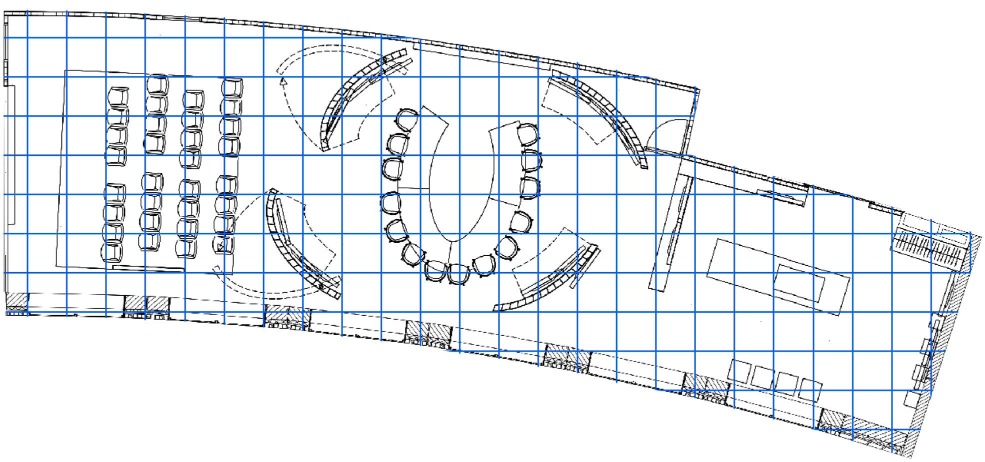


Figure 52: Subdivision based on grid method

Zone

Zonal subdivision is done by separation of the areas based on the lay out of the floor plan. The separating objects define the borders of the zone. These borders can be either hard (e.g. walls, doors) or soft (e.g. furniture, flooring type). Generally, an area described as a zone can be represented by a basic geometric shape, such as a rectangle. For instance the floor plan of the Spark Center can be subdivided into three zones, i.e. Play zone, Business zone and Theatre. The division of the floor plan is shown in Figure 53. The clustering of the zones by size is shown in Table 12.

Table 12: Clustering for zone based method

Cluster	Description	Cell size
A	Large part of the floor area accommodating one main function	>10m
B	A group of functions or naturally separated part of a larger area.	5-10m
C	An area dedicated to a single function	1-5m

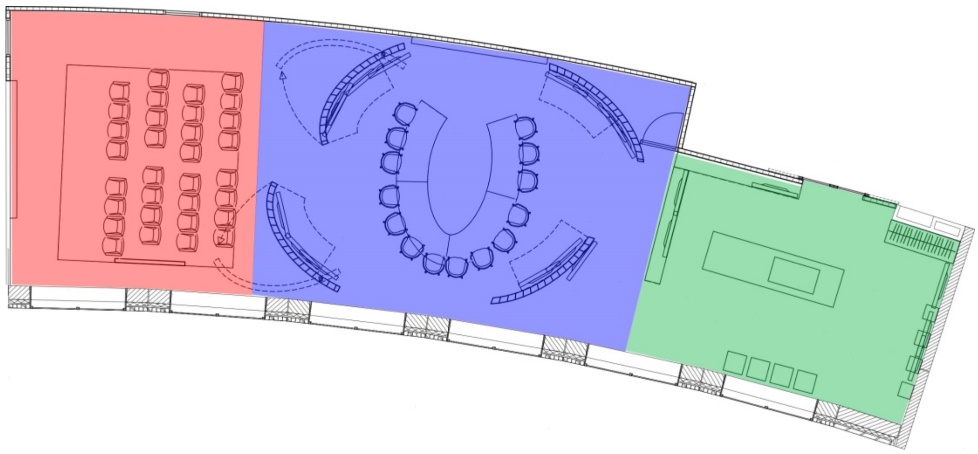


Figure 53: Subdivision based on zoning method

Function

Functional subdivision separates the areas by looking at the function of the room or space. In contrast to the zone type, this type is defined by the taking a specific element in a space that ca be defined as a function. This method can be seen as an opposite approach of the zone type. Functional subdivision can describe more specific elements which enables it to perform localization at a higher level of detail. A single zone can accommodate multiple different functions and a single function can contain more than one activity. Examples of activities are working, walking and sitting. The clustering is based on one function per separated space. The clusters B and C make it possible to localize an object among objects of the same kind, for instance in a storage room. Functional subdivision of the floor plan is shown in Figure 54.

Table 13: Clustering for function based method

Cluster	Description	Cell size
A	A group of activities	1-5m
B	An object or space dedicated to one activity	0.1-1m
C	A part of an object or space	<0.1m

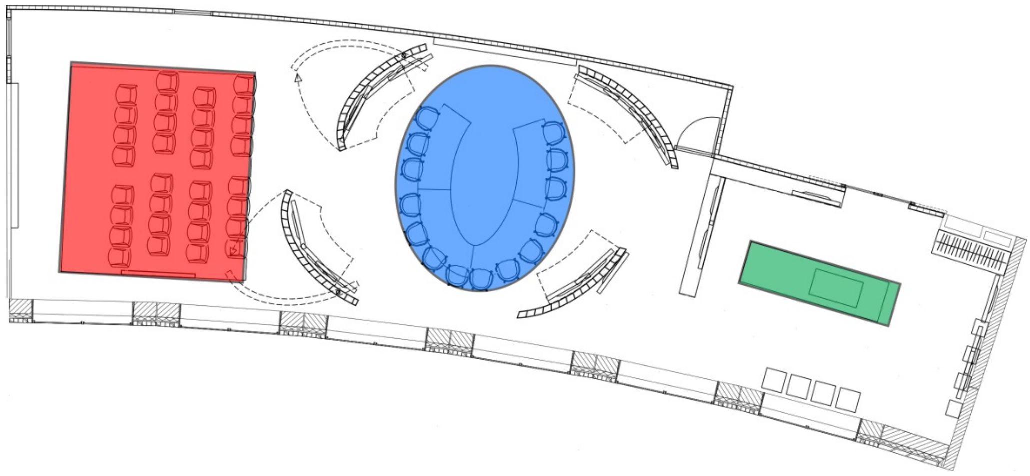


Figure 54: Subdivision based on function method and its main activity

The elements on which the division of the floor plan is based are ‘space’, containing attributes for the boundaries and ‘object’. Space can be defined as an isolated part of the floor plan that is defined unambiguously with respect to other spaces. To optimize the accuracy and availability of the position estimate, propagation of the radio signal through the boundaries of a space is favourable. The attributes for ‘space’ are wall and floor, where floor is only necessary to be set when the tracking mode is set to 3D. The other element for determining the subdivision of the floor plan is ‘object’. It can be defined as an interior element that influences the radio signals in such a way that it affects the resulting positioning estimates in a negative manner. For that reason, it is an important variable for both determining the placement of the *locators* and resulting form that the availability of the radio signal on a specific spot on the floor plan. All elements should have common attributes (i.e. height, width, translucency, thickness) which can be used in generalizing the model for applications in other buildings. The assumption is, based on the pre-processed test results, that localization on room level is possible. Localization on sub-room level should be possible to a certain extent, depending on the outcome of the tests.

4.2.2. Methods for map matching

This section consists of two parts. First, the positioning data is matched to each of the location types. The second step is to determine the reliability of localization for the test cases, which were defined in section 3.5. Based on the outcome of these matching analyses, a method is described to improve the matching process.

Map matching

In this section the reliability of the locations based on the locations types is discussed. For the map matching analysis, the matrix shown in Figure 4 is used. Three different location setups are tested on the basis of the Spark Center floor plan. The processed measurement data of the second and third test is used for this analysis. In order to find the percentage of measurements per scenario, the following method is used. The input dataset for the analysis is the 10s data, which contains the average x and y values and the x and y values of the grid point. The grid points are intersected with the polygon describing the area for localization.

The resulting points are assigned to one of the scenarios based on the accuracy and SD values of the average measurements. The threshold for the ‘good’ and ‘bad’ values is set to 0,5m for the accuracy, based on the maximum radius around each grid point where unambiguous allocation of the grid position is possible. For the precision, the threshold value is set to 0,1m based on the maximum SD values for the well covered areas in the Spark Center. To optimize the localization method, three parameters are added to the intersection. To describe the influence of building structure and furniture a method for functional constraints is added.

Point-in-polygon

The *grid* type is tested in the Theatre zone for determining the row and seat number. A cell in the grid represents a chair area in the seating area. The cell size is set to 0,5m x 0,5m, which half the grid size of the test data. For every cell, the points that are localised inside and the ones that are outside the polygon are assigned to one of the scenarios. The threshold for being localised correctly, the cell is set to 0,25m deviation from the grid point to make sure that the position estimate is actually inside. The results are shown in Figure 55. The test dataset consisted of 23 points of which 6 are localized in one of the chairs in the theatre. The remaining 17 points are localised outside deviating from 0,01m to 8,23m towards the border of the cell. The cause for the incorrect localization of so many points can be found in the coverage of the *locators*. The high-resolution range of *locator* 5 is not covering a large part of the seating area. In addition to this, some points are positioned outside the *tracking area* due to DoP and reflection from the windows.

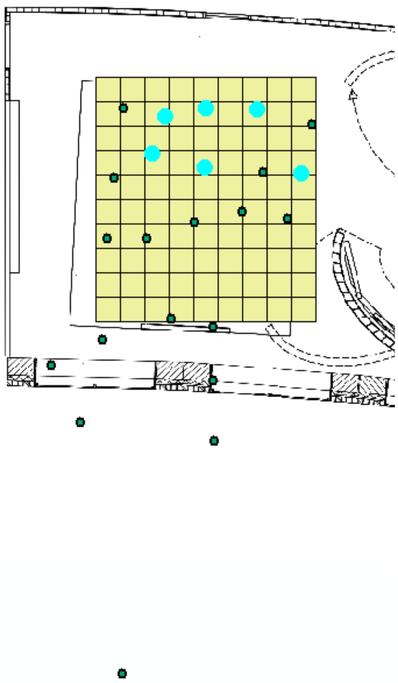


Figure 55: Points marked blue are located correctly based on the size of the grid cell

In the business zone two ellipse shaped areas are defined for testing the *zoning* type. The inner zone is situated around the U-shaped table and the outer zone covers the rest of the area where people walk and stand in front of the demo systems. In Figure 56, the points selected for the inner and outer zone are shown. In the left image, the blue points that are outside the inner zone are assigned to the wrong location. This is also the case for the points in the right image.

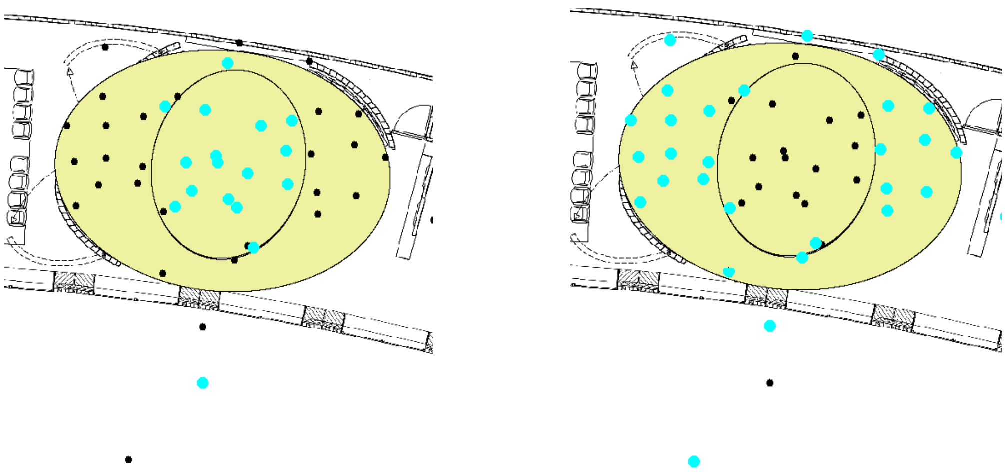


Figure 56: Points selected for map matching for the inner and outer zone

The third, *functional*, type is tested in the Play zone by localizing the tag in the area around each separate desktop that is situated there. The desktops arranged along the wall are representative for the use case of the IV pumps as they are placed next to the patient's bed close to the wall of the room. Due to the shape and orientation of the floor plan the analyses types are not exactly aligned with the desktop area. For analyses purposes this is not a problem because the grid does follow the orientation of the shapes. Two out of seven tag measurements are localized correctly; two are localized outside the functional area.

