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Real-Time Indoor Location Tracking in Construction Site Using BLE Beacon Trilateration

Master's Thesis
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ABSTRACT OF
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A real-time indoor location tracking system prototype for construction site resource tracking was developed in this Master's Thesis. The positioning technology used was Bluetooth Low Energy Beacons and the method was trilateration. The prototype developed in this work is built upon a simpler version of a location tracking system prototype developed in iCONS research project in Aalto University. The contextual purpose of this work was to investigate in which ways a coordinate level indoor positioning system could enhance production control in construction. The lean construction philosophy is the theoretical background of this research topic.

The Design Science research method was followed. The process of implementation was documented in detail. The prototype was tested in a construction site to determine the location of a person carrying a BLE beacon. The accuracy turned out to be around 10 meters at best when there was least movement. Various aspects other than accuracy have also been evaluated, and ideas for improvement are presented.

The value and the applications of an ideally working coordinate level real-time location tracking system for construction production control was assessed in light of the research literature and the experience gained from creating and testing the prototype. Such a system would have a significantly positive impact on the productivity, transparency, and safety in construction.

Keywords:	BLE beacon, BLE trilateration, RTLS, lean construction management, construction production control
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Tässä diplomityössä kehitettiin reaaliaikainen sisätilapaikannusjärjestelmä rakennustyömaan resurssien seurantaan. Paikannustekniikkana toimi Bluetooth Low Energy (BLE) -majakat ja niiden paikantaminen trilateraation avulla. Työssä kehitetty prototyyppi rakentui Aalto-yliopiston iCONS-tutkimusprojektissa kehitetyn yksinkertaisemman paikannusjärjestelmän päälle. Tässä työssä tutkittiin, millä tavoin koordinaattitason sisätilapaikannusjärjestelmä voisi parantaa tuotannonohjausta rakentamisessa. Lean-rakentaminen on tämän tutkimusaiheen teoreettinen tausta.

Design Science -tutkimusmenetelmää sovellettiin tässä työssä. Menetelmän mukaisen artifaktin toteutusprosessi dokumentoitiin yksityiskohtaisesti. Prototyyppiä testattiin oikealla rakennustyömaalla BLE-majakkaa kantavan henkilön sijainnin määrittämiseksi. Tarkkuus ylsi parhaimmillaan noin 10 metriin, kun liikettä oli vähiten. Tarkkuuden lisäksi järjestelmän muita aspekteja on myös arvioitu ja parannusideoita esitetty.

Ideaalin reaaliaikaisen paikannusjärjestelmän arvoa ja sovelluksia rakennusalan tuotannonohjauksessa arvioitiin sekä tutkimuskirjallisuuden että prototyypistä saadun tiedon valossa. Tällaisella järjestelmällä olisi merkittävä vaikutus rakentamisen tuottavuuteen, läpinäkyvyyteen ja turvallisuuteen.

Asiasanat:	BLE-majakka, BLE-trilateraatio, RTLS, lean-rakentaminen, rakentamisen tuotannonohjaus
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Abbreviations and Acronyms

BIM	Building Information Modeling
BLE	Bluetooth Low Energy
LBMS	Location-Based Management System
LSE	Least Square Error
MQTT	Message Queuing Telemetry Transport
RasPi	Rasberry Pi
RSSI	Received Signal Strength Indicator
RTLS	Real-Time Locating System
TPTC	Takt Planning and Takt Control
UWB	Ultra Wide Band

Contents

Chapter 1

Introduction

It is a fact that construction projects in different parts of the world suffer significantly from delays and cost overruns. The planned schedules are rarely successfully followed [23] [3] [9]. As a traditional labor intensive industry, construction industry in America, Europe, and Finland has been slow in investing on digital innovations and applying them compared to many other sectors in the last twenty years [39]. In Germany and Great Britain, the labor productivity of construction has lagged behind the total economy by 20 percentage points between 1995 and 2014 [1].

The reasons for bad schedule adherence in construction are many. Construction projects are by nature physical and involve high degrees of complexities in terms of logistics, materials, and labor. In addition, there are also social, economical, cultural, and environmental complexities which depend on the circumstances. E.g., there could be bad weather or language barriers among international workers from various trades. These kind of complexities are hard to predict, as the construction field and its actors are heavily scattered. There are also high mobility rates because of prevalent subcontracting. [16] [5] In Finland, the proportion of foreign labor in building construction has increased from 10 percent to 20 percent between 2009 and 2019, and meanwhile, the proportion of workers through subcontracting has increased by 27 percentage points. [44] The problems in construction production tend to belong to the class of *wicked problems* that do not have a single optimal solution [8].

Nevertheless, much of the complexity in a construction process can be handled with control actions once the situational picture is sufficiently known. [20] This type of decision-making that affects directly the value-adding work on site is known as *production control* (used as synonym for Project Production Management (PPM) as defined in [42]). Since there will be unpredictable scenarios in any real construction project, it means that it is not enough to have a ”perfect” plan from the beginning, but even more important to maintain an up-to-date situational picture of the construction site [9].

This leads to the topic of this Master’s thesis, because to have a real-time indoor location tracking system for the construction site *is* to enhance the situational picture of the construction site. This thesis is about a particular implementation of a particular indoor positioning technology applied for construction site. It is meant to fit into the wider context of the digitization of construction site.

1.1 Digitization of Construction

Significant steps of digitization have been taken in the tools of architectural and structural design since 1980s.*Computer Aided Design* (CAD) have been evolving into *Building Information Modeling* (BIM). BIM carries not only geometrical and physical information but also other information spanning across the life-cycle of a building, including costs, scheduling, construction, and maintenance. [4] BIM provides great potentials for many aspects of construction project management and beyond, such as BIM-based safety management during construction [36] and construction life cycle maintenance through BIM [17] [24].

Despite of the potentials, as we move from the realm of building design, i.e. architectural design and structural design, to the realm of building construction in action, digitization is still far from maturity [60]. This is partly explained by the fact that building as a *process* is, in a sense, clearly more dynamic than building as an object; there is simply more ambiguity and less control in producing a building than in designing a building. However, the problem has been acknowledged. In the EU, the US, Canada, Brazil, Japan, Korea, Australia, and New Zealand, both the government and the construction industry itself have taken the digitization of construction industry through the use of BIM as a strategic objective with large investments [39] [60]. Some predict that the construction field is ready for a digital disruption. The advancements in the digital infrastructure, especially with wireless networks and the coming of 5G and the Internet of Things, has laid foundations for the unprecedented vast collection and processing of construction site data for the benefit of increasing the productivity of construction. [1]

The theoretical background that provides a reason for developing digital solutions in construction is found in the *lean construction* philosophy. It deals with the idea of production waste, which originates from the automobile industry of Toyota. [56] *Lean construction research* has been focusing on how to reduce *waste* in construction. Here *waste* is defined broadly as anything that does not increase value for the customer [29]. Examples of such wastes include the waiting times of the workers and the materials, the overestimated quantities of materials brought to the construction site resulting in left overs, and the unnecessary movement of materials, and etc.

Simulations have shown that the lean principles have the potential to reduce different kinds of waste in construction, such as reducing the mistakes and improving the workflow [41]. Beyond simulations, the lean construction philosophy has given birth to various practical systems that directly address the construction production control. These systems are frameworks, methods, and tools that directly shape the daily operation on site, forming best practices and habits. Successful examples include Last Planner System (LPS) [57], Location-Based Management System (LBMS) [43], Takt Planning and Takt Control (TPTC) [38], and Third Party Logistics (TPL) [50] [18]. These systems that apply lean principles have succeeded to reduce construction waste in real projects. Some of them have been implemented as commercial software, while others have so far been implemented as prototypes.

1.2 Location Information on Site

Lean construction theorists have paid special attention in location information. Behzadan et al (2008) identifies the location information as a central element of a user's (e.g. a construction worker's) context in a construction site [7]. A worker's context is the key for determining the relevant information for him at a given moment. The context is like a mental model that the worker needs in order to work. Such a context could be value-adding task (e.g. drywall installation) that needs to be done with specific standards, with a set of available tools, and within a given time constraint. Determining and maintaining such contexts for each worker is not trivial. Up-to-date location information of a worker is a prerequisite (though not sufficient) for it. Same applies to materials and equipment. Although they are not independent actors possessing free will, they still have a location and purpose in the construction site.

Sacks (2016) suggests that improving the *location flow* has the greatest potential for improving the overall construction production flow [54]. LBMS and TPTC, which are location-based methods targeted to improve the location flow (as defined in [54]) in construction, have proven to be effective in real construction projects as they have succeeded in reducing wasted effort (as a *type* of construction waste in lean construction terminology). Both treat the location as a unit of analysis [34] [21][38]. For example, a case study in

Brazil succeeded in reducing the project duration from eleven to six months with TPTC [15].

Given the proposed essential role of location information in lean construction, it follows that the location information of the resources (the workers, the materials, and the equipment [11]) in the construction site is highly valuable. It provides a considerable advancement in maintaining an up-to-date situational picture on site. Such information has the potential to serve various objectives related to logistics, schedule adherence, safety etc. [66]. With real-time location information, the overall progress could be better monitored, which would help to make more accurate control actions and more reliable forecasts during construction. This would mean significant reduction of construction waste in many ways, which would increase the total productivity.

Location information can be valuable also in retrospect. Having a record of how the resources have moved in the construction site throughout the project provides an access to the project history in an unprecedented way. In principle, this could make construction process completely transparent, which could, together with an appropriate usage of BIM, benefit the life cycle management of a building. [4]

1.3 Thesis Background: iCONS

The background of this thesis is in the iCONS (*Intelligent Construction Site*) research project led by Aalto University in collaboration with several other universities and companies from the construction field in Finland, China, the United States, and Brazil. The organizations involved in this project formed a consortium with a common goal of developing means to reduce construction waste, aligning well with the lean construction philosophy. The real-time location tracking of resources was among the emphasis of iCONS. [59]

iCONS started from the well identified problem: there was a lack of real-time situational picture in construction production. To address this issue, Aalto University developed a prototype of real-time location tracking which was used in various research use cases within iCONS [65] [66]. This prototype used BLE beacons and Raspberry Pi (RasPi) mini-computers as hardware (see Figure 1.1). BLE beacons worked as mobile tags whose location was to be determined, while the RasPis worked as fixed gateways whose location was known and was used as reference points to determine the locations of the beacons. This prototype records the location of a beacon based on its proximity to a nearby gateway. The BLE beacons were of the size of 2 euros coins. The RasPis (which were of version 3) had the dimensions of 9 cm x 5 cm x 2.5 cm with the covers.

In addition to the iCONS prototype, the trilateration based prototypes presented in [45] [48], and the conceptualizations in [7] kindled a research interest to pursue trilateration with BLE.

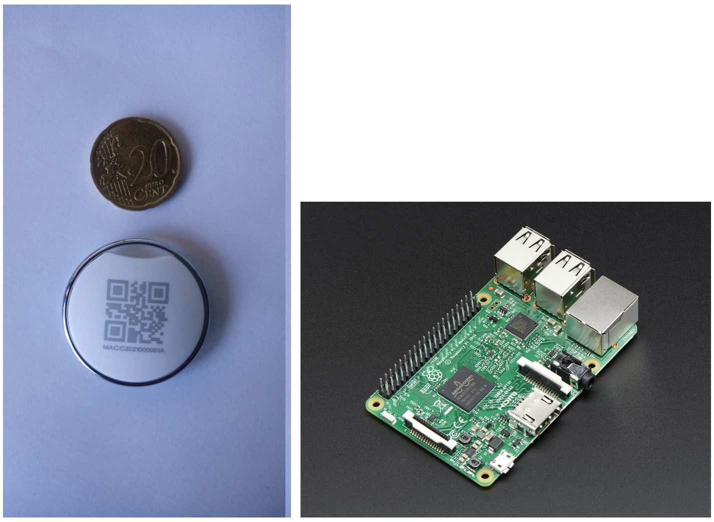


Figure 1.1: System hardware: BLE beacon and RaspPi

1.4 Research Objectives

Inspired by the prototype developed in iCONS, there emerged an ambition to develop the iCONS prototype further. So far the prototype recorded the location of a BLE beacon as the assigned area of the nearest gateway. The gateways and their corresponding areas were determined for each case study. The layout of the construction site largely determined where it was feasible and meaningful to put gateways. Usually a gateway represented a room, an apartment, or some other logical area.