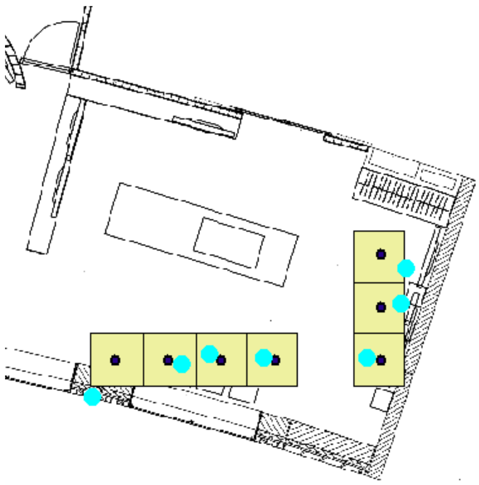


Figure 57: Points selected for locating a tag per desktop based on functional type

The matrix for the different location types can now be filled out. In Table 14, the distribution of the measurements used for localization is shown for each scenario of the map matching matrix. The results for the grid type derogate from the results of the other two types. This is caused by the fact that a large number of points in this dataset are influenced by the lack of coverage of this area of the Spark Center. Also the relatively small size of the grid cells (0,5m) has a negative effect on the outcome of the analysis.

Table 14: Results of localizing assigned to a scenario of the map matching matrix

			Scenario's			
			1	2	3	4
			A+, SD+	*A+, SD-*	*A-, SD+*	*A-, SD-*
Location types	**Grid**		26%	-	74%	-
	Zone	0	82%	-	12%	6%
		1	72%	-	17%	10%
	Function		71%	-	29%	-

Quuppa positionAccuracy (PA) parameter

The quality of the position of the tag can be added as a factor of influence. This factor is based on the coverage and range of the tag with respect to the *locator*. As an indication for the reliability of the position estimate the PA parameter can be used for computing this factor. As mentioned in section 2.1.7 this parameter does not describe the distance from the real value to the measurement based on the uncertainty. However, the PA does describe the reliability of the measurements to a certain extent as can be concluded from comparing it to the SD in Figure 43.

The PA can be used to give an indication of the reliability of the position measurement. In this case the PA can be translated to a percentage based on the minimum and maximum PA value for a set of measurements on a specific location. Another application of the PA is to use it as an input value for setting the threshold for division of the data into reliable and unreliable positions. A localization model for the test cases, using the PA, is defined in section 4.2.4.

Functional Constraints (FC)

The second layer that is added to the reliability parameter is a functional constraint. For a certain type of asset, a space can be subdivided into areas where the object can be and where it cannot be localized. For instance, an IV pump attached to a mobile stand can only move around in places on the floor plan were no obstructions such as furniture are placed. For another type of object, the opposite can be true. This constraint can be added as a first layer to the map matching of the positions.

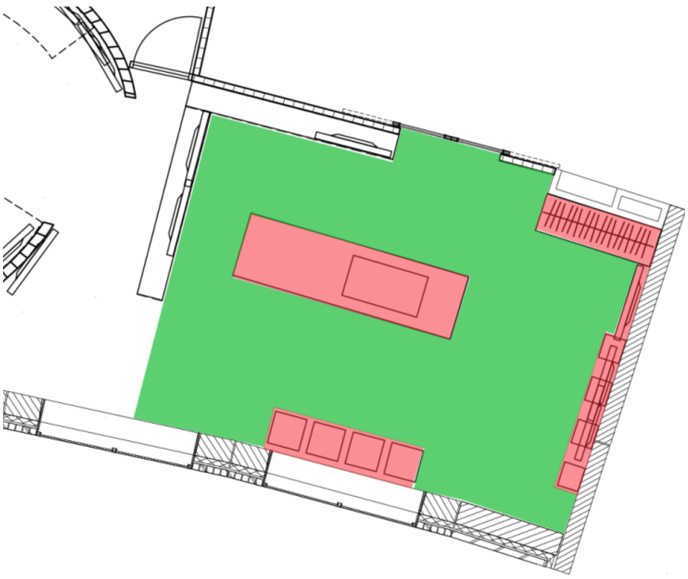


Figure 58: Example of functional constraints for localizing IV stands

As an example the wooden table in the play zone is defined as a functional constraint for localization, because an IV stand can only be moved on an empty floor surface. For computation of the reliability of the location of the tag a factor of 0 can be set for the table and a factor of 1 can be set for the floor surface. In Figure 58 the example described above is shown for the Play Zone.

Shape Related Probability
The third layer is a variable based on the place of the position with respect to the boundary of the location. For instance, if a location polygon is described by a circle, localization in the middle of the circle is done with a certain reliability coming from the position estimate. Assuming that this reliability is the same for all position estimates, localizing a tag at the boundary of the polygon has a higher chance to be seen outside the circle than when it would be in the middle of the polygon. Regardless of the coverage parameter of the position in the *tracking area*, the tag at the boundary has a lower probability to be located at the right location, i.e. inside the polygon.

In Figure 59 a concept for describing the probability value for localization is shown. The outer circle represents the border of the location where an asset can be localized. The dashed circle indicates the area where localization of the tag on this location can be done with a maximum certainty. Distance A is the radius from the cg which can be variable for irregular polygons. Distance B indicates the radial distance of the area where the positioned tag is given a decreased certainty of being localized in this polygon. This distance is based on the maximum accuracy value for the dataset in the positioning range. As the phenomenon of increased probability for localizing an asset outside the border only happens near this border, the uncertainty value for area A can be the same throughout the polygon.

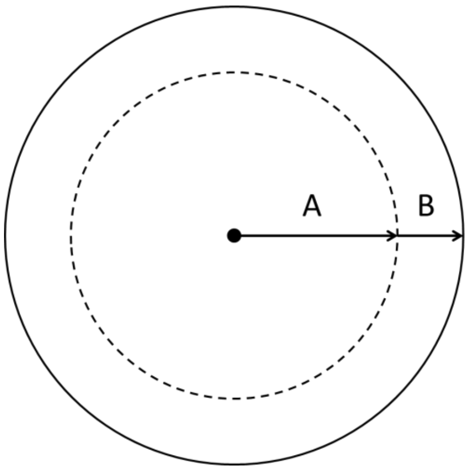


Figure 59: Concept for probability of localization from the center of gravity towards the boundary of a polygon

For all types of polygon shapes, the area where the localization is not influenced by the border phenomenon is described by a certain distance from the center of gravity (cg). This area defines the highest probability which changes to a lower probability around the boundary in all directions. To describe this phenomenon, a factor is added to the PA for the both the range distances from the center of gravity towards the boundary. The factor can be described by the PA and a percentage for the probability of correct localization. For positions in the + area, this percentage is 100% and for positions in the +/- area the percentage is 50%. The inverse of this percentage factor is used to multiply the PA value. This way, the positions with a relatively low PA are still located in the polygon. Positions at the boundary, despite having a high accuracy, are labelled as less reliable because of the higher probability of being wrongly located.

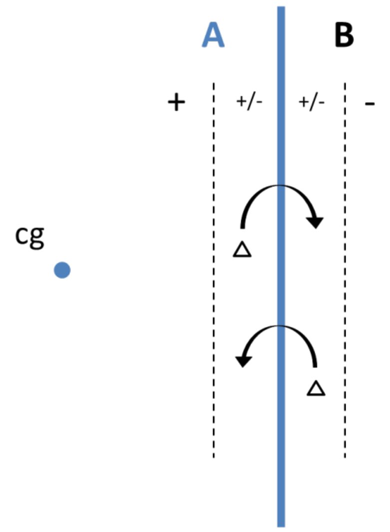


Figure 60: Increased uncertainty for localization around the border of a polygon

Summary of map matching

The point in polygon approach for map matching can be optimized by adding a combination of the suggested methods, i.e. PA, SRP and FC. Firstly, an estimate for the reliability of the position is indicated. The *positionAccuracy* parameter returned by Quuppa can be used for this. Analyses have shown that this parameter can be used as an indication for the reliability of a measurement. Secondly information about buildings parts and furniture can be used to add constraints to the localization polygon. And thirdly the probability of a tag being localized in the middle of a polygon or at the boundary has to be taken into account for localization. The application of these methods is twofold. They can be used to design a correction model for localizing assets in an indoor environment. Another application is using the SRP and FC method to adjust the default PA value and assigning a custom reliability variable to each localization result.

4.2.3. Reliability of test cases

Below, six test cases for localization of IV pumps in the hospital are described and analysed for the Spark Center test grid. For each test case a sub dataset is selected that matches the situation described in section 3.5.1. The locations for the storage room are selected in the Play Zone in the Spark Center. The locations for the patient's room are selected in the Business Zone. Due to the orientation of the furniture and the distribution of the grid points representative subsets are selected close to the defined test area for test cases I, II and IV. For every test case the accuracy and precision of the position measurements of the subset are used to select one of the reliability scenarios. For every test case, the reliability values of that specific location are taken into account.

I: Cupboard along the wall

The first test case is situated in the upper left corner of the Play Zone. Five positions are used for determination of the reliability scenario, which is shown in Figure 61. The grid points are shown in green and the position measurements in purple. The accuracy values are above the threshold for 80% of the points. The SD values, on the other hand, are above the threshold for 20% of the points. The reliability scenario for this subset is 3, which means low accuracy, high precision. This result indicates that localization at the borders of a room is unreliable because the distance to the *locators* is larger and DOP can occur due to the position of the points with respect to the *locators*.

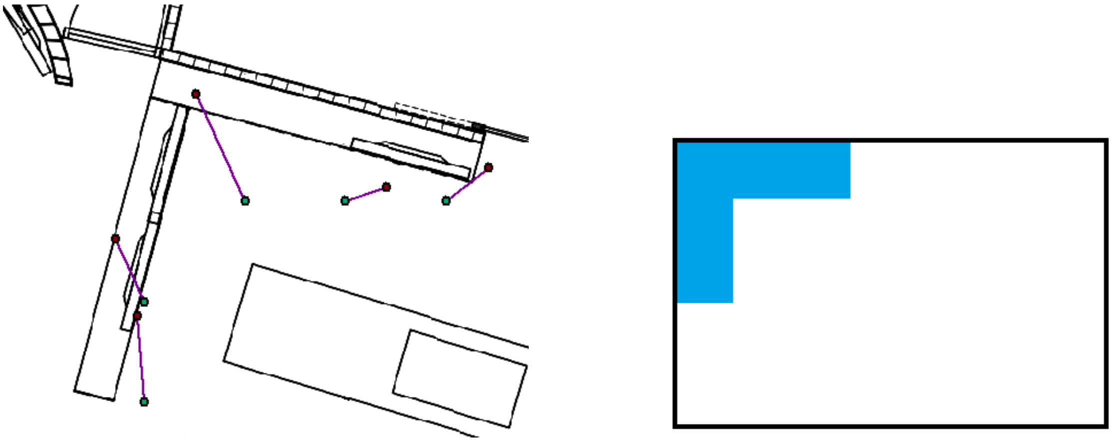


Figure 61: Sub dataset of test case I: Scenario 3 (l) and the schematic location for map matching (r)

II: table in the storage room

The second test case focusses on localization on a table in the storage room. Since there are no grid points measured on the table in the middle of the Play Zone, six points in the area next to it is selected. In Figure 62 these points are shown. This area is still in between *locator* 1 and 2, which should give the same characteristics for coverage of the grid points. For both the accuracy and the precision of the measurements, the values are below the threshold. For this test case scenario 1 is selected. Compared to the first test case, the reliability of these measurements is significantly higher. Around the boundaries of the table there is a chance of wrong localization, especially because of the lower accuracy values. For these values a shift towards the inside of the polygon, in this case the table, should resolve this issue.

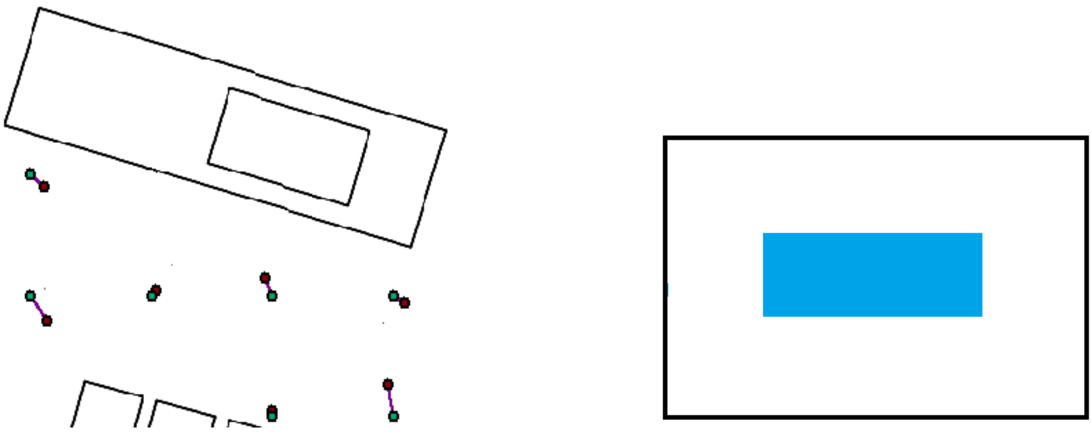
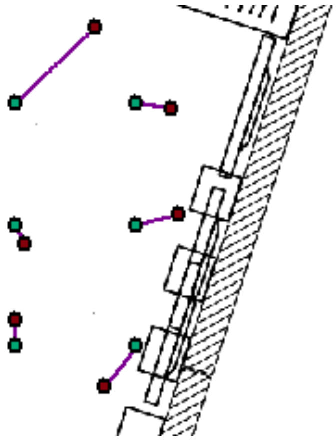


Figure 62: Sub dataset of test case II: Scenario 1 (l) and the schematic location for map matching (r)

III: Walking space around table

The third test case covers (a part of) the open floor space. In Figure 63 the six data points representing the open space are shown. The accuracy and precision of the points corresponds with what could be expected from a location in the high resolution range. The point in the upper left corner makes an exception as the accuracy is low compared to the other points. In the middle of an open space this error is of less influence to the localization of the tag. Based on these findings, scenario 1 is selected for localization in the open space area. For lower accuracy values, meaning a larger deviation from the actual position, functional restraints can be applied to correct for this error.



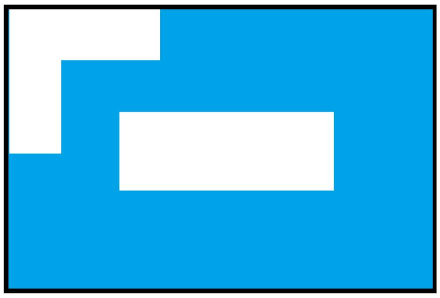
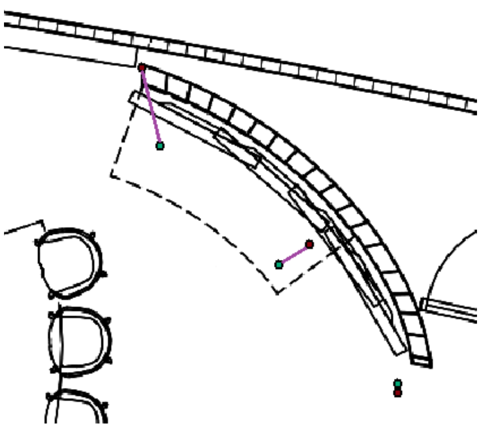


Figure 63: Sub dataset of test case III: Scenario 1 (l) and the schematic location for map matching (r)

IV: Cupboard in the corner

The fourth test case is situated in a patient's room on one of the hospital wards. The sub dataset for this case is taken around one of the four curved walls as they have a similar location to the cupboards in a patient's room, i.e. in the corners of the room. Also medical equipment, such as IV stands and hart monitors are situated next to a patient's bed. Possible reflection from the equipment is taken into account in the test case. In Figure 64 the three points selected for this test case are shown. The values for the precision show acceptable results for all three points. The accuracy values show significant deviation from the real value. However, these values are still within the threshold range, which implies a reliability scenario of 1.

The cause for the relatively large errors is multipath because of the reflection of the wall's material and the TV screens. Compared to the results from test case I, these points return better values for positioning at the border of a room. The main reason for this is better coverage of the *locator*, as the distance to the closest locater is much shorter. In both cases the error is pointing towards the border of the room. For localization in a cupboard, the relatively large accuracy errors should not cause the system to return a wrong location. The *tracking area,* implemented in the Quuppa system, and the wall separating the rooms prevent the tag to be located on another location or in another room.



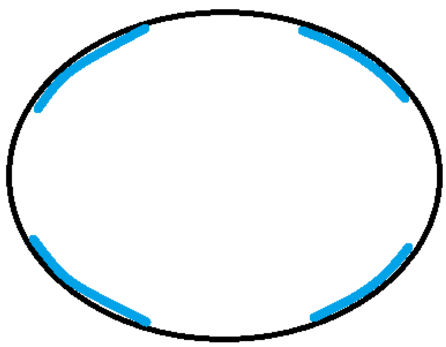


Figure 64: Sub dataset of test case IV: Scenario 1 (l) and the schematic location for map matching (r)

V: Patient's bed

The fifth test case is situated on the U-shaped table in the middle of the Business Zone. The location in the room is representative for a patient's bed in a single patient nursing room. For this test case, four point measurements are selected for grid points located on the table. The measurements and grid points are shown in Figure 65. All measurements show a clear deviation with respect to the grid point. In this specific case all tags are localized correctly, i.e. on the table. The point to the far right is located in the boundary zone that is described by the SRP method in section 0. The other three points on the left side are located towards the center of the table and are localized correctly despite of the relatively low accuracy values. In the case of wrong localization due to low accuracy of the measurements, a functional restraint can be added.

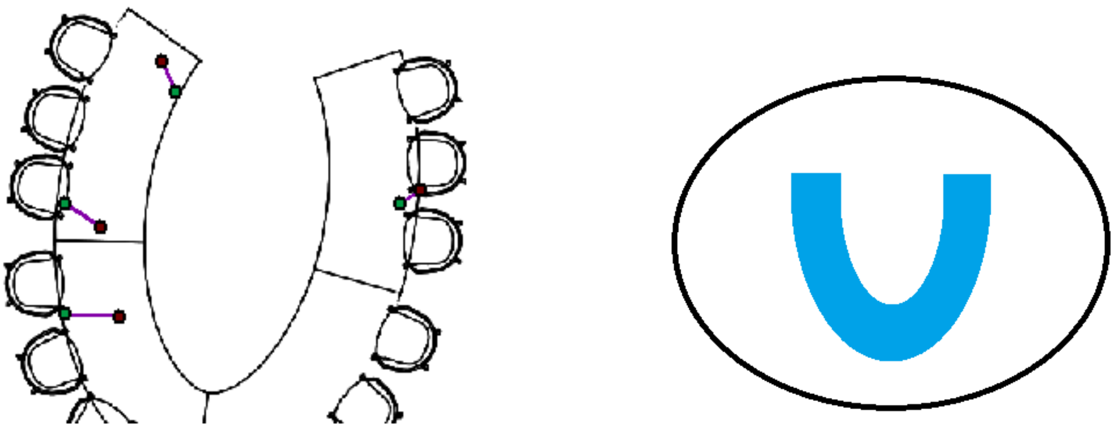


Figure 65: Sub dataset of test case V: Scenario 1 (l) and the schematic location for map matching (r)

VI: Walking space around bed

For the sixth test case, five points are selected in the open space area enclosed by the U-shaped table. The accuracy for these points is below the threshold limit for all points except for one. However, the values are relatively high and cause wrong localizations for two other point measurements. The precision is above the threshold for three of the points. Based on these values, scenario 2 is selected for this test case. Remarkably, the points with low accuracy give good results for the precision and vice versa. This means that the signal is not distorted by obstructions or other environmental influences.

This specific location is situated in between two *locators* which causes the reliability of the position measurements to be lower compared to other high-resolution areas. The phenomenon of decreased reliability between two *locators*, described in section 2.3.2 is applicable here as the accuracy error happens in the direction of the LoS of 180^o to both *locators*. Two points are located on the table, where they actually are in the open space in the middle of the table. This error can be corrected by adding functional restraints. As these points are located in the border zone of the table polygon, they are assigned to a lower reliability category for being localized on the table. A correction model for this kind of error is described in section 4.2.4.

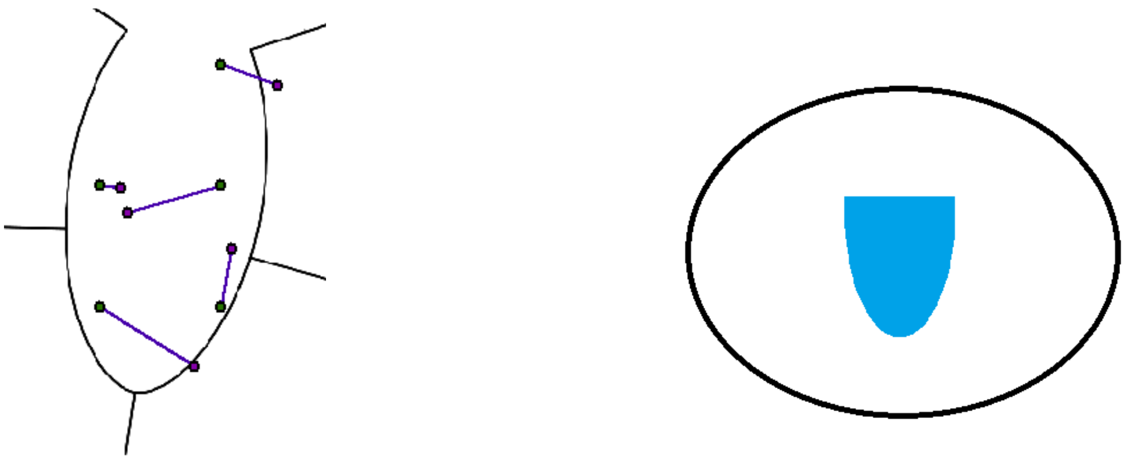


Figure 66: Sub dataset of test case VI: Scenario 2 (l) and the schematic location for map matching (r)

The performance of localization of the test data based on the reliability is shown in Figure 67 for each test case. Localization along a wall is difficult due to the relatively large distance of the tag to the *locator*, assuming that the *locator* is in the middle of the room. In the case of localizing in the open space in the middle of the table the average accuracy value exceeds the threshold. This dataset was taken from a location in between two *locators* where the reliability of the measurements is lower due to the geometry of the combined measurements. In this case the error values are small which makes it possible to correct the positions using the SRP method.