Seeing the benefits and the potentials of the original prototype for advancing production control, it was only natural to pursue a higher granularity for location tracking. An iCONS consortium partners from China was interested in having a location tracking system that could track the coordinates of a worker for safety management purposes. This could be theoretically achieved by trilateration as long as the signal of a beacon is received by three or more gateways whose coordinates are known. The mathematical principle is simple, but implementing it on top of the existing prototype would require dedicated effort. This turned out to be a suitable topic for a Master's thesis as a continuation of the promising iCONS research. As the iCONS research project had already approached its end, another research project, DiCtion (Digitalizing Construction Workflows), was initiated to succeed iCONS. The research done in this thesis was conducted within DiCtion. Upgrading the prototype to a next level of accuracy would benefit further research efforts and open up new opportunities for case studies on resource tracking and other related topics on construction sites.

1.4.1 Research Questions

This thesis attempts to upgrade an existing location tracking system while studying and searching for useful applications for it in the lean construction context. To claridy the idea of this thesis, let us break down the main title of this thesis, *Real-Time Indoor Location Tracking in Construction Site Using BLE Beacon Trilateration*, into parts and examine the implications of each concept.

Real-Time implies that the information needs to be received without or with very little delay. Delayed information have less worth for maintaining a situational picture.

Indoor Location Tracking. Most of the work happens indoors, especially after the structural phase. GPS is not available indoors because of the obstruction of signals [51] [48]. Also, GPS does not really cover the z-axis (i.e., the height).

Construction Site is a dynamic environment in which changes ought to happen every day. The kind of changes and the size of changes vary depending on the phase and task. E.g., tasks during the interior phase are of smaller scale than that during the structural phase.

BLE Beacon uses the frequency range around 2400 MHz. [22] BLE was considered to be suitable for its cheapness and simplicity. The beacon transmits a signal every second. The iCONS prototype uses BLE beacons with iBeacon protocol developed by Apple. [58].

Trilateration is a mathematical method to determine the position of a point based on its distances to three other known points (see Figure 1.2). A beacon signal received by a gateway has a *received signal strength* (RSSI) value which can be translated into a distance. This makes it possible to implement trilateration with the same hardware used in iCONS.

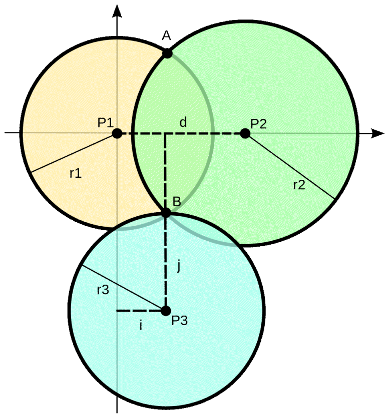


Figure 1.2: Trilateration in xy-plane; distances r_1, r_2, and r_3 can be known from the respective RSSI values.

Given the introduced background, this Master's thesis attempts to answer the following two research questions:

RQ1. **How does trilateration increase the accuracy of a previous real-time indoor positioning system using BLE beacons in a real construction site?**

RQ2. **What additional values can the trilateration of BLE beacons bring to the production control of construction?**

RQ1 aims to compare the accuracy of the to-be-developed trilateration based location tracking system to that of the previous system used in [65], which is based on the detected proximity of the nearest gateway. RQ1 will be answered by a test case conducted in a real construction site. Location data produced by the two systems will be collected simultaneously and then analysed and compared. RQ2, while using the results from RQ1, goes beyond this test case and looks for answers from research literature and other field-related sources.

1.4.2 Thesis Structure

Chapter two provides a literature review on lean construction, location information in construction site, and indoor positioning technologies and algorithms. Chapter three presents the method used in this research. Chapter four depicts the implementing of the artifact. Chapter five narrates the testing of the upgraded prototype in a real construction site. Chapter six evaluates the results and the knowledge contribution. Finally, Chapter seven concludes with directions for further research.

Chapter 2

Literature Review

The purpose of this chapter is to form an extensive understanding of the current state of indoor location tracking in the construction context. Here we will review the research literature on this topic. The research literature can be roughly classified into two main categories that complement each other: literature about lean construction management and production control and literature about indoor positioning technology as such. The second category provides the technical tools for bringing solutions to the problems identified and clarified in the first category. Some sources fall on both categories, and others only touch them slightly.

2.1 Lean Construction

In Chapter 1, we presented that the central aspiration of lean construction, originating from manufacturing, is to reduce waste. Here, let us look more closely into the philosophy of lean construction. Bertelsen and Koskela (2004) synthesizes the characteristics of lean construction and argues that lean thinking in construction has to go beyond the lean thinking in manufacturing, from which it was adopted originally [8]. The idea is not that the lean principles derived from manufacturing do not apply in construction, rather, that those principles alone are insufficient for construction industry. The *five principles of Lean Production* presented by Womack and Jones (1996) are the following:

1. *Specifying value by specific product*
2. *Identifying value stream for each product*
3. *Making value flow without interruptions*

4. *Letting the customer pull value from the producer*
5. *Pursuing perfection*

The first and the last principle are quite general, but the rest of them (nro. 2-4) target to the optimization of flow. Now, in manufacturing the value stream has a more or less sequential structure; work and processes are following one another in a strict order. From this setting it is quite intuitive to apply the nro. 2-4 principles. The Value Stream Map of manufacturing is easy to visualize as a sequence. The pulling of value means that it is the customer's demand for a unit of a product that turns on the production stream. This principle prevents overproduction and the costs caused by it.

However, in construction there are many parallel value streams that coexist and eventually converge. The structure of the value streams in construction include sequences, but their structure resembles more of directed networks with a single end-node representing the final deliverable building. For value streams with complex structure, the application of the principles nro. 2-4 becomes rather abstract and is hard to visualize in 2D. So this is the limitation of the traditional manufacturing based lean thinking. Construction seems to dwell in a higher dimension than manufacturing.

2.1.1 Complexity, Flow, and Location

Bertelsen and Koskela (2004) define the construction production: *"Construction is a complex production of a one-of-a-kind product undertaken mainly at the delivery point by cooperation within a multi-skilled ad-hoc team."* [8] Out of this definition the complexities of construction can be outlined. The *one-of-a-kind product* already differentiates construction from manufacturing. Buildings are unique instances which are complex as such. The *ad-hoc teams* means that the teams are usually put together for one specific occasion. This common practice is caused by the non-constant project based schedules of construction. *Delivery point* means that the building is built where it stands. It is not a portable object.

Due to the complex nature, Bertelsen and Koskela (2004) suggest that construction production becomes a *wicked problem*, meaning a problem that cannot be exhaustively solved and therefore does not have a single correct solution. They claim that such problems should be solved by consensus among the stakeholders, preferably as many as possible to enlarge the ownership of the decision. [8] Bertelsen and Koskela (2004) and Bertelsen and Sacks (2007) propose that construction projects should be regarded not as a fully predictable, linear, and ordered system that can be effectively optimized to the smallest detail from top-to-down before the construction has begun. Rather, they should be regarded as inherently dynamic and complex phenomenon that depends on a situational bottom-up management across the project duration. [8] [9] This brings the necessary emphasis on adequate social interaction, which leads the workers from different trades towards self-organization, spontaneous co-operation, and mutual learning. This does not deny the inevitable need for compromises on site. Bertelsen and Koskela (2004) call it *Management as co-operation and learning.* In practice, the purpose is to tackle the vast complexities of a construction site as locally as possible, at best between individuals. Henrich et al (2007) also points out the complex nature of construction projects and rejects the deterministic management methods that neglect the changing nature of construction environment and the human factors [26]. These lean construction thinkers purposefully bring the social aspect into the big picture, utilizing the intellect of people to tackle the extra complexities of construction compared to manufacturing. Such emphasis on social factors are found in Takt Planning and Takt Control (TPTC) and Last Planner System (LPS), both being management methods following the philosophy of lean construction [21][57].

Previously we discussed the optimization of flow as the main objective of the Five Principles of Lean Construction. Sacks (2016) compares and contrasts the production flow in manufacturing and production flow in construction and formulates the characteristics of good construction flow in theory [54]. He borrows much vocabulary from manufacturing, but transforms the theory of flow in manufacturing into a theory of flow in construction. The concepts of *product flow* and *operation flow* are distinguished from manufacturing. The former means the flow of how the raw material(s) transform into the product by going through different intermediary forms; it is a work flow in which 'work' is a *noun.* The latter means the flow of the operations done to the materials that transform them gradually into the final product; it is a work flow in which 'work' is a *verb.* The success of waste reduction in manufacturing lies in the separate analysis and optimization of these two different streams of flow. In factories, operation flow constitutes from successive work stations at fixed locations, and the product flow occurs as the movement of the materials through all the work stations on an assembly line. Operation flow is fixed and product flow is moving. In construction, it is vice versa: operation flow is moving (as workers move across the building under construction), while product flow occur in fixed locations. The building and the rooms do not change their locations, but the work (operations) performed on them by the workers move across the whole product, which is the building itself. From this theoretical background, Sacks suggests that improving the operation flow as a flow of locations has the greatest impact for improving the total production flow in construction, because it is the most neglected aspect. [54]

Kenley and Seppänen (2010) present the Location-Based Management System (LBMS) for construction. It treats location, i.e. spaces of a building, as the unit of analysis. The building is broken down into a hierarchical location breakdown structure (LBS), and the scheduling of different tasks, with the consideration of the needed material quantities, are made based on the five-layered logical relationships between the different tasks and their corresponding traders. [35] The Critical Path Method (CPM) is a project management and control method that has gained much popularity within construction in recent decades. The idea of CPM is to calculate a critical path for a project, i.e., the shortest possible duration for accomplishing a project when considering all the tasks involved in it [43]. LBMS contains CPM, but offers more because of the layered-logic. [34] LBMS is essentially a tool for practicing lean construction. It also goes hand in hand with the theory of achieving location flow in construction [54] and in a continuous manner for each traders [34]. Takt Planning and Takt Control is also a production control system for construction. Although it is not regarded as a *location-based method* as such [21], it still implements the location flow in construction. It does to in a bottom-up rather than a top-down fashion that is a characteristic of LBMS [21]. Last Planner System (LPS) is pull production control method, which targets at removing project constraints through social processes, such as weekly meetings for creating detailed plans only for the upcoming week. LPS, with its social interactions, complements LBMS by bringing agility to production control through bottom-up approach. This way the top-down and bottom-up methods converge with effective synergy. [57]. Olivieri et al (2019) compares CPM to LBMS and LPS through a survey reaching 532 construction professionals from Brazil, China, Finland, and the US. One of the supported hypothesis was that LBMS and LPS both supported and improved production control in construction. On the other hand, CPM was primarily used in construction projects because of contractual requirements, so its focus is not in production control in the first place but rather in other aspects of project control. [42] Compared to CPS, LBMS reduced the number of mobilizations and demobilizations by 14-37 % [43]. These results support the claim of Sacks (2016) that with acknowledging the location flow the overall work flow (both as *noun* and as *verb*) can be significantly improved [54].

Understanding the theoretical significance of location to construction flow invites for practical solutions fostering it. Sacks et al (2017) introduces a metrics called *construction flow index* (CFI). CFI measures various aspects of flow. It measures the adherence of the actual production flow to the planned one, and also the degree of continuity of trades and their locations.

[55] Borrowing the terms from Sacks (2016), the overall product flow (of how locations in a building become ready through different mutually dependent operations) is improved by improving the operation flow (of how the workers move from one location to another) across locations. Given that the operation flow in construction site moves across the locations, this requires the ability to track the location information of operations, i.e., the location of the human and material resources that perform the operations. CFI also relies on the ability to measure resource locations. This topic has been studied in Zhao et al (2018a) and Zhao et al (2018b) (see Chapter 1.3) [65] [66], which influenced the background of this thesis.