Test case		**Accuracy**	**Precision**	**Scenario**
Number	*Name*			
I	Cupboard along the wall	0,74	0,27	3
II	Table in the storage room	0,17	0,05	1
III	Walking space around table	0,39	0,03	1
IV	Cupboard in the corner	0,39	0,02	1
V	Patient’s bed	0,35	0,09	1
VI	Walking space around bed	0,57	0,09	3

Figure 67: Results of map matching for the test cases. Test case I and IV need adjustment of the localization method.

4.2.4. Localization model

The input elements of the localization model are the position measurements retrieved from the Quuppa system, the locations defined in the test cases and the functional constraints of the environment and the target objects. Based on the result of map matching, several of scenarios are possible. In the case of IV pumps, the height is fixed when they are attached to an IV stand. Assuming that the pumps are being localized using the 2D mode of the Quuppa system, using the z value for determining the location is not possible. This localization model makes a distinction of the data based on the PA parameter. In section 0 the switch value (threshold) for the PA to make the distinction of reliable and unreliable positions is given. Based on each of those groups of measurements a correction model is defined below. The description of this model is subdivided into three schemas. Schema A covers the division of the measurements for the reliability. Schema B and C show the steps regarding the correction methods based on the SRP and FC respectively. In Figure 68 the proposed localization methods are shown. In general, SRP is used for small position errors and FC is used for large position errors.

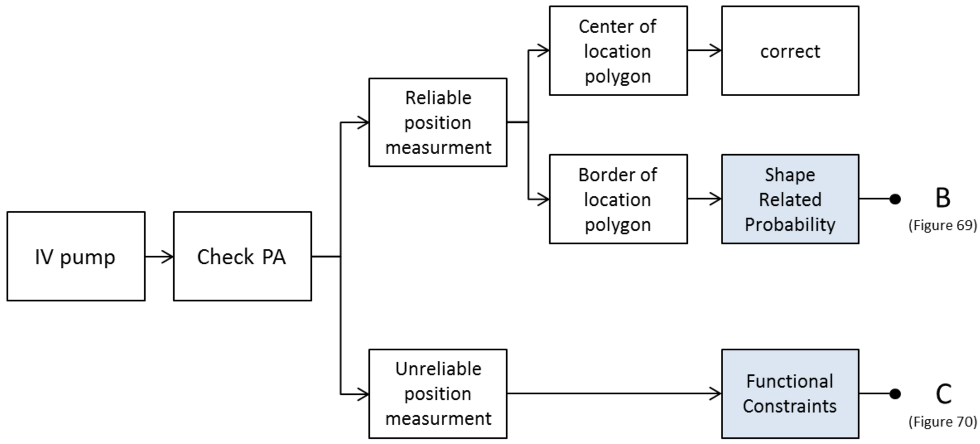


Figure 68: A: Decision tree for a localization model for IV pumps

For reliable positions, i.e. PA < threshold value, two options for localization are defined. As can be concluded from the data processing and analysis, the Quuppa system is able to return highly accurate position estimates up to 10cm accuracy. In the case of a reliable in the 'center' of the location polygon, a point-in-polygon match is sufficient. The location output is the name of the polygon that was defined in the test cases, e.g. cupboard in storage room or corner in patient's room x. In Figure 69 the steps for applying the SRP method are shown. When the tag is positioned in the border zone of the location polygon the SRP method can be used to add a decreased reliability value to the point. This value is calculated by adding a reducing factor of 50% to the reliability percentage based on the PA range. The percentage for the PA can be calculated as a ratio of the minimum and maximum PA for the position measurements at a certain location. To correct the position measurement towards the right location an x, y shift is suggested. This shift is an adjustment of the x and/or y coordinates of the position can be based on the error vectors of the covariance matrix. Based on the results from this research it is not possible to define the angle or direction to make an adjustment for the position in this border zone. Further testing and analysis is required to define a correction method for this specific situation.

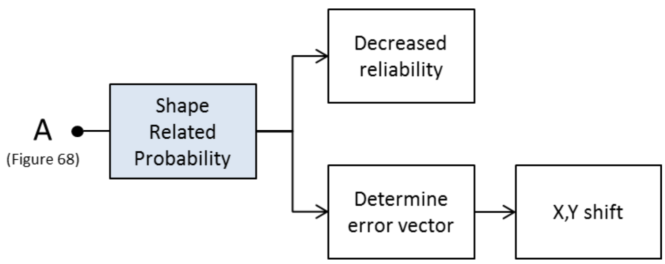


Figure 69: B: Decision tree for correction of the position and adjustment of the reliability

For unreliable positions, i.e. PA > threshold value, the accuracy is expected to be significantly lower compared to the other group. In this case the measured position is between 0,5m and 1m+ away from the actual position. The requirements of the use are used for adding constraints to the localization model. The relevance of taking the context of the environment into account is described by [39]. Identification of the context can be done using the properties and characteristics of the objects that need to be localized. Information about the default height, location and behaviour of the IV pumps can contribute to the identification of the right location. In Figure 70 the decision tree for assessing the need for correction of the position is shown.

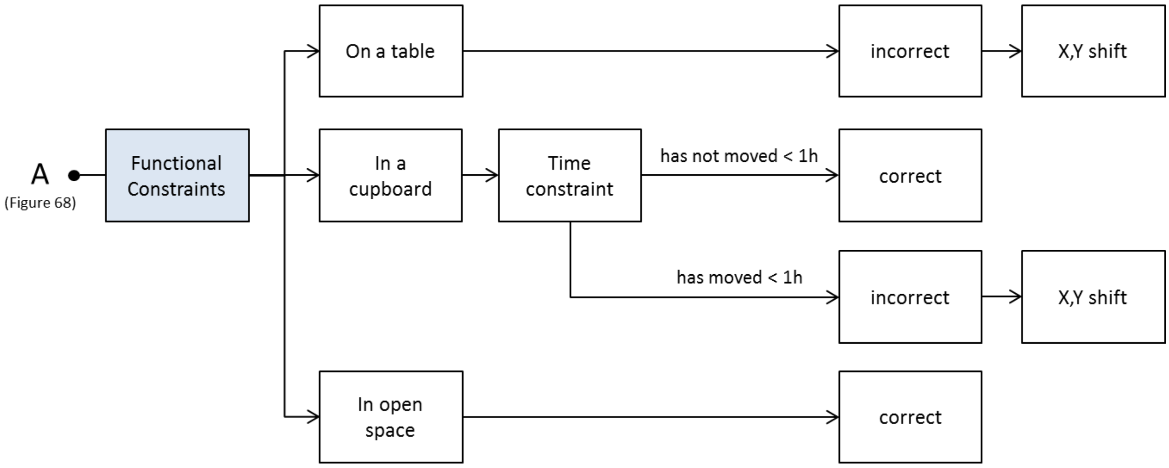


Figure 70: C: Decision tree for correction of the unreliable positions. For incorrect positions an x, y shift is required

For the unreliable position measurements, the Functional Constraints method is added to the model. As the type of asset is known for a tag, this information can be used to assess the test areas. For this model the requirements for localizing an IV pump are taken into account. Localization on a table is considered as an incorrect result which needs an x, y shift. Localization in a cupboard can be determined by checking the previous locations and time stamps of the object. If the object has not moved for a significant amount of time (in the case of IV pumps, 1h+) the pump is stored in a cupboard or in the corner of a room. Positions that have moved in the last hour are matched to the open space location. A distinction between the storage room and the patient's rooms is not necessary since these locations are too far apart to cause ambiguity. Walls separating rooms can eliminate ambiguity issues on the condition that the rooms are covered by different *locators*.

For test case I and VI, the reliability of the localization results is below the threshold for the accuracy value. For case I a functional constraint can be added to localize the assets in the cupboard. Assuming that the cupboard is placed against a separating wall, correction of the position error is limited in this situation because the wall, i.e. boundary of the tracking area, already puts a constraint on the position measurements from the outside of the room. In case VI both the SRP and the FC method can be used. The positions that are localized wrongly are seen on the table in the border zone, while the actual location should be the open space in the middle. For SRP, the correction vector can be used to add an x, y shift towards the open space. The FR method should also result in correct localization when the height component of the tag can be taken into account for distinguishing between table and open space. To make this possible, the positions should be returned in 3D by the Quuppa system.

5

Conclusions and Recommendations

In this section the conclusions of the project are discussed. In addition to the conclusions of the tests and analyses, the knowledge about the use case and Quuppa system are taken into account. Below, an answer to each individual sub-question is given in order to answer the main research question. Some recommendations for further research and application development based on the outcome of this research are given at the end.

5.1. Conclusions from analyses

5.1.1. Data processing

The conclusions for the data processing can be divided into remarks with respect to the structure of the data and to the quality of the measurements. A comparison of the mean and median of the position data do not show major differences for the average value of each measurement. Except for the areas where the dispersion of the measurements is relatively high (Compare Figure 41 and Figure 42). Causes for the low precision of the measurements are reflection of the radio signal and Dilution of Precision (DoP) for positions near the borders of the *tracking area*. Not all tags return the same number of measurements for a similar tracking period. This can be caused by a combination of hardware issues, fluctuations in quality of the radio signal (environmental influences) and the chosen configuration specifications of the system. Some tags return duplicate results for a measured position. These duplicates are not relevant for the estimate of the position over time because they have the same time stamp. The cause for this lies in the method used for logging as the latency of the positioning system prevents it of returning an updated position within less than 0,1s.

The second group of concluding remarks can be used as input for the analysis section. The reliability of the technical parameters of the tag's position depends strongly on the position with respect to the *locator*. Closer positions show better results than positions that are further away. This information can be used to place the *locators* in the most optimum way depending on the application. The data generally shows two types of position estimates. The majority of the measurements have a high accuracy and a high precision. Other output results show low accuracy and a high or low precision. For further analyses a distinction between 'reliable' and 'unreliable' results is made. The third test showed that positioning outside the *tracking area* is not possible. In the hallway inside the building the tags are not even detected by the system. A possible cause is the influence of the material of the wall separating the Spark Center and the hallway. This is investigated into further detail in section 4.1.3.

5.1.2. Data analysis for positioning

From the results of the tests and analyses three main conclusions can be drawn. Firstly, the effect of environmental influences on the performance of the positioning system is significant. The *tracking area* was limited to the boundaries of the Spark Center for the first and (a part of the) third test. This means that when a tag is (wrongly) positioned outside the floor plan, it is snapped to the border. In contrast to the first test the boundaries of the *tracking area* were removed during the second test, which made it possible for the tag to be positioned outside the floor plan of the Spark Center. According to documentation of Quuppa's, the system uses the tracking plane as a constraint for the calculation of the coordinates of the position estimate. Removing the tracking plane, thus the constraints, introduces artificial influences in measuring the geometry of the tags position. When the *tracking area* is defined by structural elements, e.g. interior wall, the coverage of the radio signal outside the *tracking area* is limited. Reflection and low coverage areas have a large influence on the reliability of the localization of the tags. Strategic placement of the *locators* based on the application is important for reliable position estimates.

Secondly, the range for positioning and detection determines the reliability of the measurements to a large extent. The heat map of the coverage of the system shows rather clear separation areas between the zones in the Spark Center. In the current setup, these areas return positions with lower reliability compared to the areas closer to the *locator*. This has negative consequences for the localization of tags near the boundaries as they are likely to be localized in an adjacent zone when there is no separating element between them. In the case of tracking medical equipment in a hospital: if the IV pumps are likely to be placed along the border of a room, the coverage of the positioning system should be sufficient at these locations.