Zhao et al (2018b) conducted various case studies in which the workers' location data in the construction site during the interior construction phase was recorded and analysed. Beacons were given to the workers who participated in the case study, and the gateways were installed across the construction sites so that each gateway represented a specific area. During the case studies, the beacons were detected by the gateways and each beacon at each moment was distinctively associated to the gateway whose received signal strength indicator (RSSI) from that beacon was the greatest among all the gateways receiving signals from the same beacon. Each gateway represented a single location; each beacon could be associated to at maximum one gateway at a single moment; each gateway could have zero, one, or more associated beacons at any moment. The tracking data was recorded and stored in a cloud database, from which it was fetched and analysed. [66]

The results of iCONS case studies (which all used this prototype) revealed interesting facts about the studied construction sites. In average, only 30 % of work time was used for value-adding activities and materials moved six times before they were consumed. It became clear that there was a significant amount of construction waste hidden in bad logistics. The prototype proved to be successful in helping to measure construction waste in the interior phase. [61]

Elsewhere, similar research has been carried out. In fact, this prototype was very similar to one used in Han et al. (2015), which was applied in hospital environment to detect the locations of patients and personnel [25]. Park et al (2016b) was closer with a similar construction context. There, the element of trilateration that was lacking in iCONS researches was applied. The accuracy of 1 2 meters was achieved with BLE technology in together with motion sensors. [45] Furthermore, Park et al (2016a) applies that same system for real-time on-site safety monitoring. [47] Similar applications of utilizing location tracking systems in construction sites are conceptualized in Behzadan et al (2008). There the location information of workers is used even more extensively. [7]

2.1.2 Sub-contracting and Social Aspects

Both Sacks (2016) and Bertelsen and Koskela (2004) point out that the practice of sub-contracting prevalent in construction, which is not the case in manufacturing, brings additional complexity to the production control. González et al (2016) shows that the mistakes by subcontractors is one of the most frequent sources for construction project delays, the second most frequent reason being conflicting plans [23]. Because of specialization, the trade contractors, who are often sub-contractors, often work in several construction projects simultaneously, which means that the workers of a specific trade may be visiting more than one construction site. For handling this dimension of the complexity, Sacks presents a third axis into the dual-axial model of *process* (product flow) and *operation* (operation/location flow) that is *portfolio. Portfolio* axis deals with the managing of one or more construction projects. From its bird-eye-perspective, the complexity of sub-contracting that cross the project boundaries can be seen and possibly addressed. Projects are not isolated systems, but workers come and workers go. [54] Without diving deeper into the inter-project related complexities, let us look into the social aspects of the sub-contracting.

Regarding sub-contracting, while Bertelsen and Koskela (2004) brings in front the dynamic and social aspects of construction, Sacks (2016) seems to be holding a step back, claiming that there is still a lot to optimize in the processes through understanding the flow of production in construction. The former sees subcontracting as a source of complexity that differentiates construction from manufacturing; the latter sees that an unnecessary amount of complexity has been shifted to the subcontractors. The former thinks that subcontractors ought to handle a degree of complexity independently; the latter thinks that subcontractors should not be given too much complexity to handle. However, Sacks does not contradict Bertelsen and Koskela, but rather demonstrates that the theories of manufacturing can still be adopted into construction, despite of the differences, because those differences can be exactly defined and the theoretical leverages can be translated from manufacturing to construction. This is what Sacks's *portfolio, process, and operations* (PPO) model signifies, the formulation of a theory of flow in construction. So we can say that these two papers, in fact, complement each other. With a more robust theoretical foundation for construction flow, the dynamic human aspects emphasized by Bertelsen and Koskela (2004) can be better established. In case of subcontractors, it is both reasonable to think that subcontractors ought to have some independence in planning their work, and that the main contractor should avoid burdening the subcontractors with extra complexities, such as ambiguous schedules.

From a philosophical point of view, the fundamental question is how to balance between top-to-down planning and control and bottom-to-up feedback and self-organization. These two mechanisms easily contradict each other. The better they match each other, the better the project organization will function. The same philosophical question applies to project organizations in any field. In construction it is perhaps a harder question because of its the complexity. The improvement of communication is a generic and yet not a worthless answer to this deep question.

The nature of information in construction is special. Construction site is an environment under constant change. The building gets built in setps, but not in a linear fashion but as parallel, independent, and mutually converging processes. In the end everything needs to match. Such a dynamic process sets certain requirements for the information flow. The reality of a construction itself is objective, and therefore an objective, unambiguous understanding of the state of construction is needed among the stakeholders, for those working on site and for those making decisions outside of it. In other words, an objective *situational picture* of construction progress is crucial [11]. This concerns the product flow in Sack's theory. A situational picture ought to answer the question "how are the things on site in reality?". Another information aspect is *transparency*, which deals with the sharing of the situational picture in order to localise decision making [31].

Increasing the situational picture and the transparency can be significantly aided by information technology, as it allows the sharing of information. This has been demonstrated by the prototypes in [66] [47] [45]. As mentioned in the Chapter 1, IT has decisively entered design fields (architecture, structural engineering) and project management, while is still rather immature in construction production control. Now, it would be naive to think that IT could solve everything problem in production control. No, that is not what we suggest. Nevertheless, knowing its limitations, there are many things that it could improve.

2.1.3 Production Control and IT

The limitations can be found in the nature of complexity in construction. As mentioned in Chapter 1, in construction projects a distinction is made between production control and project control, the latter meaning the management of contracts and contractual requirements [42]. Both belong under the umbrella of project management but are by nature different. Production control influence actions on site, while contracts affect the incentives and motivations of different stakeholders.

In a typical construction site operated by a single general contractor and multiple sub-contractors, some challenges are contract related, and those belong to contractual management. Other challenges are process and construction physics related, and those belong to production control. Construction physics is another term meaning the same as *construction flow* as described in [54], only with a slight difference of nuance [26]. So production control deals with construction physics and tries optimize it.

Adverse contracts are contracts between contractors in which there are underlying conflict of interests, e.g., a contract in which the disclaimer clause shifts the realized risk to one party [64]. Problem occurs when the incentives of different parties do not converge. Adverse contracts lower the threshold to selfish local optimization by a trader in expense of the total project, which can break the process dependencies of other trade contractors and thus hinder the total operation flow of the project. [54]

The underlying conflict of interests may also be more subtle. For example, if the tiling trade contractor gets paid for every accomplished tiling done, it has the incentive to accomplish the tilings as fast as possible, but if tilings are done before the concrete has sufficiently dried in bath rooms, there will be high risks of moisture problems. Once this mistake is noticed, the tilings have to be reinstalled with sufficient time buffer. Such re-work belongs to the kind of *waste* that lean construction seeks to eliminate. On one hand, this requires non-adverse contracts aligning the interests of all contractors together so that the local optimization will never override the total optimization. On the other hand, it requires sound production control that ensures the fluent work flow between the contractors who perform different works that depend on each other in various ways. In this case, the reason for the mistake could have been caused by either one or both of the defective factors (bad contractual incentives, problems in work flow and communication). Lean construction would target to optimize both factors to minimize the waste and the risks induced by it.

The latter problem is something that can be solved through improving production control. Production control influences the value generation of the project most directly, as it it influences *how* the building is built. After the construction project, the building will stand there for decades if not centuries. The posterity will not remember the contractual relationships among the subcontractors, but they will judge the quality of the building.

It is important to acknowledge the appropriate role of information technology in construction context; what is the right place to develop and use it and and what should be the expected solution space for it. Information technology cannot solve contractual problems (although digital tools are surely useful for contract management), but it can help to solve problems in production control, which has been shown in [56]. IT can narrow down the gap between the top-down planning and control and the bottom-up feedback and self-organization through enhancing overall situational awareness and transparent communication.

The construction site situation picture that technology is able to provide can and should be accessible not only to project managers but, to a reasonable extent, to the workers also. Transparent access to this information will enable better decentralized decisions, i.e., local decisions by individual trade contractors which do not contradict the overall production flow but align with it. That way the subcontractors and their workers can participate in the collective design of the project flow. Howell and Ballard (1999) points out that decentralized control will be motivating from workers point of view [29]. Ideally this would result in both autonomous decision making that is coherent with the total situational picture; there would be unity in autonomy.

With today's digital infrastructure (extensive and diverse radio networks, GPS, personal smart mobiles, cloud services etc.), the medium for digital information exchange is extensive and allows the real-time transfer and sharing of unprecedentedly large amounts of data. Two key technologies are pivotal. Firstly, the 4G mobile devices allows the gathering of the situational information remotely. Secondly, cloud services enables the ubiquitous storage and access to that information. Such technologies have been already applied in various lean construction production control softwares, including VisiLean [13], SiteDrive and Congrid [2]. In reality and in the end, production control is about human decisions, but technological tools ought the help this human decision-making process. That is the proper role of IT.

2.1.4 Sustainability

Another aspect of lean construction is sustainability. Construction industry is a major consumer of natural resources, especially materials and energy. Thus reducing the waste it generates has a significant impact on sustainable development from a global perspective. Urbanization has accelerated the construction industry globally. Many have acknowledged the environmental impact of construction in addition to the economical impact of it [37] [30]. In European Union, construction industry generates 40 % of man-made waste and buildings consume over 40 % of the total energy consumption in 1998 [30]. Much of the environmental impact occurs during the life-cycle of a building, but the impact of the construction phase should not be underestimated. A building that is built with deficiencies will end up generating significantly more costs afterwards, especially if also considering the indirect consequences, e.g. health issues caused by moisture or mould problems.

The potential of IT in construction also reaches the sustainability dimension. Through the improvement of production control, less natural resources will be wasted if quantities can be estimated more accurately. Also the life cycle management improves with sensor data. With the sensor data indicating key values during a construction process, it becomes possible to record a digital 'history' of the construction process. Imagine a scenario: ten years after a building is built, mould is detected from a corner of a room. Then if a digital history of the construction process exists, one can check the work conditions from the data records and make more accurate diagnosis of the defect.

2.2 Indoor Location Tracking and Construction Management

As the importance of the location information on construction site has been widely discussed in the previous chapter, let us continue with the technicalities of location tracking. Indoor location tracking with BLE has been a popular research topic in the past decade. Compared to many other technologies, BLE stands strong as an affordable, light, and resilient option [48]. Its immense potential has been acknowledged in a variety of fields, including construction management. Many approach the topic from the construction management perspective, aiming to develop location tracking tools explicitly for construction site [46] [47] [45] [65] [11]. Other papers discuss the different radio technologies and their suitability for indoor positioning by trilateration without specifically addressing the construction context [67] [14] [62] [32]. In this section we look into these previous research papers and draw a picture of the state-of-art of indoor location tracking using BLE beacons. We especially take a deeper look into the research literature related to resource tracking in construction site.

2.2.1 Trilateration with BLE

Indoor positioning with BLE has been studied extensively due to its ubiquity, cost efficiency, and scalability [14]. Positioning algorithms with trilateration require reliable distance measurement, because the distances between the beacon (signal transmitter) and three or more gateways (signal receivers) are the inputs for trilateration algorithms (recall Fig. 1.2). Trilateration is not the only method to obtain the position information from three independent signals. There are also Time Difference of Arrival (TDOA) and Angle of Signal Arrival (AOA) methods based on the angles of received signals [40]. However, these methods have been incompatible with BLE technology [14]. Comparisons have also been made between BLE and WiFI and other technologies [7]. Several papers mention the advantages of WiFi and Ultra-Wide-Band over BLE in terms of distance range and accuracy [14] [33]. However, accuracy is not the only metric for evaluating a positioning system. Often there are trade-offs between accuracy and other factors [40]. Because of its cost-efficiency, power-efficiency, and other convenience factors, BLE has been regarded as an attractive technology for implementing scalable indoor positioning systems based on trilateration [19][62]. These advantages of BLE align well with the requirements of construction sites. This is shown in research papers related to location tracking in construction site [46] [47] [45].

Most of the BLE based positioning studies are conducted in generic stable indoor environments. They usually focus on accuracy. They have achieved accurate results by combining BLE with other technologies or techniques. Zhu et al. (2014) uses sophisticated mathematical methods for handling the instability of RSSI and achieves the accuracy of less than 1.5 meter error during 80 % of the time [67]. Paterna et al. (2017) achieves even higher accuracy with weighted trilateration combined with Kalman filtering and channel diversity [48]. Röbesaat et al. (2017) achieves the accuracy of less than one meter by combining BLE trilateration and dead reckoning with Kalman-based fusion [52]. Kalman filter is a method for estimating the hidden variables based on inaccurate and uncertain measurements [6]. Dead reckoning is a positioning method where the current location estimate predicts the next position estimate. As a method it is vulnerable to cumulative errors, so trilateration brings constant error-correction to the position estimates. Rusli et al (2016) acknowledges the challenge of trilateration indoors caused by obstacles such as walls. It presents a correction method that is based on first detecting certain strategic reference points in an indoor floorplan and then calculating the average of the point given by trilateration and the reference point nearest to it. [53]

There are also studies on BLE based positioning systems applied explicitly to construction site. These type of studies tend to have a specific application, and they are not usually limited to trilateration but also use other mathematical methods or other technologies. Park (2016a) recognizes the noisy and dynamic characteristics of a construction site and uses probabilistic positioning algorithms together with motion sensors to compute the location rather than using trilateration algorithms that rely on accurate distance measurements [47]. Park et al. (2016b) implemented a system for automated construction site safety monitoring which uses a dense web of stationary BLE beacons that is integrated with a BIM model and cloud [47].

Cheng et al. (2011) and Cheng et al. (2013) use UWB and GPS for location tracking in construction site and combine that information with other digital prototypes designed to enhance the production control in construction [12] [11].

Wang et al. (2013) presents three trilateration algorithms using RSSI: Centroid, Least Square Estimate, and Three-border. The difference between their performance was quite small. All performed well. The paper states that the positioning accuracy comes from two factors: the accuracy of the trilateration algorithm, and the accuracy of the RSSI value that is used as input for a trilateration algorithm. [62]

2.2.2 Challenges with RSSI

There are many challenges with the *received signal strength indicator* (RSSI) for trilateration in the construction context. Most of the indoor positioning systems using trilateration of the RSSI of BLE have to assume a stable indoor environment, which construction hardy ever is, as it suppose to change constantly. From purely signal propagation perspective, there are noise and interference. Multipath effect occurs when a signal travels along different routes to the receiver so that the travelled distances differ. Consequently the RSSI for a same signal will differ. In addition to the multipath effect caused by the space, there are also people and objects moving in a construction site. Wang et al (2013) shows that human body attenuates the RSSI signal by 6 dBm [62], so it also matters where exactly a beacon is carried (in case of person) or attached to (in case of object). Bluetooth radio frequency range is from 2400 to 2480 MHz, which belongs to the Industrial Scientific Medical (ISM) radio band that is much used by home devices, e.g. WiFi and microwave oven. Hence, the possible and often probable presence of ISM-applications is another source of signal instability in addition to multipath effect. [46]

Nevertheless, the fluctuations of RSSI measurements due to environmental factors can be softened with mathematical methods. These include average filtering, Kalman filtering, and weighted trilateration [62] [46] [12] [48] [52]. Trilateration depends on the distance estimates that are based on the RSSI measurements. In reality, there are variations in the measured RSSI value even for the same distance. If the measured RSSI value was used directly for trilateration, the obtained coordinates would be extremely inaccurate. For this reason, using a sequence of RSSI values can achieve more reliable distance estimates for trilateration. This is also known as noise filtering, and there are many noise filtering algorithms [46]. Park et al. (2015) shows the radical improvement of noise filtering to the poor accuracy of trilateration [46]: three noise filtering algorithms were tested and ranked by their error reducing effect. The Kalman filter produced the least error, followed by 5 moving average method and 3 moving average method, in this order. The moving average method calculates the average of the recent N locations obtained through trilateration. The moving average method is also used in the positioning prototype used in iCONS case studies [66], [65] and is also present in the artifact implemented in this thesis (will be discussed in Chapter 4), although, to be precise, in these cases the moving average is taken from the measured RSSI values instead of the coordinate values.

There are also other ways to reduce the total noise of BLE trilateration. Jiménez and Seco (2017) presents a case study where BLE trilateration was applied together with Pedestrian Death-Reckoning (PDR) for object finding from a smart phone [33]. This use case could be transformed into a construction site where a worker wants to find a tool by using his smart phone. This study and Park (2016a) are similar in the way they both use motion sensors to counter-balance the noise of BLE signals, although the latter does not use trilateration algorithm but probabilistic algorithm instead [47].

Despite the known challenges with signal fluctuation, trilateration with RSSI was the next step to increase the precision to the existing BLE positioning system. This decision was both practical and based on the relevant research literature. For BLE trilateration using RSSI readings, the same set of hardware that were used in iCONS research project was available, i.e., BLE beacons and RasPi gateways [65]. The size and the design of the beacon was suitable for construction workers, as the beacons are of the size smaller than a 2-euro coin. The cost of the hardware was also a significant factor: the unit price for a beacon was only 4 euros, and the battery lasted a couple of months with the transmission frequency of $1s^{-1}$. The beacons used in the previous work did not have motion sensors so those more complex hybrid methods presented in [48] could not be implemented in the artifact of this thesis.

Chapter 3

Methods

From Peffers et al (2008), *"The development of the artifact should be a search process that draws from existing theories and knowledge to come up with a solution to a defined problem."*[49] Here in this this thesis, the *artifact* will be the upgraded location tracking system. The *existing theories* cover the lean construction philosophy. The *existing knowledge* are here in one hand the studies assessing the needs for production control in construction, and on the other hand the research papers about trilateration and indoor positioning technologies. The *defined problem* is the bad operations flow in construction, which, looking from the lean construction perspective, could be to some extent solved by a coordinate level real-time location tracking system for tracking workers, equipment, and materials on site.

This thesis uses Design Science as the research approach to answer the research questions presented in Chapter 1. Design Science method will be used to develop an artifact realizing the real-time indoor location tracking in construction site using BLE beacon trilateration. The implemented artifact will be an upgraded version of the indoor location tracking system that was used in iCONS, using the same set of hardware [65]. After the development of the artifact, the new location tracking system will be tested in a real construction site environment. The root problem that this artifact aims to tackle is the lack of methods to measure the operation flow in construction. Upgrading the accuracy of the location tracking system in iCONS would be a concrete steps towards solving this problem. Previously we have discussed the validity of the selected technology through literature. Design Science was selected, because it fit the real life scenario behind this thesis. Design science is about creating and evaluating IT artifacts intended to solve identified organizational problems [49]. In this case, the organizational problem, which was first introduced as part of the DiCtion research project, was the need for a coordinate level location tracking system as an upgrade to an existing system. However, this particular case is not the end goal of this thesis, as this same problem extends to the lean construction field more widely, as the advantages of such a location tracking system has many proposed use cases from literature [7] [66] [47].

The structure of this thesis follows the Publication Schema for Design Science Research Study presented in Hevner (2013) [27]. This is evident from the way the chapters are organized in this thesis. *Introduction* defines the problem and its significance and presents the research questions after defining the key concepts. *Literature review* investigates the prior work relevant to the problem and possible solutions. *Methods* (this chapter) describes the specific Design Research approach that was adopted and refers to the authorities behind the theory of the method, which will be the content of this chapter. *Artifact Description* describes the implemented artifact in an appropriate level of abstraction. *Evaluation* discusses how useful the artifact turned out to be after testing it, and what are the implications of it. In this thesis, Chapter 5: *Test Case* precedes the Evaluation chapter to document the results of the test cases conducted with the implemented artifact. *Discussion* (in [27]) is meant to interpret the results and put them back into the research context presented in the introduction, showing their knowledge contribution in a wider research context. In this thesis, Chapter 6: *Evaluation* includes this content. *Conclusions* restates the most important findings of the work and suggests directions for future research. [27]

3.1 Design Science

The choice of Design Science needs a justification. Hevner et al (2004) points out that natural science based behavioral-science paradigm asks "what is true?" while engineering based design-science paradigm asks "what is effective?". In engineering sciences, where one studies not "how things are" but rather "how things could be", often the more emphasized question falls on the latter category. It is more important to ask what is effective, although indisputably all effectiveness in the end must base itself on what is true. Natural sciences bring the true building blocks, while engineering creates something new out of them, something that did not yet exist before the touch of human. These two paradigms incorporate different processes and approaches, as one discovers and the other creates. Hevner and Gregor (2013) calls the two types of knowledge *descriptive knowledge* (Ω-knowledge) and *prescriptive knowledge* (Λ-knowledge) [27].

Peffers et al (2008) introduces a methodology of using Design Science for IS research. It starts from recognizing the limitations of the existing research paradigms used in IS that are based on natural sciences and social sciences. As a knowledge contribution, it presents a methodology for using Design Science, which had traditionally been used in engineering disciplines, in IS research. [49] Applying Design Science in IS research targets to bring pragmatism into the IS research which has often remained distant and lacking real life applicability [27]. In abstract terms, building is about bringing an idea into fruition, making a word into flesh. The existence of a detailed blueprint of a building is still not a building, similarly as an idea or an intention alone is incomplete without action. Lean construction, especially the production control part of it, is mostly about practice, and little if anything about the design. Production control addresses the question "how to build effectively?" from different angles. Location data of resources in construction site is an element to answer this question, as is discussed in Chapter 2.1.1.

Thus, Design Science method is relevant to the topic of this thesis. Due to technological advancements, the production control of a construction project can be regarded as a discipline consisting of problems relating to information technology and organizations. Of course, this is not the only perspective of production control, but it is a perspective that is gaining more significance. A construction site is a complex but limited environment where people and materials move continuously. These movements are knowledge intensive as they require continuous management at various levels. There are general topics and there are specific topics. Nevertheless, the successful utilization of information technology within and between the organizations is important for effective lean construction. The artifact to be implemented in this thesis, a location tracking system, is a piece of technology that will affect the way the organizations in construction behave.

New technology will bring new practices. Hevner et al (2004) also argues that IS research ought to be proactive and reactive with respect to technology and its relation to behavior [28]. Improving the production control is about improving the behavior in organizations. Eg., it could be about getting situational picture and monitoring workplace safety better. In this way, IS research covers production control in construction. Thus, Design Science method is suitable for this research.

3.1.1 Relation to Location Tracking on Construction Site

So how is Design Science applied in our particular study? Borrowing the words from Peffers et al (2008), "The development of the artifact should be a search process that draws from existing theories and knowledge to come

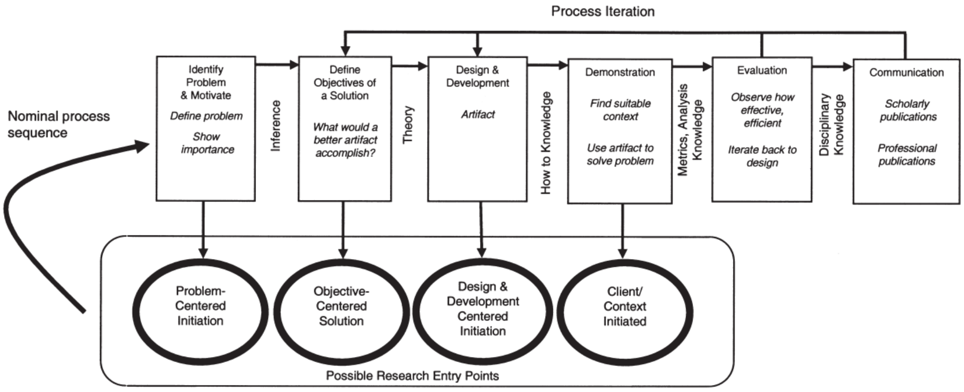


Figure 3.1: DSRM Process Model taken from Peffers et al (2008), *Figure 1. DSRM Process Model.* p.54

up with a solution to a defined problem." (s. 49). It creates a mental model for practising Design Science [49]. After a synthesis of the elements found in seven research papers applying Design Science method, it presents a process model consisting of six activities in a sequence. They are *Problem identification and motivation*, *Objectives of a solution*, *Design and development*, *Demonstration*, *Evaluation*, and *Communication* (see Fig. 3.1). In practice, this thesis follows a single iteration of this DSRM Process.

In our case, the problem identification was clear. The problem is bad production control that causes bad construction flow [61]. This consists of various aspects, including the widely generated construction waste and the risk for safety hazards which is ever present in construction sites [36]. The motivation was high, because improving the production control in construction has both large human (safety) and large economic (productivity) impacts [1]. Shorter project duration benefits all stakeholders. The objective of a solution was to track the location of resources in a construction site more accurately than what an existing location tracking system allowed. The existing prototype showed promising results by providing a practical tool to measure how much time a construction resource (worker, material, equipment) has spent at particular locations. This tool allowed for measuring the uninterrupted working time per location, as well as how many times a material was moved within the construction site before it was consumed. [65] Design and development in this study begins from upgrading the existing prototype by introducing trilateration on top of the Cell of Origin method. Demonstration will be conducted in a real construction site environment. Evaluation will follow after the analysis of the observations.

The thesis structure is faithful to the mental model presented by Peffers et al (2008) and also to the Publication Schema for Design Science Research by Hevner and Gregor (2013) [49][27]. Peffers et al (2008) also presents possible entry points to Design Science research (see Fig. 3.1). The *design & develpment centered approach* is applied in this study, as in this case both the problem domain and the solution domain were fairly well established through the previous iCONS studies and the other lean construction management literature (recall Chapter 2).

3.1.2 Assessment

The first research question will be answered through first creating the artifact and then performing a test case. The purpose of the test case is to test how the new coordinate level location tracking system performs in a real construction site. It aims to answer the first research question *RQ1: How does trilateration increase the accuracy of a previous real-time indoor positioning system using BLE beacons in a real construction site?* As the question implies, we are interested in finding out the additional value that trilateration brings to the specific existing prototype, not trilateration in general. Of course, trilateration in general is also discussed in order to lay the background to the trilateration implemented in this thesis.