Thirdly, the number of returned positions over time for each measured grid point does not seem to have a significant influence on the reliability of the position. This makes the system potentially useful for RT tracking. The accuracy parameter seems determinative for the correctness of the position. No relation between the standard deviation and the accuracy could be found in the analyses. The reliability of the technical parameters of the tag's position depends strongly on the position with respect to the *locator*. Closer positions show better results than positions that are further away. This information can be used to place the *locators* in the most optimum way depending on the application. The *positionAccuracy* parameter (PA) is a good estimate for on-the-fly assessment of the quality of a measurement. A direct correlation between PA and the accuracy values calculated from the measured coordinates cannot be found. However, the values for PA show the same structure and results for sub-parts of the dataset.

5.1.3. Location types and map matching

Three location types were defined, based on a grid, zones and functions in the floor plan. The grid type showed the worst performance, mainly because of the small size of the cells used for this type (0,5m). The zonal type showed the best performance, 82% correct localization in the outer polygon. The performance result of the zone type can be explained by the coverage of the positioning system. Since the size of the polygon is similar to the area where the localization is carried out and the structural elements of the building define the border of the location polygon. This way, the range of the positioning system determines success for localization to a large extent.

The point in polygon approach for map matching can be optimized by adding a combination of the suggested methods, i.e. PA, SRP and FC. Firstly, an estimate for the reliability of the position is indicated. The *positionAccuracy* parameter returned by Quuppa can be used for this. Analyses have shown that this parameter can be used as an indication for the reliability of a measurement. Secondly information about buildings parts and furniture is used to add constraints to the localization polygon. And thirdly the probability of a tag being localized in the middle of a polygon or at the boundary has to be taken into account for localization. The application of these methods is twofold. They can be used to design a correction model for localizing assets in an indoor environment. Another application is using the Shape Related Probability and Functional Constraints method to adjust the default PA value and assigning a custom reliability variable to each localization result.

5.1.4. Test cases and localization model

Based on the test cases the positioning system shows good results for localization as in four out of six cases the points were correctly localized. In these two cases the value for the accuracy returned a result below the threshold value. Based on the outcome of the analysis for positioning and the test cases the accuracy of the measurements can be regarded as the main indication for the performance. Errors in the accuracy value inevitably result in errors in localization. The model defined for localization of the IV pumps can mitigate or correct these errors. For error detection, the *position Accuracy* parameter can be used to assess the reliability of a single position measurement. Based on the reliability the measurements can be divided into two groups, one containing the highly accurate positions and the other containing the low accuracy positions. For both a correction method is defined. For small position errors the Shape Related Probability can be used, where the Functional Constraints method is better for larger errors.

5.2. Answering the sub questions

What are the possibilities and limitations of the Quuppa system?
In order to make an assumption about the performance of the system for locating IV pumps in a hospital, the specifications provided by Quuppa and the use case requirements are compared. In general the specifications of the positioning system exceed the requirements for asset tracking. However, the environment specific aspects have a major influence and require a custom setup and configuration. The drawback of using Bluetooth is that it is not generally available in public spaces and requires a local setup of specific hardware. However, the sub-meter accuracy and high precision of the Quuppa system make the technology potentially suitable for positioning indoors, especially for localizing objects in complex buildings such as a hospital.

What are the technical and operational performance parameters and how can they be measured?
To measure the performance of the positioning system, a number of parameters were defined for the technical- and for the operational aspects of the analyses. The technical parameters, i.e. accuracy, precision, coverage, latency and update rate, cover the specifications of the system on the one hand and provide input for testing subjects. The technical parameters are measured directly by the system or can be derived from the Quuppa output. The operational parameters, i.e. building structure and materials cover the other part of the spectrum. These parameters were used to define the location types. Values for these parameters are derived from analyses of the test data and knowledge about the test environment. Input for the assessment of the effect of built materials and

building structure is based on the results for the accuracy and precision of the position estimates and on information about radio signal propagation and building materials. The operational parameters together with the coverage and geometrical theory of the positioning method were used to analyse the constellation of the *locators* for an optimum system setup. The reliability of the measurements was investigated by analysing the structure of the collected datasets based on the accuracy and precision parameters. The latency and update rate are derived from the data output and configuration tool respectively. These parameters were used to measure the ability for localization in real time.

What is the performance of the system based on the technical requirements?
The scope of the use case is to localize medical equipment, e.g. IV pumps, in rooms where the assets are supposed to be during use and storage. In both situations the pumps remain in the same place for a longer period of time which is less demanding for the system regarding the latency and update parameters. The accuracy and precision influence the coverage of the floor plan for the technical part. The precision of the position, based on the standard deviation, is acceptable for positions that are not influenced by environmental aspects. The system offers sub-meter accuracy for the majority of the measured positions, which makes the system suitable for identification of specific assets on a single location up to furniture level, e.g. on a table, in a cupboard.

The update rate and latency are used to configure the system for testing based on the requirements for real time positioning. The demo software license offers up to 100 Hz update rate and 0,1s latency. The basic license is not suitable for real time because of the latency of 1min. The latency of 0,1s used in the tests is sufficient for static localization and low speed movements of the IV pumps. The tests show that single measurements are quite reliable for well covered areas. Taking more measurements over a longer period of time does not show significant improvement in the accuracy and precision of the position estimate. The assumption is that the reliability of the position improves when more measurements are taken and used for averaging and calculation of the standard deviation. In this test case, positions measured for 10s showed similar results for dispersion and accuracy based on the average compared to when the position was measured for 60s.

A custom setup can be defined for this system based on the coverage and the use case characteristics. As the system underperforms significantly outside the high-resolution range of the *locator*, the *locator* must focus on the area of interest. There is a significant difference in coverage of the high-resolution range between one and two *locators* per room. Due to the cone shaped range and geometrical issues regarding the positioning method, locations at the borders of the *tracking area* are subject to errors. When the borders of a space are included in the area of interest, a minimum of two *locators* is recommended for areas similar to the test location.

What is the performance of the system based on the operational requirements?
The results for the operational parameters show that the coverage determines the performance of the system based on a predefined level of accuracy (<1m). The signal sent out by the tag is very sensitive to metal surfaced obstructions. This brings some limitations to the direct environments of the area of interest. Especially in hospitals where bed frames and IV stands contain metal surface reflection might cause issues for the reliability of the position. In general line-of-sight between tag and *locator* is recommended as the Bluetooth signal is easily blocked by pieces of furniture and interior walls. The detection of the tags outside the positioning range of the *tracking area* is limited.

In particular (interior) walls separating rooms and outer walls block the radio signal to a large extent and limit the (detection) functionality of the positioning system. Also glass surfaces block signal propagation of the tags. The upside of this phenomenon is that localizing in clearly separated spaces is possible with a high reliability. Because of the strength and properties of the Bluetooth signal the coverage of a particular *locator* deteriorates significantly when the signal is obstructed by constructive elements such as interior or exterior walls. The reliability of locating an asset on room level is high as the tag is not likely to be located in an adjacent room.

How can the results of the test and analyses be put into a model for localization of assets using Quuppa technology?

The main difference in the characteristics of people and assets is that assets tend to stay in the same place for a longer amount of time without moving. This puts the focus for localization of assets on returning a reliable position for static objects. Based on the comparison of the accuracy, precision and standard deviation of the data from different time spans, a relatively low update rate up to 5 Hz is sufficient for getting reliable position estimates. Storage furniture is generally located along the wall of a room which moves the area of interest from the middle (where people are) to the sides where the cupboards are. Based on localization of the tags according to the three defined location types, i.e. grid, zone and function based, the grid type performs significantly less compared to the function and zone type. The main reason for this was that the data used for the grid test had low coverage of the positioning system. The tags on the part of the grid based location type that had better coverage of the system were localized more correctly. For the other types, over 75% of the tags of that part of the Spark Center were localized correctly.

Because of the influences of Dilution of Precision, when the *locators* are positioned around the center of the floor plan, adding a *tracking area* can improve the success of localization in closed spaces. According to the tests, the tags are positioned further away instead of closer to the *locator* when the *tracking area* was removed. This means that the *tracking area* can function as a built-in geofence. For localization in smaller clusters, a subdivision of the space up to 10cm can be achieved for the high-resolution range of the positioning system. The results for the zone type show a significant improvement in localization for the inner area, which is in accordance with the other findings with respect to the reliability and coverage. For the function type the localization success rate is only 70% which is influenced by the low amount of points taken into account. Although this is the best covered part of the Spark Center, the reliability of the localization is influenced by reflection from the computer screens. Localizing at the chosen accuracy level of 0,5m should be achievable in a similar situation.

The positions can be located in predefined sub-spaces representing a location on (sub-)room level. In order to develop a localization model for assets three methods can be used to improve the point-in-polygon intersection of the position estimates and the location clusters. The parameter for the reliability (*positionAccuracy*) can be used as an indicator for position results that require a correction of the location it was assigned to, based on the point in polygon method. The shape related probability method and functional constraints improve the intersection method by adding x, y shifts based on the characteristics of the IV pump and the reliability of the position measurement. Based on the correction model and the reliability parameter a system can be built for localization and tracking of assets in a hospital. The model developed in this research can be translated to a localization algorithm and implemented into an asset tracking system.

5.3. Answering the main research question

Does the technical and operational positioning performance of Quuppa technology meet the localization requirements for asset tracking in a hospital environment?

For the technical performance a sub-meter accuracy level can be achieved for locations that are within the high-resolution range of the *locator*. The level of accuracy and precision for positioning at the smallest cluster levels can only be achieved throughout the floor plan when having a dense distribution of *locators*. A measure for the density of the constellation is the radial distance of the high-resolution range. In the Spark Center this distance is between 2 and 5m for respectively 1 and 2+ *locator* covered areas. This distance is depending on the height of the *locator* with respect to the floor. The number of returned positions differs for tags measured at the same time for equal settings with respect to latency and update rate. The cause of this can be found either in issues in the hardware of the tag or in the radio signal not being captured by the *locator* because of reflection and obstructions. Relatively low update rates are possible for asset tracking because the reliability of the position estimates is independent from the amount of measurements taken.

The Area of Interest (AoI) is the main driver for determining the constellation of the *locators.* Because of the architectural lay out of a hospital, characterized by a large number of small rooms, the positioning system should be able to return an unambiguous location with a high reliability. Ceiling height is a restrictive factor for the coverage of a single *locator*. Even in large open spaces quite a large number of *locators* are needed to cover the floor plan. Another restrictive factor is the structural elements of the building. This is actually in favour of the application of indoor positioning as the tag can be localized unambiguously on room level when each room has at least one *locator* installed. Obstructive elements such as ventilation shafts and light rails decrease the coverage. Installing the *locators* at a lower height will reduce the coverage which results in a trade-off between placing more *locators* per m^2 and risking obstruction of a part of the range.

Based on the outcome of the map matching the Quuppa system can be used for localization of IV pumps in a hospital. The point-in-polygon intersection returns results of over 70% of correct localizations. To optimize the localization method, the values for reliability based on the Quuppa output are used together with constraints for obstacles in the area of interest (AoI) and a correction for the bias in assigning positions to a location at the border of the polygon. The level of accuracy in the high resolution range is sufficient to distinguish objects up to 0,1m in size, e.g. beds and IV pumps. The test cases showed that localization in the test areas, i.e. table, cupboard, open space, is possible with a high reliability. Outside the high resolution range, the performance of the system is lower which results in incorrect localization for locations smaller than 1m, e.g. a cupboard.