The topic of applying BLE trilateration for indoor positioning is not new. Neither it is a completely new idea to use it for tracking resources in construction site [45]. Thus, this study does not claim to explore a new idea. Rather, it explores the possibilities of a particular implementation of indoor real-time location tracking using trilateration with BLE beacons. The special aspect of this work is the fact that the coordinate level positioning is to be implemented on top of the Cell of Origin positioning only by extending the software. The hardware stays the same, although the way how they are used might change. One possible contribution of this work will be to show how positioning systems with BLE could have different levels of granularity that can be easily controlled from software.

Criteria for evaluating the artifact include utility, quality, and efficiency throughout the search process. The implementation of an artifact is indeed a search process. It begins from comprehending the original prototype and continuing all the way to fine tuning the new prototype. In between, there is the process of drawing ideas from existing theories and knowledge [49]. RQ1 could be augmented into three components of utility, quality, and efficiency in the following way: as the new prototype will implement BLE trilateration for indoor environments of construction site, . . .

1. *how* does the new prototype affect the *utility* of location tracking compared to the original system?
2. *how* does the new prototype affect the *quality* of location tracking compared to the original system?
3. *how* does the new prototype affect the *efficiency* of location tracking compared to the original system?

These questions will be answered qualitatively with the support of the quantitative evident acquired from testing the artifact (will be discussed in Chapter 5). The second research question, RQ2, *what additional values can the trilateration of BLE beacons bring to the production control of construction?*, will take a wider perspective and extend the discourse beyond the results to RQ1. This question will be assessed based on the experience gained during the implementation and testing of the artifact together with the reviewed literature. This will be addressed in Chapter 6.

Chapter 4

Implementation of Artifact

This chapter will present the implementation of the artifact, that is a coordinate level location tracking system for indoors of construction site using BLE trilateration. The whole process is documented her. It begins from getting to understand the original prototype used in the previous iCONS research projects and proceeds step by step to describe the artifact and the tools used in developing it. The development of the artifact belongs to the successor of the iCONS research project, the DiCtion research project. This is the main chapter of the thesis.

4.1 The Original Prototype

The original BLE location tracking system was developed as part of the iCONS reserach project. Zao et al (2018a) used this location tracking system to determine how much time a worker spends on-site productively (see Chapter 1.3) [65]. The system consists of three components: the BLE beacons, the RasPi gateways, and the cloud, which comprise of virtual Ubuntu servers running on Amazon Web Services (AWS). Each Ubuntu server is called an *instance*, and each instance is independent so that separate case studies can be run in different instances. In practice, each instance could be assigned to a specific site. The system architecture is presented in the Fig. 4.1. Python is the programming language used in this system.

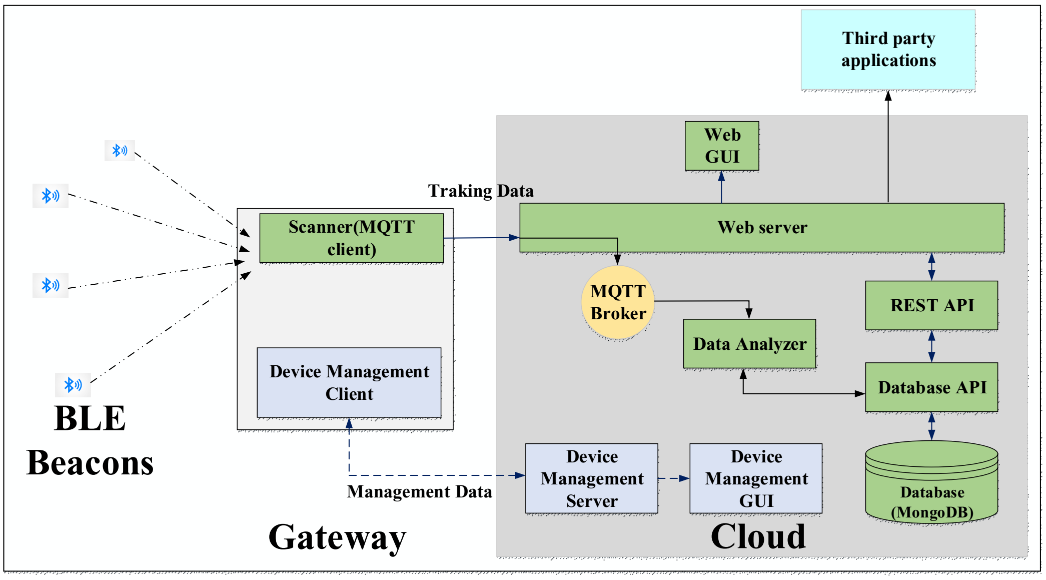


Figure 4.1: System architecture of the original prototype

4.1.1 BLE Beacons

BLE beacons is the simplest of the three components. BLE beacon uses Bluetooth Low Energy (BLE) radio technology [22]. It transmits radio signals containing its MAC-address in a particular transmission interval and power. Any device that is compatible to BLE can receive this signal. The beacon used in this system could be manually switched on and off, and the transmission lasted until the battery ends. It works with a single 3 V lithium button battery. Its transmission power ranges from -30 dBm to 4 dBm. The higher transmission power, the shorter duration of battery.

4.1.2 Gateway

The beacon signals are collected by the gateways. The collected data is transmitted to the cloud in an adjustable time interval. The gateways have the mediator role between the beacons and the cloud. The connectivity of the gateways is provided by WiFi or cellular technology.

The gateway used in this system is RasPi, a Linux mini computer. For this system, it is configured with two separate modules, which are independent on each other. The Scanner (MQTT client) is for detecting the incoming beacon signals, and the Device Management Client is a channel to manage the device from the cloud. A gateway is like a radar that constantly scans for beacon signals. Whenever it receives any signal, it sends it to the MQTT Broker in the cloud.

4.1.3 Cloud

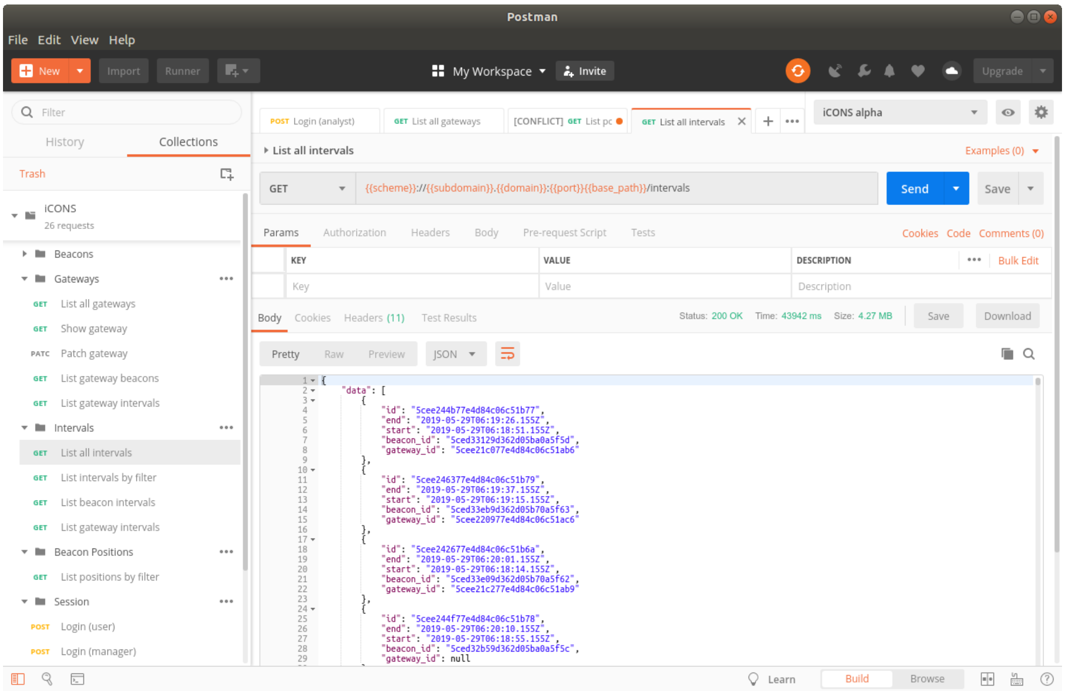
Cloud is the most complex component in this system and has many modules. The intelligence of the positioning system is entirely in it. The green boxes in Fig. 4.1 represent modules that handle signal data. The MQTT Broker is the module that receives beacon signal packages from all the gateways. The gateway sends the tracking data using Message Queuing Telemetry Transport (MQTT) protocol. Each data package sent by a gateway contains one or more beacon signals and has a single timestamp. See Fig. 4.2 below showing an example of a data package. The arriving data package, in the form of a MQTT message, triggers the Data Analyzer module. Data Analyzer works as the brain of the positioning system and its main responsibility is to specify the nearest gateway. It identifies the beacons in the package, checks the RSSI-value of each beacon, compares them, and decides whether to change the gateway association to a closer beacon. Database API handles the data flow to the Mongo DB Database. Web server is the server through which to view and edit the location tracking system. It has the access to the Database through REST and Database APIs. The Web GUI is what the user monitoring the system uses. The REST APIs enable the access of third party applications to the cloud. For example, mobile applications to add, remove, and update beacons in the system, and also to acquire the location information of the beacons. The Device Management Server and GUI are modules through which the gateways are managed.

```
{
"beacons": [
  {"rssi": -83, "mac": "c1:00:44:00:00:8e"},
  {"rssi": -100, "mac": "c1:00:44:00:00:e3"}
  ],
"timestamp": "2019-03-15 15:36:38",
"epochtime": 1552656998.927434,
"gw_name": "icons-hv-016"
}
```

Figure 4.2: Example of a data package sent by a gateway. The transmitter gateway (icons-hv-016) and the beacons (c1 :00:44:00:00:8e and c1 :00:44:00:00:e3) are specified.

4.1.4 User's Tools

For operating the location tracking prototype, several tools and interfaces are available for the user. The Device Management GUI is a web page from which the names and the broker addresses of the gateways could be checked and modified in a user-friendly way. The beacons need to be registered into the system through REST API requests, which have been done with the third-party application Postman. Fig. 4.3 below displays the API response for the 'List all intervals' request. This request returns a collection of Interval objects from the database, where each object tells to which gateway a beacon has been associated during a specific time interval, from start to end. In the left panel of the screenshot, there are requests for different purposes classified according to their topic (Beacons, Gateways, Intervals, Session). Through REST API, the raw data from the positioning system is acquired for usage. Dedicated applications could be built on top of these APIs. For data analysis, a Python script is written for exporting the raw data into csv-format, which is easy to manage in Excel or other similar tools.



GET {{scheme}}://{{subdomain}}.{{domain}}:{{port}}{{base_path}}/intervals

Status: 200 OK Time: 43942 ms Size: 4.27 MB

```
{
    "data": [
        {
            "id": "5cee244b77e4d84c06c51b77",
            "end": "2019-05-29T06:19:26.155Z",
            "start": "2019-05-29T06:18:51.155Z",
            "beacon_id": "5ced33129d362d05ba0a5f5d",
            "gateway_id": "5cee21c077e4d84c06c51ab6"
        },
        {
            "id": "5cee246377e4d84c06c51b79",
            "end": "2019-05-29T06:19:37.155Z",
            "start": "2019-05-29T06:19:15.155Z",
            "beacon_id": "5ced33eb9d362d05b70a5f63",
            "gateway_id": "5cee220977e4d84c06c51ac6"
        },
        {
            "id": "5cee242677e4d84c06c51b6a",
            "end": "2019-05-29T06:20:01.155Z",
            "start": "2019-05-29T06:18:14.155Z",
            "beacon_id": "5ced33e09d362d05b70a5f62",
            "gateway_id": "5cee21c277e4d84c06c51ab9"
        },
        {
            "id": "5cee244f77e4d84c06c51b78",
            "end": "2019-05-29T06:20:10.155Z",
            "start": "2019-05-29T06:18:55.155Z",
            "beacon_id": "5ced32b59d362d05ba0a5f5c",
            "gateway_id": null
```

Figure 4.3: Postman was used for performing API requests for operating the positioning system.

In the case studies, gateways were placed in a construction site to determine particular locations within a construction site [65]. Each gateway corresponds to a particular area, which could be of varying size and function (e.g. entrance, corridor, apartment etc.). Beacons transmit BLE signals every second, and gateways send the data to the MQTT Broker (see 4.1) whenever it receives a beacon signal. The system keeps a record of the gateway that receives the strongest signal of a beacon, for each beacon. This gateway is defined as the associated gateway for a beacon. However, Database is accessed only when the associated gateway of a beacon changes, since the case studies focused on observing how much time a beacon spends at a particular location (as area). The data collected into the database (in a collection named `Interval collection`) tells when a beacon enters and exits a location. The difference between the two timestamps gives the uninterrupted time spent in that location.

The algorithm of Data Analyzer contains the main intelligence of the location tracking system. It is visualized in Fig. 4.4. For a newly detected valid beacon, an association to the detecting gateway is established. For a beacon that is already associated to a gateway and is now detected by the same gateway, the connection strength RSSI (in dBm) is updated. If the signal to another gateway is sufficiently higher than the connection to the currently associated gateway, the beacon association is switched to the new gateway. The *RSSI-history* is a gateway specific array that keeps record of the latest ten measured RSSI values of the beacon that is associated to it. This array is the basis for determining the association strength of a beacon-gateway pair.

Essentially, Data Analyzer algorithm is a *proximity-based* positioning algorithm that works with the Cell of Origin method [40]. It detects the closest gateway for each beacon and assigns the location of that gateway as the location of the beacon. The algorithm in detail is illustrated in Fig. 4.4. The hysteresis condition is checked to prevent the Ping Pong effect. Ping pong effect happens at the border areas between two gateways where the signal strength of a beacon to two different gateways are close and thus change back and forth. This undesirable effect is reduced by determining a *hysteresis value* (in dBm). Hysteresis is an extra threshold above which the signal received by the new gateway must reach compared to that of the currently associated gateway in order for the gateway association of a beacon to change from the currently associated gateway to the new gateway. Without hysteresis, there would be frequent back-and-forth hopping of association of a beacon between two gateways at the border area.

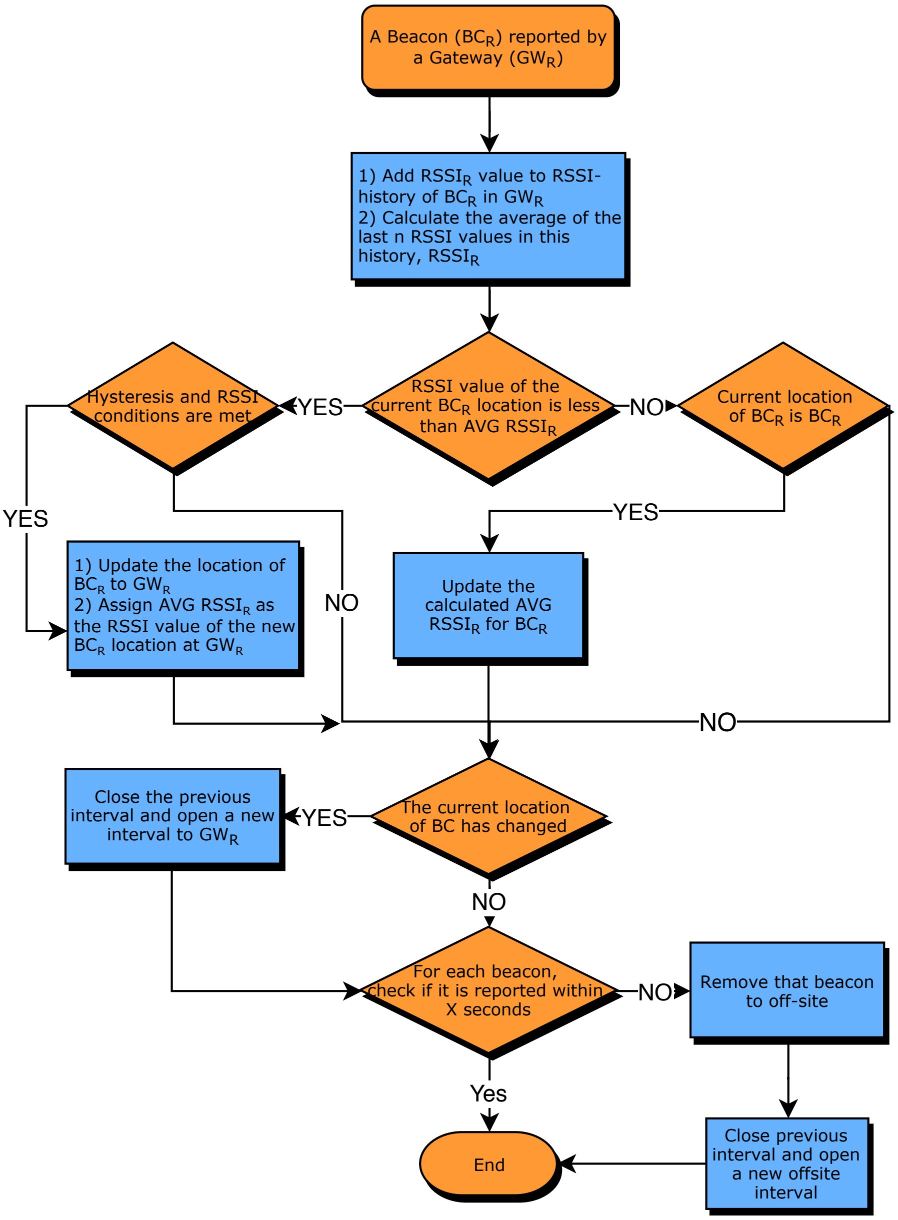


Figure 4.4: The Original Data Analyzer: a proximity-based positioning algorithm

4.1.5 Previous Results

Zhao et al (2018a) presents six case studies from four construction projects where the prototype was used to track the location of resources [65]. The cases included office and residential building construction projects in Finland,

Table 4.1: The location data of Worker 2 during a work day represented as timestamps of entering and exiting different areas (Gateways 005, 004, and 008). The worker arrived to the job-site at 8.00.41 and left at 18.43.26 and was undetected by the system between 9.01.24 and 11.48.16 (marked in orange). Taken from Zhao et al (2018) *Table 2: Time stamp for Worker 2 on May 12th in 24-hour format.*

Worker	Gateway	Entering timestamp	Exiting timestamp
2	005	08.00.41	08.02.03
	004	08.02.03	08.02.24
	005	08.02.25	08.59.31
	008	08.59.32	09.01.23
	Not in range	09.01.24	11.48.16
	005	11.48.17	13.03.02
	004	13.03.03	14.59.52
	005	14.59.53	15.03.39
	008	15.03.40	15.05.31
	005	15.05.32	15.09.44
	004	15.09.45	16.09.31
	005	16.09.32	18.37.40
	004	18.37.41	18.43.26

Brazil, and China, a plumbing renovation project in Finland, and a ship cabin furnishing project in Finland. Table 4.1 shows the form of the collected data for a single beacon: each table row represents either en entrance or an exit to/from an area with a timestamp. Each beacon in the use cases produced such a data set. Beacons were carried by workers and attached to equipment and material racks and packages. These results of the original prototype are presented here in order to clarify the point of departure for developing the new coordinate level positioning.

The case studies covered various perspectives of production control, and the study identifies four classes of use cases for real-time resource tracking: *Task status monitoring*, which compares the actual activities with planned activities,*BIM integration for onsite condition check*, which visualize the work processes for ensuring the fulfillment of dependencies in the work flow at each location, *Safety control*, which can be used for monitoring dangerous zones with alarm triggers, and *Resource searching*, which decreases the time wasted for searching for tools and materials on site.

4.1.6 Tests and Improvements

Tests were conducted to verify the behavior of the positioning prototype. Especially the change of gateway association of a beacon moving between two gateways was tested. The test setting was such that two gateways were placed at different ends of a calm office corridor. The beacon was attached to a 180 cm stand and the stand was moved between these two gateways with varying speed. Let us name them gateway A and gateway B. The hypothesis based on the Data Analyzer algorithm (see Fig. 4.4) was that the gateway association of the beacon should change from A to B when beacon moves from A to B after passing the middle point between A and B. However, the experiment showed strange results: the change happened only after the beacon had reached gateway B and waited there for a couple of minutes. When walking back from B to A, the same happened: the gateway association changed back to A after a long wait at the position of A. This was explained by the configured hysteresis condition, which was 25 dBm. This value, which is the threshold for the change of association, appeared to be too high as it made the beacon too insensitive for changing the gateway association. After setting the hysteresis to 15 dBm, the results clearly improved, and the change of gateway association happened quicker. Nevertheless, there was notable fluctuation in how the gateway association changed from one to another. First, the reason for this problem was unknown, but the answer was found from the Data Analyzer source code.

While studying the source code of the prototype, a software bug was found from the Data Analyzer module 4.1. There was an error that neglected the update of the current beacon-gateway association RSSI value (i.e. AVG RSSI of the beacon-gateway history) when the new measured RSSI is higher than the existing association RSSI value. In other words, when a beacon entered an area and its association is changed to the gateway defining that area with an associated RSSI value, the associatid RSSI value never *increased* when the beacon further entered the area after already being associated to the gateway representing that area. The decrease of the association RSSI value as the beacon moved farther from the associated gateway worked correctly. The consequence of this bug is that if the initial association RSSI value is low, it means that the beacon gets very easily associated to other gateways regardless of how close to the current gateway it gets. To function correctly, as depicted in Fig.4.4, the association RSSI value must be able to both decrease and increase depending on whether the beacon moves closer or farther from the currently associated gateway.

This software bug was easily fixed in the Data Analyzer source code. After the bug fix, similar experiments were repeated, where the original hypothesis was consistently fulfilled. Here it is necessary to mention that the results obtained in the previous case studies that used the prototype with this bug most probably have suffered from errors.

4.2 Developing the New Positioning System

So far the existing prototype has been described. Its defect was diagnosed and fixed so that the algorithm now worked as designed. The next step was to upgrade the prototype into a next level of positioning accuracy, i.e., coordinate accuracy. The idea was to bring this new feature on top of the the existing features. None of the existing features was meant to be removed.

For adding the coordinate-level positioning accuracy with trilateration, there were several things to consider which are not obvious. Firstly, the density of gateways will have to be increased, because a beacon should detect at least three gateways all the time (recall Fig. 1.2). Secondly, the total amount of produced data will increase significantly as the location had to be continuously determined. In practice, this means that every second the system inserts a coordinate entry into the database for each beacon. The original prototype inserted an entry into the database only when a beacon enters or exits an area. So with the new coordinate level tracking positioning system, the database input increased by orders of magnitude.

The development of the coordinate level tracking system required several steps, which are the following:

1. Determining the relationship between the RSSI and the distance.
2. Implementing a trilateration algorithm that takes as input the associated RSSI values of the nearest $N > 3$ gateways and outputs a xy-coordinate in a specified area (e.g., 4th floor).
3. Declaring the new data structures required for processing and storing coordinate data, including a new database schema for beacon positions.
4. Modifying the Data Analyzer, the Database API and possibly other modules so that the coordinates of the beacons get calculated and stored into the database, and that the beacon coordinate data can be accessed through REST API.

The architecture of the new positioning system that gives coordinate information of beacons is depicted in Fig. 4.5.