To improve the localization in these places, functional constraints can be introduced for locations based on the type of object that needs to be localized. In a 2D positioning configuration the area where the object cannot be localized is excluded from the location polygon. The height component could be used to exclude locations for localization based on the default height of a certain object. However, this is not possible within the scope of this research because it requires 3D position estimates. For small position errors along the border of a location polygon, the shape related probability method can be used for correction of the based on the error vector of the measurement. The velocity of the asset puts no restriction on the reliability of the system for localization as the location of an asset is generally required for static objects, i.e. in storage or in use.

5.4. Recommendations and future research

5.4.1. Recommendations for test methodology

Regarding the test methodology there are some remarks and improvements. Placing the tags on a grid to measure the positions in order to create a homogeneous dataset of points had some drawbacks for the purpose of analysis. To be able to assess the reliability of the exact test case situation, the tags should be placed on these specific locations during data collection. For this research sample data from the grid measured datasets was used as input for the test cases. Secondly, for each measurement the number and id of the *locators* that are involved in measuring the angles towards the tag should be made available. This data can be used to indicate the reliability of a measurement as measuring every tag position by using at least two *locators* will improve the reliability of the returned x and y coordinates. This information is not made public by Quuppa because it is a part of their positioning algorithm.

5.4.2. Further development of the localization model

A correction grid can be designed for correcting the error vector that can be derived from the covariance matrix in the output of a Quuppa position estimate. This correction grid should be based on multiple sets of measurement data for a specific location in order to correct for the position error made at that specific grid point. The covariance matrix that is returned with every position estimate by Quuppa consists of four elements. The first two variables describe the error of the measurement for the x value in the x and y direction. The other two describe the error for the y value in both directions. Based on these values an error ellipse can be constructed. The values of the error vectors can be used to correct large positioning errors and shift the coordinates in the direction of the largest error vector.

A second subject for further research is to test the performance of the system in 3D mode. The Quuppa system can determine the 2D position estimates, x and y, when the height of the tags is fixed. In 3D mode the system measures the height coordinate and returns x, y and z coordinates for each tag. For this project the system was configured in 2D because the objects that needed to be localised, i.e. IV pumps, are all attached to a stand at the same height. However, to improve the functional constraints method the height of the object is of interest. The z coordinate of a tag measurement can be used to add an extra constraint in the z direction for localizing based on the type of object. For example, a certain object is not supposed to be localized on a table. In the case of a z coordinate of (approximately) 0, the constraint can correct the location of the IV pump to the closest table.

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Glossary

Area	2D plane in a floor plan
Data packet	Output received from the positioning system in a certain format.
Locator	Receiver device as a part of the Quuppa positioning system
Location	Place with attributes about the identity added by human beings
Position	Point in a space represented by coordinates (x, y, z)
Room	Confined space with a unique name or number
Space	3D area
Tag	Transmitter device as a part of the Quuppa positioning system
Tracking area	Area of interest where the tags can be positioned by the Quuppa system
UDP logging	Pushing data packets from the server to a file on a computer

Appendix A: Test data

1. Processed position measurements per grid point of the first test of 28th of July 2015

grid_id	x_grid	y_grid	tag_id	x_avg	y_avg
5	1	5	001830ed4e43	1,12	5,96
6	1	6	001830ed4a73	1,99	7,02
8	2	2	001830ed5842	1,47	2,94
9	2	3	001830ed737a	1,76	3,08
10	2	4	001830ed7898	2,43	3,81
11	2	5	001830ed4e43	2,10	5,3
12	2	6	001830ed4a73	2,19	6,74
14	3	2	001830ed5842	2	0,8
15	3	3	001830ed737a	2,87	3,3
16	3	4	001830ed7898	2,96	3,91
17	3	5	001830ed4a73	3,7	5,35
18	3	6	001830ed4e43	3,36	5,71
19	4	1	001830ed5ac8	4,57	1,16
20	4	2	001830ed5842	3,6	2,66
21	4	3	001830ed737a	4,31	2,76
22	4	4	001830ed7898	3,95	3,71
23	4	5	001830ed4e43	4,08	4,99
24	4	6	001830ed4a73	4,15	5,28
26	5	2	001830ed5842	5,15	1,9
27	5	3	001830ed737a	5,15	2,8
28	5	4	001830ed7898	4,78	3,68
29	5	5	001830ed4e43	5,17	4,84
30	5	6	001830ed4a73	4,9	5,51
31	6	1	001830ed5ac8	5,83	1,4
32	6	2	001830ed5842	5,59	1,69
33	6	3	001830ed737a	6,03	2,23
34	6	4	001830ed7898	5,12	3,87
35	6	5	001830ed4e43	5,37	5,36
36	6	6	001830ed4a73	6,3	6,32
37	7	1	001830ed5ac8	7,22	-0,31
38	7	2	001830ed5842	7,2	1,53
39	7	3	001830ed737a	6,98	2,69
40	7	4	001830ed7898	7,05	3,2
41	7	5	001830ed4e43	7,41	4,75
42	7	6	001830ed4a73	7,12	5,9
43	8	1	001830ed5ac8	8,6	0,39
44	8	2	001830ed5842	8,15	1,61
45	8	3	001830ed737a	8,19	2,8
46	8	4	001830ed7898	7,97	3,55
47	8	5	001830ed4e43	8	5,09
48	8	6	001830ed4a73	8,02	5,22
49	9	1	001830ed5ac8	8,77	0,12
50	9	2	001830ed5842	9,06	1,53
51	9	3	001830ed737a	8,69	2,96
52	9	4	001830ed7898	9,04	4,07
53	9	5	001830ed4e43	9,31	5,26
54	9	6	001830ed4a73	8,78	6,07
55	10	1	001830ed5ac8	10,53	0,63
56	10	2	001830ed5842	10,2	2
57	10	3	001830ed737a	10,16	2,96
58	10	4	001830ed7898	10,14	3,72
59	10	5	001830ed4e43	10,41	4,91
60	10	6	001830ed4a73	11,93	6,14

grid_id	x_grid	y_grid	tag_id	x_avg	y_avg
61	11	1	001830ed5ac8	10,96	1,22
62	11	2	001830ed5842	11,31	1,86
63	11	3	001830ed737a	11,4	2,55
64	11	4	001830ed4e43	8,93	4,64
65	11	5	001830ed4a73	10,74	5,69
66	11	6	001830ed7898	9,23	6,31
67	12	0	001830ed5ac8	15,03	-0,86
68	12	1	001830ed4a73	12,92	1,41
69	12	2	001830ed5842	12,25	2,1
70	12	3	001830ed737a	12,09	3,06
71	12	4	001830ed7898	12,82	4,37
72	12	5	001830ed7bc5	1,46	4,52
73	13	0	001830ed4e43	12,84	5,14
74	13	1	001830ed4a73	13,56	0,38
75	13	2	001830ed5ac8	13,5	0,68
76	13	3	001830ed5842	12,23	1,26
77	13	4	001830ed4f47	11,02	2,37
78	13	5	001830ed737a	13	2,79
79	14	0	001830ed7898	13,06	3,84
80	14	1	001830ed4e43	12,43	5,03
81	14	2	001830ed5ac8	14,36	0,88
82	14	3	001830ed5842	14,07	1,94
83	14	4	001830ed737a	14,27	2,91
84	14	5	001830ed7898	14,1	3,83
85	15	0	001830ed4e43	13,98	5,48
86	15	1	001830ed4a73	10,06	6,42
87	15	2	001830ed4a73	14,46	0,09
88	15	3	001830ed5ac8	15,43	0,28
89	15	4	001830ed5842	15,2	2,33
90	15	5	001830ed7898	15,34	4,3
91	16	-1	001830ed4e43	15,01	5,31
92	16	0	001830ed737a	13,22	5,7
93	16	1	001830ed7898	16,01	-0,29
94	16	2	001830ed5842	16,78	0,12
95	16	3	001830ed4a73	15,45	0,61
96	17	-1	001830ed5ac8	16,19	1,48
97	17	0	001830ed5842	16,78	1,81
98	18	-2	001830ed737a	16,14	2,95
99	18	-1	001830ed4a73	17,87	-1,3
100	18	0	001830ed737a	17,92	-1
101	18	1	001830ed737a	17	-0,77
102	18	2	001830ed5842	18,43	0,52
104	19	-1	001830ed5ac8	17	1,09
105	19	0	001830ed7898	17,81	4,63
108	20	-2	001830ed4a73	19,82	-1,66
109	20	-1	001830ed737a	20,22	-0,66
110	20	0	001830ed5842	20,11	-0,03
111	20	1	001830ed5ac8	20,56	2,45
113	21	-2	001830ed4a73	20,74	-2,44
114	21	-1	001830ed737a	21,14	-0,9
115	21	0	001830ed5842	21,19	0,45
116	21	1	001830ed5ac8	22,02	0,46
117	21	2	001830ed7898	21,24	2,47
118	22	-3	001830ed4e43	21,97	-2,85
119	22	-2	001830ed4a73	21,89	-2,14
120	22	-1	001830ed737a	22,32	-1,21
121	22	0	001830ed5842	22,47	0,11
123	22	2	001830ed7898	22,7	1,82
124	23	-3	001830ed4e43	22,63	-3,47
125	23	-2	001830ed4a73	23,17	-2,32
126	23	-1	001830ed737a	23,02	-1,54
127	23	0	001830ed5842	23,66	-0,32
128	23	1	001830ed5ac8	24,12	0,2