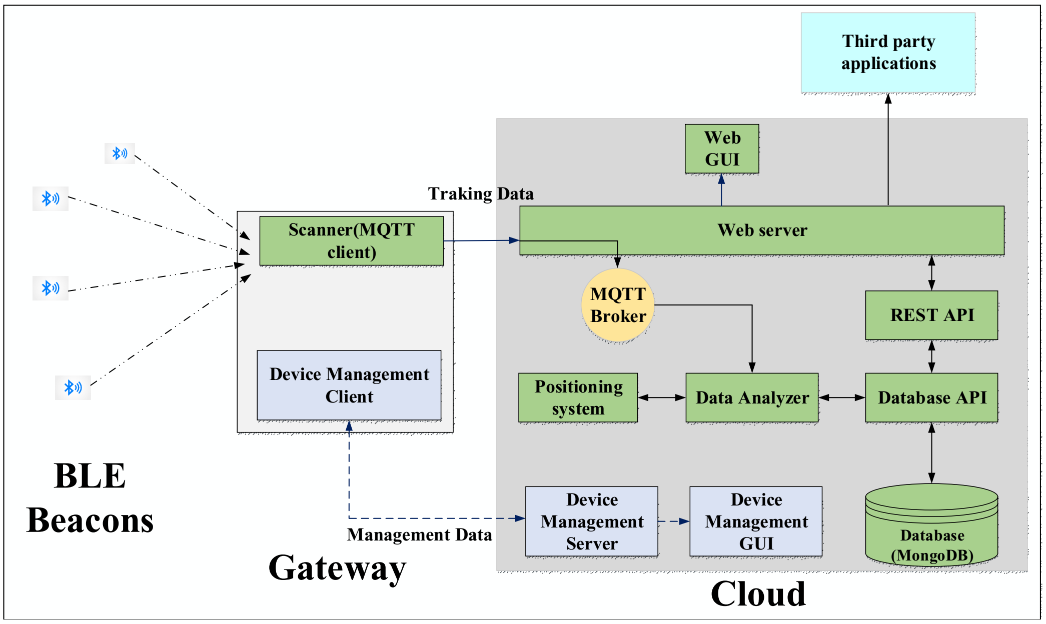


Figure 4.5: System architecture of the new location tracking system

4.2.1 RSSI-to-Distance Relationship

Since trilateration with BLE relies on the distance calculated from RSSI, the relationship between the two must be predictable. Wang et al (2013) presents a simplified indoor radio propagation loss model that takes into account the reference transmission power of the beacon, A, and the environmental factor, n.

$$d = 10^{\frac{A-RSSI}{10n}} \tag{4.1}$$

from which we get

$$RSSI = A - 10n \log d \tag{4.2}$$

The reference transmission power A represents the RSSI at distance $d = 1$ meter [67]. The environmental factor n indicates the attenuation of the radio signal due to the space and the medium. It is also referred to as the attenuation factor [67] and is usually determined experimentally [62] [10]. For this system, $n = 2$ was selected after experiments determining the distance-to-RSSI relationship. Fig. 4.6 shows the distance-to-RSSI measurements with two gateways and two beacons: distance is in the x-axis, and RSSI is in the y-axis. The yellow and the orange data sets show the measurements for individual beacons, while the blue data set shows their average. The green dotted line shows the expected RSSI as function of distance following the mathematical formula above with $n = 2$, which is followed closely by the measurement data. The transmission power was set such that $A = -59$ dBm, while the transmission power was -12 dBm.

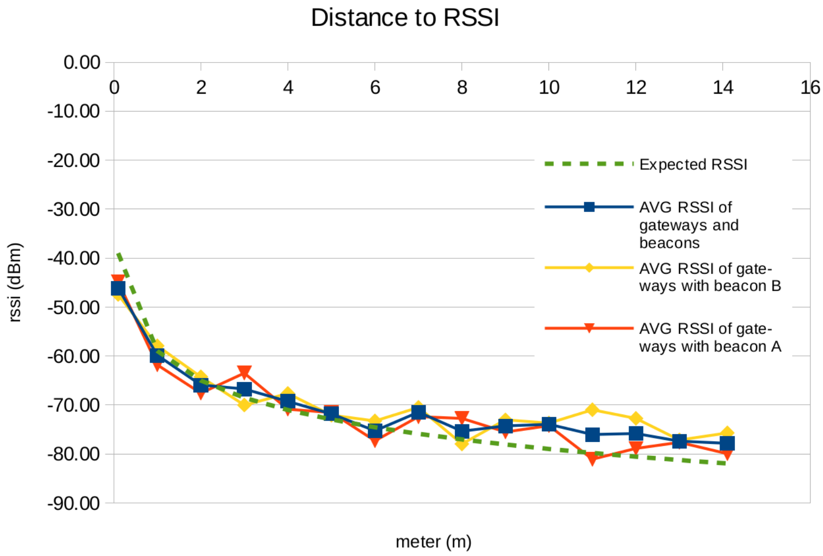


Figure 4.6: Distance-to-RSSI relationships

4.2.2 Coordinate System and Gateway Positions

Trilateration requires a coordinate system. The construction site must be located within a coordinate system in order for the coordinate level location tracking to be possible. In this prototype, it was decided to use local coordinate system that could be arbitrarily defined. A local coordinate system could anyways be mapped into a global coordinate system when needed. With a local coordinate system, points could be mapped into the a floorplan once the floorplan was fixed into the local coordinate system.

To define a local coordinate system for a floorplan, two steps are required: 1) defining the position of the origin with respect to a point in the floorplan, and 2) scaling the axis, in meters, to correspond the scale of the floorplan image. Then the gateways placed in the floorplan image (representing the real location in the actual building) get a xy-coordinate value. After having fixed coordinates for the gateways, trilateration becomes possible. In this prototype, the position of the gateways are defined by a JSON file `gateway\_locations.json` specifying areas, which include gateways, which each have a local coordinate (see Fig. 4.7).

```
[
  {
    "area_id": "Area_1",
    "gateways": {
      "gw_1": {
        "x": 27,
        "y": 54
      },
      "gw_2": {
        "x": 36,
        "y": 36
      },
      "gw_3": {
        "x": 81,
        "y": 54
      },
      "gw_4": {
        "x": 90,
        "y": 27
      },
      // ...
    }
  },
  {
    "area_id": "Area_2",
     // ...
  }
]
```

Figure 4.7: Example of `gateway_locations.json` file that determines the gateway locations in the local coordinate system.

How should gateways be put in a building then? This is a very important question for trilateration. BLE signals belong to the ultra high frequency waves, which penetrate thin walls, but perform best when the signal travels line-of-sight (LOS). The main challenge of the walls is not that they block the signal, rather that they cause the signals to scatter and reflect, causing multipath effect. Multipath effect makes the measured RSSI values fluctuate; some wave fronts travel longer distances than others. This means that some measured RSSI values are smaller than others even though the source of the signal is unique. Multipath effect causes inaccuracy to the coordinate data obtained through trilateration. Thus it should be minimized. To some extent, the placing of gateways can reduce multipath effect. Gateways should be put to places where there is a maximum chance for LOS to the beacons. This means that high positions are the most suitable. Also, gateways should be evenly distributed in each open space so that the nearest gateways used for trilateration will have LOS to a beacon in the space. The distances between the gateways should not be more than the effective range of the beacon signal, which is 30 meters with the transmission power -12 dBm based on the measurements (see Fig.4.6). This means that gateways should be placed at most 30 meters away from each other such that they are in LOS with respect to each other.

In reality, the spaces vary a lot, and it might not be possible to always place the gateways in this optimal way. The more complex floorplans, the more challenges in placing the gateways. Usually there will be compromises duo to circumstances (as will be with the test case later on).

4.2.3 Trilateration Algorithms

Trilateration requires the selection of at least three gateways and their estimated distance to a beacon. It was intuitive to select the nearest three gateways for trilateration, as it was suggested in [46]. This selection of gateways is based on the average RSSI value of the gateways detecting this beacon. This average RSSI value for a gateway is calculated from the latest three RSSI records in the history buffer of this beacon-to-gateway connection. In Wang et al (2013), six latest RSSI records were used for averaging, but that was for a stationary setting [62]. Here we expect movement and thus kept the sample number for averaging lower. Thus, the input for trilateration function takes three nearest gateways determined by their average RSSI values.

Now, one could argue why not use the maximum RSSI instead of the average RSSI, since multipathing can only reduce the RSSI value compared to the real LOS RSSI value that is obtained from the signal traveling the shortest possible distance. This sounds like a valid theory, but however, Fig. 4.6 shows that the average RSSI per distance follows the theoretical curve (Expected RSSI) well. The maximum RSSI per distance would not have fit the theoretical curve but it would have given higher RSSI values. This surprising result is hard to explain. One possible explanation is that in addition multipath effect, other signal instabilities are caused by the interference by other radio traffic that uses the same Industrial Scientific Medical (ISM) radio band that BLE uses and WiFi uses [46]. Regardless of the cause, the empirical evidence that the average RSSI fits the rssi-to-distance model (Equation 4.2) suffices to justify its usage for trilateration.

The trilateration algorithms are implemented in the Positioning System module (See Fig. 4.10). Two trilateration algorithms are implemented and tested. The first one is Least Square Estimation (LSE) and the other one is Centroid algorithm, both taken from [62]. LSE turned out to be more accurate when it yields coordinate values, as was the case in [62], but the Centroid algorithm yields coordinate values more frequently. LSE suffered from low output rate. Centroid positioning algorithm turned out to be holistically a little bit more reliable, which was the reason why it was eventually chosen. Nevertheless, both algorithms are described in detail, as both were implemented.

4.2.3.1 Least Square Estimate

LSE algorithm estimates the beacon position from the distance measurements by finding the position that minimizes the square error of the measurements [62]. Mathematically, this is done by finding the estimate $\boldsymbol{x}$ that minimizes the following equation:

$$f(\boldsymbol{x}) = (\boldsymbol{Ax} - \boldsymbol{b})^2 = (\boldsymbol{Ax} - \boldsymbol{b})^T(\boldsymbol{Ax} - \boldsymbol{b}) \tag{4.3}$$

where $\boldsymbol{A}$ is a 2×2 matrix (in case of choosing $N = 3$ nearest gateways for trilateration) and $\boldsymbol{b}$ a 2×1 column vector obtained from measuring the distances d_1, d_2 and d_3 from three gateways. More specifically, $\boldsymbol{A}$ and $\boldsymbol{b}$ are:

$$\boldsymbol{A} = \begin{bmatrix} (\boldsymbol{x_1} - \boldsymbol{x_2})^T \\ (\boldsymbol{x_1} - \boldsymbol{x_3})^T \end{bmatrix} \tag{4.4}$$

and

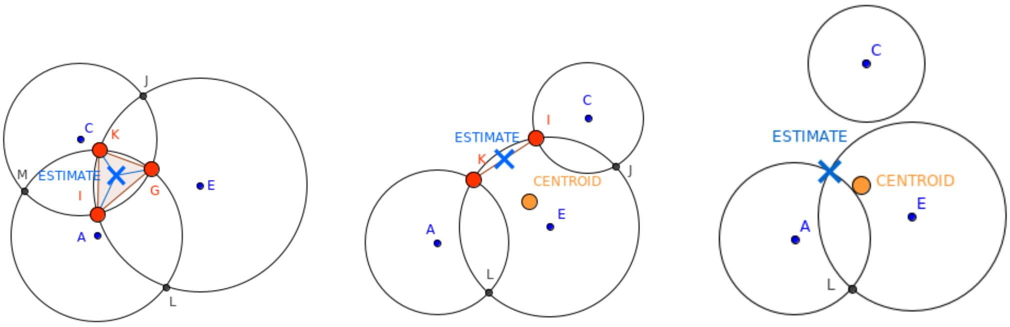
$$\boldsymbol{b} = \begin{bmatrix} \boldsymbol{x_1} \cdot \boldsymbol{x_1} - \boldsymbol{x_2} \cdot \boldsymbol{x_2} - d_1^2 + d_2^2 \\ \boldsymbol{x_1} \cdot \boldsymbol{x_1} - \boldsymbol{x_3} \cdot \boldsymbol{x_3} - d_1^2 + d_3^2 \end{bmatrix} \tag{4.5}$$

where $\boldsymbol{x_1}, \boldsymbol{x_2}$ and $\boldsymbol{x_3}$ are the xy-coordinates of the three gateways in a local coordinate system. Given $\boldsymbol{A}^T\boldsymbol{A}$ is non-singular, the location estimate with LSE algorithm is determined by the following formula:

$$\boldsymbol{x} = \frac{1}{2}(\boldsymbol{A}^T\boldsymbol{A})^{-1}\boldsymbol{A}^T\boldsymbol{b} \tag{4.6}$$

4.2.3.2 Centroid Algorithm

The Centroid algorithm is based on finding the centroid of the polygon confined by the inner intersections of the circles. The radius of the circles indicate the measured distance from the beacon to the gateways. There are three ways how three circles may intersect with each other (see Fig. 4.8): full intersection (a) occurs when all three circles intersect with each other, yielding six points of intersections in total. Semi-full intersection (b) occurs when one circle intersects two other circles but the other two circles do not intersect with each other, yielding four points of intersection. Partial intersection (c) occurs when two circles intersect with each other but the third circle does not intersect at all, yielding only two points of intersection.



(a) **(b)** **(c)**

Figure 4.8: Centroid algorithm scenarios

The Centroid algorithm applied in this system deals with these three scenarios in the following way: first, the centroid is determined for the triangle formed by the three gateway locations (yellow point, 'CENTROID'). The *inner intersection* for each pair of intersecting circles having two intersection points is the intersection nearer to the centroid of the three gateway locations. For full intersection scenario, beacon location is estimated to be the centroid of the triangle formed by the inner intersections of the circles (triangle KGI in (a)). The centroid C is found by the formula

$$C = (\frac{x_1 + x_2 + x_3}{3}, \frac{y_1 + y_2 + y_3}{3}) \tag{4.7}$$

where $(x_1, y_1), (x_2, y_2)$ and (x_3, y_3) are inner intersection points. For semi-full intersection scenario, beacon location is estimated to be the middle point of the line segment connecting the two inner intersections. For partial intersection scenario, beacon location is estimated to be the inner intersection out of the two intersections. When there are no intersections, the algorithm does not yield any coordinate.