2. Processed position measurements per grid point of the 10s dataset of the second test of 17th of August 2015

grid_id	x_grid	y_grid	tag_id	x_avg	y_avg	x_med	y_med	xy_StdDev	x_StdDev	y_StdDev
2	1	2	001830ed5842	0,995	2,462	1,500	2,745	0,909	0,762	0,496
3	1	3	001830ed737a	1,015	3,780	1,015	3,770	0,065	0,064	0,012
4	1	4	001830ed7898	-0,840	4,815	-0,790	4,800	0,060	0,058	0,017
5	1	5	001830ed4e43	2,580	5,415	2,580	5,415	0,017	0,000	0,017
6	1	6	001830ed4a73	2,110	5,885	2,110	5,885	0,072	0,035	0,064
7	2	1	001830ed5ac8	0,855	-0,156	0,850	-0,160	0,100	0,092	0,040
8	2	2	001830ed5842	2,296	-6,471	2,275	-6,500	0,326	0,065	0,319
9	2	3	001830ed737a	1,990	2,440	1,990	2,430	0,012	0,000	0,012
10	2	4	001830ed7898	2,125	3,660	2,050	3,600	0,111	0,087	0,069
11	2	5	001830ed4e43	2,315	5,085	2,315	5,085	0,029	0,006	0,029
12	2	6	001830ed4a73	0,928	6,569	0,910	6,560	0,786	0,774	0,139
13	3	1	001830ed5ac8	1,441	-1,332	1,410	-1,340	0,145	0,067	0,129
14	3	2	001830ed5842	1,890	0,370	1,860	0,370	0,058	0,035	0,046
15	3	3	001830ed737a	2,783	2,440	2,780	2,430	0,030	0,015	0,026
16	3	4	001830ed7898	2,908	4,170	2,910	4,170	0,027	0,024	0,013
17	3	5	001830ed4e43	3,160	4,915	3,160	4,915	0,006	0,000	0,006
18	3	6	001830ed4a73	3,175	6,370	3,160	6,370	0,017	0,017	0,000
19	4	1	001830ed5ac8	4,143	-0,481	4,170	-0,480	0,110	0,088	0,067
20	4	2	001830ed5842	3,283	0,790	3,320	0,790	0,145	0,138	0,045
21	4	3	001830ed737a	3,765	2,769	3,770	2,770	0,051	0,029	0,042
22	4	4	001830ed7898	3,985	3,876	3,980	3,880	0,019	0,013	0,014
23	4	5	001830ed4e43	4,008	5,094	4,010	5,090	0,032	0,027	0,018
24	4	6	001830ed4a73	4,004	5,521	4,010	5,520	0,022	0,013	0,018
25	5	1	001830ed5ac8	4,178	-1,699	4,180	-1,705	0,172	0,038	0,167
26	5	2	001830ed5842	4,138	0,624	4,140	0,620	0,079	0,025	0,075
27	5	3	001830ed737a	4,733	2,979	4,730	2,980	0,022	0,017	0,015
28	5	4	001830ed7898	5,160	3,795	5,160	3,795	0,006	0,000	0,006
29	5	5	001830ed4e43	5,046	5,065	5,050	5,065	0,025	0,021	0,013
30	5	6	001830ed4a73	4,699	5,638	4,700	5,640	0,035	0,017	0,030
33	6	3	001830ed737a	5,670	2,835	5,650	2,835	0,024	0,023	0,006
34	6	4	001830ed7898	5,950	3,763	5,965	3,750	0,070	0,061	0,035
35	6	5	001830ed4e43	6,180	4,765	6,180	4,760	0,013	0,012	0,006
36	6	6	001830ed4a73	6,010	5,275	5,990	5,270	0,024	0,023	0,006
37	7	1	001830ed5ac8	4,755	-2,120	4,730	-2,050	0,086	0,029	0,081
38	7	2	001830ed5842	7,190	1,535	7,190	1,520	0,017	0,000	0,017
39	7	3	001830ed737a	7,130	2,815	7,130	2,815	0,006	0,000	0,006
40	7	4	001830ed7898	6,915	3,835	6,920	3,840	0,025	0,021	0,014
41	7	5	001830ed4e43	7,252	4,334	7,250	4,340	0,051	0,017	0,048
42	7	6	001830ed4a73	8,059	5,725	7,810	5,710	0,626	0,620	0,088
43	8	1	001830ed5ac8	8,683	-5,693	8,660	-5,875	0,345	0,029	0,344
44	8	2	001830ed5842	7,816	2,139	7,820	2,140	0,042	0,028	0,031
45	8	3	001830ed737a	8,052	2,892	8,060	2,890	0,023	0,018	0,015
46	8	4	001830ed7898	8,045	3,840	8,040	3,840	0,041	0,024	0,032
47	8	5	001830ed4e43	7,956	4,670	7,990	4,690	0,220	0,212	0,060
48	8	6	001830ed4a73	8,210	5,541	8,210	5,530	0,086	0,054	0,067
49	9	0	001830ed4a73	9,653	-0,385	9,640	-0,380	0,076	0,058	0,049
50	9	1	001830ed5ac8	9,674	1,390	9,680	1,395	0,082	0,041	0,071
51	9	2	001830ed5842	8,950	2,197	8,950	2,190	0,033	0,017	0,028
52	9	3	001830ed737a	9,087	2,653	9,090	2,650	0,027	0,013	0,024
53	9	4	001830ed7898	9,110	4,102	9,110	4,100	0,016	0,012	0,010
54	9	5	001830ed4e43	8,020	6,077	8,020	6,080	0,068	0,035	0,058
55	10	0	001830ed4a73	10,800	-1,900	10,840	-1,810	0,106	0,068	0,082
56	10	1	001830ed5ac8	10,025	1,520	10,000	1,510	0,031	0,029	0,012
57	10	2	001830ed5842	10,492	1,983	10,470	2,000	0,082	0,066	0,049
58	10	3	001830ed737a	10,333	2,786	10,330	2,790	0,050	0,038	0,031
59	10	4	001830ed7898	9,724	4,381	9,710	4,390	0,073	0,050	0,054
60	10	5	001830ed4e43	10,089	4,657	10,090	4,660	0,064	0,056	0,032

grid_id	x_grid	y_grid	tag_id	x_avg	y_avg	x_med	y_med	xy_StdDev	x_StdDev	y_StdDev
60	10	5	001830ed4e43	10,089	4,657	10,090	4,660	0,064	0,056	0,032
61	11	0	001830ed4a73	11,705	0,010	11,690	0,012	0,021	0,017	0,012
62	11	1	001830ed5ac8	11,535	1,735	11,535	1,730	0,041	0,040	0,006
63	11	2	001830ed5842	11,780	1,510	11,780	1,510	0,016	0,012	0,012
64	11	3	001830ed737a	11,170	2,980	11,070	2,970	0,116	0,115	0,012
65	11	4	001830ed7898	10,882	4,278	10,840	4,280	0,130	0,122	0,044
68	12	1	001830ed5ac8	12,243	0,360	12,240	0,360	0,062	0,046	0,042
69	12	2	001830ed5842	12,088	2,482	12,170	2,490	0,182	0,166	0,074
70	12	3	001830ed737a	11,233	2,780	11,240	2,780	0,037	0,036	0,009
71	12	4	001830ed7898	12,465	3,831	12,500	3,830	0,119	0,115	0,030
72	12	5	001830ed4e43	11,522	5,608	11,540	5,600	0,072	0,047	0,054
73	13	0	001830ed4a73	12,085	0,408	12,050	0,400	0,225	0,214	0,071
74	13	1	001830ed5ac8	10,803	-3,490	10,790	-3,500	0,141	0,092	0,107
75	13	2	001830ed5842	13,224	2,155	13,230	2,160	0,026	0,021	0,016
76	13	3	001830ed737a	13,191	3,120	13,190	3,120	0,090	0,082	0,036
77	13	4	001830ed7898	13,350	3,982	13,350	3,990	0,032	0,022	0,023
78	13	5	001830ed4e43	11,837	6,197	11,840	6,175	0,038	0,021	0,032
80	14	1	001830ed5842	14,090	1,300	14,090	1,300	0,000	0,000	0,000
81	14	2	001830ed737a	14,050	1,925	14,050	1,925	0,052	0,000	0,052
82	14	3	001830ed7898	13,890	3,015	13,880	3,015	0,021	0,012	0,017
83	14	4	001830ed4e43	14,117	4,227	14,105	4,200	0,035	0,021	0,028
84	14	5	001830ed4a73	13,850	5,660	13,850	5,650	0,012	0,000	0,012
87	15	2	001830ed737a	15,180	1,830	15,180	1,830	0,000	0,000	0,000
88	15	3	001830ed7898	15,125	3,280	15,120	3,270	0,013	0,006	0,012
89	15	4	001830ed4e43	15,260	4,175	15,260	4,160	0,017	0,000	0,017
90	16	-1	001830ed4a73	16,080	-1,258	16,070	-1,260	0,054	0,038	0,037
91	16	0	001830ed5ac8	16,460	0,385	16,390	0,385	0,083	0,081	0,017
92	16	1	001830ed5842	16,313	1,203	16,320	1,210	0,053	0,038	0,038
93	16	2	001830ed737a	17,390	1,135	17,390	1,135	0,006	0,000	0,006
94	16	3	001830ed7898	16,004	2,928	16,000	2,930	0,025	0,021	0,013
95	17	-1	001830ed5ac8	16,773	-0,707	16,780	-0,710	0,038	0,025	0,029
96	17	0	001830ed5842	16,955	0,365	16,940	0,360	0,018	0,017	0,006
97	18	-2	001830ed4a73	17,551	-2,665	17,570	-2,640	0,095	0,049	0,081
98	18	-1	001830ed5ac8	17,920	-1,005	17,920	-1,000	0,013	0,012	0,006
99	18	0	001830ed5842	18,310	0,365	18,330	0,370	0,024	0,023	0,006
100	18	2	001830ed7898	18,198	3,499	18,235	3,450	0,566	0,255	0,505
101	19	-2	001830ed4a73	19,241	-2,052	19,230	-2,040	0,056	0,044	0,035
102	19	-1	001830ed5ac8	19,135	-0,250	19,135	-0,100	0,181	0,052	0,173
103	19	0	001830ed5842	19,232	0,401	19,230	0,400	0,038	0,010	0,036
104	19	2	001830ed7898	19,431	2,806	19,470	2,780	0,228	0,152	0,170
105	20	-2	001830ed4a73	19,773	-1,868	19,780	-1,870	0,033	0,031	0,013
106	20	-1	001830ed5ac8	19,988	-0,788	19,995	-0,755	0,058	0,026	0,051
107	20	2	001830ed7898	20,775	2,654	20,800	2,680	0,107	0,049	0,095
108	21	-2	001830ed4a73	20,793	-1,938	20,790	-1,940	0,043	0,032	0,029
109	21	-1	001830ed5ac8	21,350	-0,834	21,350	-0,840	0,051	0,045	0,023
110	21	1	001830ed7898	21,246	0,759	21,240	0,770	0,069	0,044	0,054
111	21	2	001830ed4e43	21,969	2,975	21,970	2,980	0,157	0,062	0,144
112	22	-3	001830ed5842	21,780	-2,805	21,780	-2,800	0,006	0,000	0,006
113	22	-2	001830ed4a73	21,810	-2,015	21,810	-2,010	0,013	0,012	0,006
114	22	-1	001830ed5ac8	22,390	-1,220	11,195	-0,610	0,000	0,000	0,000
115	22	0	001830ed737a	22,333	0,000	22,330	0,000	0,005	0,005	0,000
116	22	1	001830ed7898	22,055	1,395	22,055	1,390	0,052	0,052	0,006
117	22	2	001830ed4e43	22,590	2,075	22,550	1,970	0,130	0,046	0,121
118	23	-2	001830ed4a73	22,750	-1,945	22,750	-1,945	0,006	0,000	0,006
119	23	-1	001830ed5ac8	23,378	-0,907	23,380	-0,920	0,043	0,024	0,036
120	23	0	001830ed737a	23,486	-0,264	23,490	-0,260	0,084	0,073	0,042

3. Processed position measurements per grid point of the positioning dataset of the third test of 4th of September 2015

grid_id	x_grid	y_grid	tag_id	x_avg	y_avg	x_med	y_med	avg_PA	xy_StdDev	x_StdDev	y_StedDev
92	16	-1	001830ed5ac8	16,115	-0,130	16,110	-0,150	0,861	0,205	0,040	0,201
93	16	0	001830ed5842	15,325	-0,015	15,325	-0,015	0,270	0,010	0,007	0,007
98	17	-1	001830ed5ac8	17,138	-0,672	17,130	-0,680	0,181	0,045	0,034	0,029
99	17	0	001830ed5842	16,929	0,860	16,930	0,870	0,266	0,072	0,022	0,069
100	17	1	001830ed737a	16,712	1,626	16,730	1,700	0,399	0,198	0,054	0,190
105	18	-1	001830ed5ac8	18,139	-1,210	18,140	-1,210	0,162	0,043	0,034	0,025
106	18	0	001830ed5842	18,107	-0,100	18,110	-0,100	0,170	0,034	0,017	0,029
108	18	2	001830ed7898	17,518	3,061	17,615	2,900	1,377	0,871	0,172	0,854
111	19	-1	001830ed5ac8	19,036	-0,960	19,040	-0,960	0,166	0,067	0,052	0,044
112	19	0	001830ed5842	19,167	-0,232	19,160	-0,230	0,124	0,039	0,012	0,037
114	19	2	001830ed7898	19,415	2,137	19,420	2,150	0,299	0,072	0,026	0,067
116	20	-2	001830ed4a73	20,000	-1,956	20,000	-1,950	0,168	0,074	0,031	0,067
117	20	-1	001830ed5ac8	19,935	-0,858	19,930	-0,860	0,150	0,044	0,023	0,037
120	20	2	001830ed7898	20,425	2,328	20,420	2,320	0,344	0,120	0,035	0,114
122	21	-2	001830ed4a73	20,952	-1,730	20,950	-1,720	0,147	0,066	0,034	0,057
123	21	-1	001830ed5ac8	21,091	-1,064	21,090	-1,060	0,138	0,038	0,016	0,034
125	21	1	001830ed737a	21,406	0,883	21,390	0,885	0,209	0,069	0,049	0,049
126	21	2	001830ed7898	21,585	2,405	21,590	2,410	0,305	0,043	0,033	0,027
128	22	-3	001830ed5842	21,996	-3,289	22,000	-3,290	0,246	0,022	0,021	0,006
129	22	-2	001830ed4a73	22,008	-1,784	22,010	-1,780	0,149	0,041	0,023	0,034
130	22	-1	001830ed5ac8	22,085	-1,158	22,090	-1,160	0,137	0,028	0,018	0,022
131	22	0	001830ed737a	22,656	0,620	22,660	0,620	0,199	0,037	0,022	0,030
132	22	1	001830ed7898	22,271	2,118	22,260	2,120	0,456	0,032	0,031	0,008
133	22	2	001830ed4e43	23,305	1,503	23,300	1,500	0,897	0,038	0,036	0,012
135	23	-2	001830ed4a73	22,741	-2,334	22,740	-2,330	0,146	0,031	0,026	0,018
136	23	-1	001830ed5ac8	23,343	-0,923	23,340	-0,920	0,154	0,027	0,018	0,020
137	23	0	001830ed737a	23,278	-0,049	23,270	-0,050	0,190	0,029	0,024	0,016

Appendix B: Proof of Concept

A proof of concept can be carried out to monitor the daily routine of the assets in the hospital. Due to external aspects it is not possible to install the system and do tests in the hospital. The main focus of this Proof of Concept (PoC) is to make the locations of the IV pumps visible to the staff in real time. The proof of concept is supposed to be carried out at the Acute Opname Afdeling (AOA) in the Rijnstate Hospital in Arnhem. The use case defined in section 2.2 forms the basis for this PoC. .

Assumptions based on literature and case studies

To be able to locate the IV pumps and stands at the wards and in the storage room there need to be *locators* installed at these two locations. The assumption is made that the pumps do not become missing between these two places. Both areas need to be covered by the *locators* to be able to pinpoint the asset at a higher scale level than just the room where it is in (Beaconing). Therefore it is important to select the right clustering level for each location type. From the dashboard made available by Quuppa the system returns the location of an asset carrying a *tag* on a map in real time (RT). The *locators* can also be used to simply detect the asset entering or leaving a specific location (e.g. the ward or the supply room).

Table 15: Desired scale level for each *tracking area*

Area	Desired scale level
Hospital ward	
Patient room	<1m
Storage area	Beaconing
Central distributing room	<0.5m

RT Analyses of position data

For the use case, positions are measured in and around the ward and the supply room. The (geospatial) tools to make the data available and perform RT analyses will be described in this part. Three situations that can occur in the routine of using the IV pumps and stands in the hospital are 'In use', 'Not in use', 'Missing'. Below, these three situations are described including suggestions for RT analyses.

In use: The asset does not move, which means that it should be detected by the same scanner(s) for a longer (at least 1 hour) period of time. The asset is also localised by one of the *locators* on the ward. A possibility for RT analyses after localization is to detect when the asset is in use. In this case it should be connected to a patient. The patient is probably in bed in one of the rooms on the ward or in the neighbourhood of the nursing room. To be able to detect an asset in this state a geofence can be created that covers only the nursing rooms and its near surroundings.

Not in use: The asset remains in the same location for a longer amount of time. An IV pump that is not in use should be at the supply room or at the ward (not in a patient's room). The most ideal situation would be if the used pumps are stored in a room that can be geofenced to distinguish the 'not in use' pumps from the 'in use' ones. In the supply room all pumps are 'not in use' by default, however there are still two groups of pumps that need to be identified by the system. One group is the used, dirty pumps, the other one is the group of pumps that has been cleaned and is ready to be used again. Depending on the layout and routine of the supply room it should be possible to distinguish the one group from the other. To detect whether a device is entering the room or leaving, which implies the device is dirty or clean. This way a record can be kept of the stock. Another analysis tool is a counter, which simply counts the number of assets being detected by a *locator*. The distinction between the clean and dirty pumps should be made based on the specific location of the device. Assuming that all dirty devices are grouped in one separated place and all clean devices are grouped at another place.

Missing: The asset is not available for use. This can be identified by the system when an asset is not detected by one of the *locators* for a significant amount of time, for example 3 days. Possibilities for RT analysis are creating a geofence of the areas where the device will be 'in use' or 'not in use'. If an asset is not detected in one of these areas for a certain amount of time, the asset is reported missing and the manager will receive an alert. These situations are based on the daily routine of using the IV pumps. A description of four examples is given below, along with the localization possibilities of the Quuppa system. These examples are based on the problems that the staff, involved in distributing the pumps, runs into day in day out.

Conclusions for localization results

I: Hoarding of IV pumps
Medical equipment, e.g. IV pumps, is often needed on short notice or in an emergency situation. The process of making a request for a pump and having it delivered takes a fair amount of time. For this reason the nursing staff makes a request for a larger number of pumps than needed in order to have some spares already on the ward in case they run out. Because of this, the central supplier loses the overview of the available pumps in their inventory. Pumps that are not in use are hoarded at a certain ward, while another ward that makes a request for a new pump may not get one because the supplier has none available. Being able to locate a pump in a (part of a) room can solve this problem.

II: Status of the pump is unknown
When a pump is brought to a ward that made a request, it is unknown for how long the pump will be in use. The staff of the central supply makes a couple of rounds a day to collect all the used pumps from the wards to fill the stock. At this moment the used pumps are collected at a specified location on each ward. The information that should be made available to the supply staff is the number of used pumps at every ward. In other words, the amount of pumps that is stored in the storage spot should be available to the supplier in real time. To provide this information, the location and the status of the pumps (used/not used) should be available.

III: IV pumps 'disappear'
By default, a pump request is made through the Ultimo system and the pump is delivered to the ward that made the request. When the nursing staff is in need of a pump and wants to get around the system they might borrow a pump that 'belongs' to another ward. When the pump is not returned to the ward it was taken from, the current Ultimo system cannot keep track of the location of the pump anymore. In addition to the location of the pump, attributes for the ward it was assigned to and the time it leaves a certain known location (e.g. distributing room) should be added. Pumps that are localized outside the dedicated locations for a longer amount of time can be reported as missing and collected by the staff.

IV: Supply room cannot meet the demand
Because of the issues stated above, the central supply cannot meet the demand for new pumps at all times. A patient that needs an IV pump will have to wait for one to become available, while in fact there are some pumps that are not in use at another ward. Improvements can be made in knowing the location of each pump and being able to predict the availability of the stock. A solution for this problem suggested by the hospital management is to assign a certain number of pumps to each ward. If the location of all pumps is known, the staff can check the availability of clean pumps on other wards. A 'low in stock' alert can be send to the maintenance staff to take action and restock.

Pilot setup: IV stands/pumps in AOA Rijnstate
The current process of issuing the IV pumps is described in section 2.2. At this moment a registration system called 'Ultimo' is used to show the status of the pumps and give alerts when maintenance is needed. When the location of the pumps is provided by the Quuppa system, this information can be added to the information provided by the Ultimo system and the services of the 'Ultimo' system can be integrated into another dashboard. For installing the *locators* of the Quuppa positioning system on a larger scale, an extended star network topology is recommended. This implies that the *locators* from one wing of the AOA ward are connected to a separate switch. The switches of all three wings are connected to a fourth switch which is plugged into the Quuppa Positioning Engine (QPE). In Table 16 the hardware needed to set up the full PoC is shown. The items indicated by * are only taken into account for the Area of Interest (AoI). Infrastructure that is needed outside the AOA or storage/maintenance room is not included. In Table 17 the amount for a PoC without covering the areas in between the patient rooms and storage/maintenance room is shown. Table 18 gives a detailed overview of the number of *locators* per subarea of the AoI is shown. The amount in the 'number of *locators*' column in italic is dedicated to the difference between the 'full' and 'light' PoC.

Table 16: Amount of hardware for full PoC

Item	Amount
Locators	80
Tags	165
Switches*	4
Ethernet cables [m]*	455m
Wings	330m
Cross	125m
PC (server)	1
Quuppa Licence	PRO

Table 17: Amount of hardware for PoC 'light'

Item	Amount
Locators	53
Tags	165
Switches*	4
Ethernet cables [m]*	275m
Wings	275m
Cross	-
PC (server)	1
Quuppa Licence	PRO

Table 18: Detailed specification of the number of *locators* per room for the PoC

Location	Room	Count	Number of *locators*
AOA	**Wing 2**		
	1p	2	2
	1+p	5	10
	Other room types	4	*4*
	Hallway	1	4
	Subtotal		
	Wing 3		
	1p	2	2
	1+p	6	12
	Other room types	4	*4*
	Hallway	1	4
	Subtotal		
	Wing 4		
	1p	4	4
	1+p	5	10
	Other room types	4	*4*
	Hallway	1	3
	Subtotal		
	Cross		
	Other room types	10	10
	Hallway	5	*5*
	Subtotal		
Storage	**Storage room**	1	1
	Maintenance room	1	1
	Total		**80**

Appendix C: Reflection

The subject of this master thesis, indoor localization, is an emerging topic for research. Knowing and sharing your location has become easier because of the popularity of smartphones and other GPS enabled devices. Navigation systems have changed the way people move through public space as way finding is no longer based on habits and trial and error, but on a mathematical approach to reach a destination. Instead of sharing your location with others by verbal communication, smart devices should be able to do this automatically based on a 'trigger on event' mechanism. Since the conventional (outdoor) positioning technology of GPS doesn't work in indoor environments, other technologies and applications are needed for indoor positioning.

The field of Geomatics can contribute to solve the problem of indoor localization by doing research on wireless technologies available indoors and localization methods. This research has contributed to the latter part as a method for localization of assets in a hospital environment was developed. In addition to the results of the analysis of the positioning system information about the architectural lay out of the indoor environment was used for the design of the localization model. The results of this project can be used for developing an indoor tracking system for localization of assets. The definition of location types and clustering can be used for development of indoor navigation applications.

The master track Geomatics for the built environment covers the acquisition, management, analysis and visualization of geographic data. The data acquisition in this project consisted of the three tests that were carried out collecting the position data of the Quuppa system. The functionality of a DBMS was used to construct the dataset in such a way that it could be used for processing and analysis. For analysis and visualization Esri's ArcGIS for Desktop software was used. The maps in analysis part of this thesis document are made using the interpolation tool and other geospatial analysis functionality of ArcMap. All images with respect to the Quuppa system and its technology are taken from the software and documentation made available by Quuppa.

This graduation project was done within a 6,5-month internship at CGI Nederland in Rotterdam. The entire project had a duration of 8 months and started with a definition of the scope and research questions preliminary to the internship. The scope of the project was predetermined by CGI since they provided the use case of localization from collaboration with the Rijnstate hospital in Arnhem and the positioning technology of Quuppa's. Due to organizational and practical issues the data acquisition had not started until halfway through the project. The processing and analysis part has taken more time than planned, which has limited the possibilities to develop the model for localization into a working prototype.

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Cover photo:

http://modmedsys.com/dev/wp-content/uploads/2014/02/bigstock-Operating-Room-5634793.jpg