4.2.4 Changes in Database

The affect of the coordinate based real-time location tracking to the Database input rate is significant: more detailed data is produced more frequently. Our system is set to write the coordinate location of each beacon into the database every second. Whether this is necessary in real cases is a matter of discernment, but for this prototype the maximum frequency of location update was implemented.

The original location tracking prototype uses MongoDB as database, which the new coordinate level system extends. MongoDB is a document database where collections are parallel to tables in a relation database. A collection contains documents, which are objects in JSON structure, which are unique records. The original prototype had the following collections: *beacons*, *gateways*, and *intervals*. For coordinate level positioning, the new collection (i.e. table) *beacon_position* was defined (see Fig. 4.9). 'Beacon_id' identifies the beacon. 'Timestamp' tells when the beacon coordinate is recorded.'xy_position' gives the coordinate, whereas 'area' gives the area for which a coordinate system is determined, e.g. '1st floor'. The coordinates of the gateways and the area they belong to are defined in a configuration file in JSON format. This configuration file initiates the coordinate system. 'Nearest_gateways' is a list that contains the nearest three gateways used for triangulating the beacon coordinate.

4.2.5 Upgraded Data Analyzer Algorithm

The overall algorithm of the coordinate level positioning system is illustrated in Fig. 4.10. The blue rectangles represent actions and processes, while the orange trapezoids represent Yes-No decisions, i.e. Boolean tests. This coordinate level positioning intelligence is added into the existing Analyzer module (see Fig. 4.4), bringing more granularity to it. The starting point of the coordinate level positioning algorithm is the same as the area-based positioning algorithm (original algorithm): The event of receiving a MQTT message that reports which beacons a gateway hears and with which RSSI values (see Fig. 4.2) triggers the algorithm pipeline. The trilateration algorithm (explained in 4.2.3) is applied in the second lowest blue box "Update the coordinate location estimate for BC_R". There are various stages where the positioning can potentially fail. In order to successfully determine a beacon coordinate, each stage of the algorithm in 4.10 needs to succeed. Otherwise the coordinate remains undetermined. Depending on the circumstances, the rate of determining the coordinate successfully varies. However, it must be disclaimed that a successfully determined coordinate does not mean a truthful

```python
# Insertion schema for "beacon_positions" collection
class Insertion(SingleSchemaModel):
    _schema = {
        'beacon_id': {
            'required': True,
            'validator': id_validator,
            'coerce': to_objectid,
        },
        'timestamp': {
            'required': True,
            'type': 'string',
            'validator': date_validator,
        },
        'xy_position': {
            'required': True,
            'type': 'dict',
            'validator': xy_coordinate_validator,
            'nullable': True
        },
        'area': {
            'required': True,    # To avoid ambiguities
            'type': 'string',
            'nullable': True
        },
        'nearest_gateways': {
            'required': True,
            'type': 'list'
        }
    }
```

Figure 4.9: *beacon_position* schema, excerpt from Python code

coordinate value. It only means that a coordinate value estimate has been calculated.

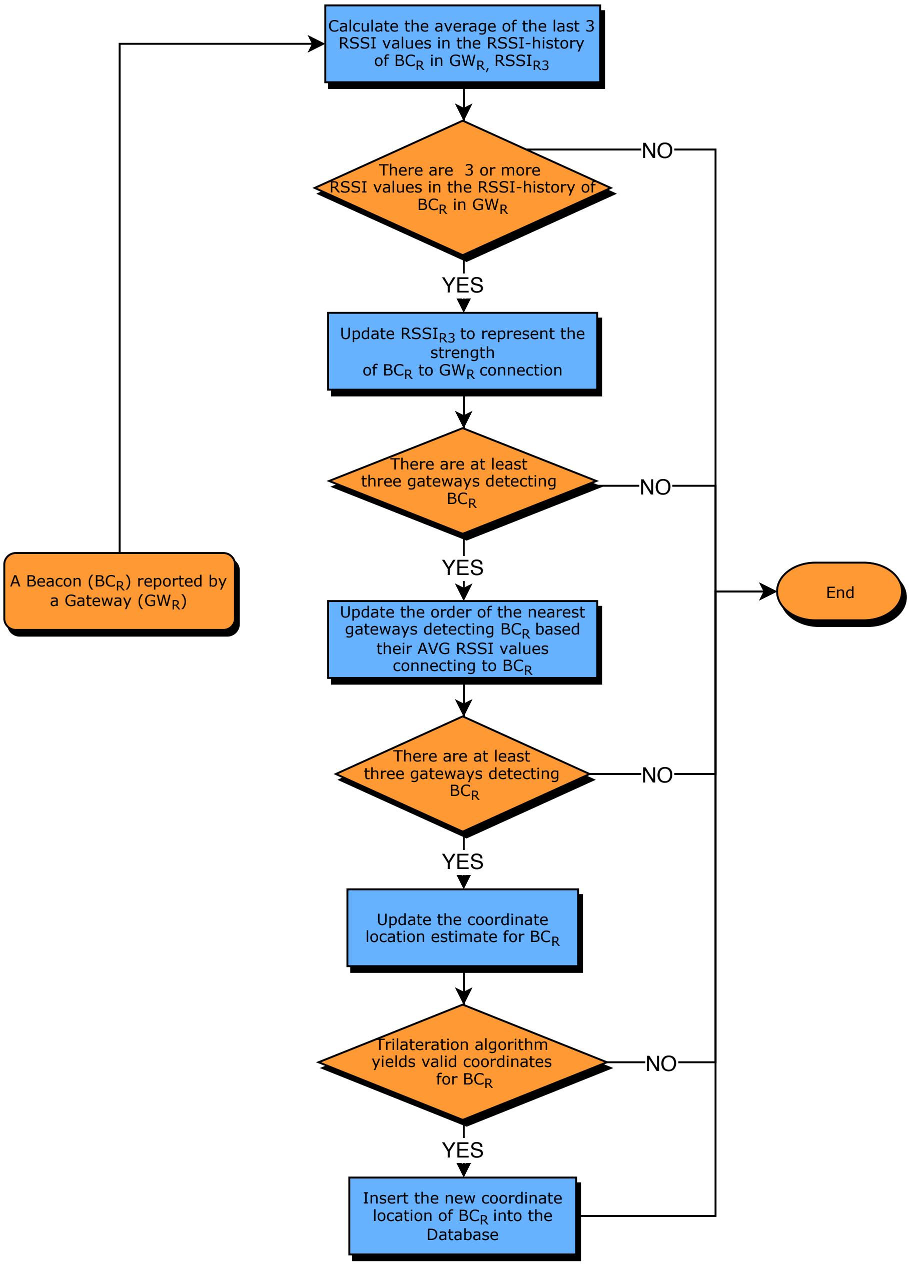


Figure 4.10: Data Analyzer algorithm: coordinate level positioning

New data structures in addition to the existing data structures were required for coordinate level positioning (also called, xy-positioning). Fig. 4.11 shows the original and the new data structures in Data Analyzer module. There is some overlap between the two sets of data structures, because the xy-positioning was designed to not alter the original area-based positioning. The new data structures draw obvious inspiration from the existing data structures, as is seen between `self.beaconsInGateways` and `self.beacons_in_gateways` and `self.current_beacon_gateway_association`.

```python
class DataAnalyzer(object):
    def __init__(self, storage):
        ...
        # Original data structures
        self.beaconCounts = dict()
        self.beaconsInGateways = dict()
        self.bcnHistoryInGws = dict()

        # New data structures for xy-positioning
        self.beacons_in_gateways = dict()
        self.current_bcn_nearest_gws_association = dict()
        self.beacon_position_estimates = dict()

        # New configurable variables
        self.number_of_closest_gateways = 3
        self.nof_latest_rssis_for_average = 3

        # Positioning module containing trilateration
        self.ps = Positioning()
        ...
    ...
```

Figure 4.11: Data Analyzer module: old and new data structures

Let us elaborate the data structures with an example: let there be n gateways and m beacons in a location tracking system instance (e.g. a construction site). Let the set of gateways be $\{g_1, g_2, \ldots, g_n\}$, and the set of beacons be $\{b_1, b_2, \ldots, b_m\}$. The variable `self.beaconCounts` is a dictionary that maps each gateway g_i, where $i = 1, \ldots, n$, to the number of beacons associated to it, ranging from 0 (when no beacons are associated) to m (when all beacons are associated). The variable `self.beaconsInGateways` is a dictionary that maps each beacon b_j, where $j = 1, \ldots, m$, to its associated gateway together with the timestamp and the association RSSI value. The variable `self.bcnHistoryInGws` maps each gateway g_i to those beacons in b_j from which it has received signals and stores the latest ten recorded RSSI values of that gateway-beacon relationship with the corresponding timestamps within the last 20 seconds. This is a collection of all the 'histories' among the gateways and the beacons, as is suggested by the name. The maximum dimension of this data structure is $m \times n \times 10$ if each of m gateways has a full 10-element-long history of measured RSSI values with each of n beacons.

The new variable `self.beacons_in_gateways` is similar to the variable `self.beaconsInGateways`, except that instead of mapping each beacon b_j to a single associated gateway, this maps each beacon b_j to a dictionary of those gateways that have recently detected beacon b_j and the reference RSSI value for the detection. The reference value is the average of the latest three RSSI values in the corresponding history of the beacon-gateway pair in the `self.bcnHistoryInGws`. The variable `self.current_bcn_nearest_gws_association` maps each beacon b_j to a dictionary of three nearest gateways and their corresponding reference RSSI values. Finally, the variable `self.beacon_position_estimates` maps each beacon b_j to its position estimate that is acquired through the trilateration algorithm. The position estimate contains an area and a xy-coordinate, but it can also be `None` if failure occurs.

The configurable variables `self.number_of_closest_gateways` and `self.nof_latest_rssis_for_average` are set to be 3 (see Fig. 4.11). The former determines how many of the nearest gateways are used for trilateration, and the latter how many of the latest RSSI values in the beacon-gateway history is used for obtaining the reference RSSI value of that beacon-gateway relationship. These variables could also be set to other values, e.g. 4 and 4. However, trilateration with Centroid algorithm with four gateways would have been computationally more expensive.

4.2.6 Testing

Primarily qualitative tests of the coordinate level location tracking prototype were first conducted in a couple of office environments before putting into use in the on-site case study. It was during this stage where the decision was made to use the Centroid algorithm only for trilateration and leave out LSE algorithm. LSE algorithm relied on more accurate distance estimates to work reliably. Centroid algorithm turned out to be more resilient, although its accuracy was slightly behind LSE. The initial testing already showed the high inaccuracy and instability of the system when tested in a 8 m times 8 m office room with fairly stable environment. At times the output coordinates were within 1-meter accuracy but other times the coordinates jumped wildly within the room and even outside the room. This deficiency remained a problem to which we did not find a solution at that time. Afterwards, many improvement ideas to this algorithm emerged, but they will be discussed in Chapter 6.

Trilateration brings the new level of granularity with the coordinate level positioning. To answer RQ1: *How does trilateration increase the accuracy of a previous real-time indoor positioning system using BLE beacons in a real construction site?*, let us look into the test case.

Chapter 5

Test Case

A suitable construction site for testing the coordinate level location tracking system (also called artifact) was found through the DiCtion research consortium. As mentioned in 4.2.2, from the perspective of testing the artifact, the idea was to test the artifact in the simplest possible floorplan layout: one where there are large open spaces and few walls. A suitable construction site was found from China through Tianjing University.

5.1 Case: MEP Installation in a Shopping Mall

The construction site in which the artifact was tested is located in Shijiazhuang, Hebei Province of China. The building is a large shopping mall where there will be plenty of small shops. The structure of the building represents the simplest layout where the artifact could and should be tested. The building consists of two ground floors, both having columns as the main load bearing structures (see 5.1 and 5.2). Since these two floors have similar layouts with identical columns, the floorplan of the 1st floor is used for visualization. There are higher floors also, but their floorplan differs significantly from the two bottom floors. The architectural design of the two bottom floors allows a high degree of modularity for the space usage; depending on the needs of the individual stores, walls can be erected. There are very few load bearing walls in those floors, and those few are located at the elevator shafts and stair cases. The entire second floor is an open space carried by a regular rectangular grid of vertical columns. The nearer distance between the centers of two regular columns (corresponding the edge of a rectangle grid) is 9.0 meters.

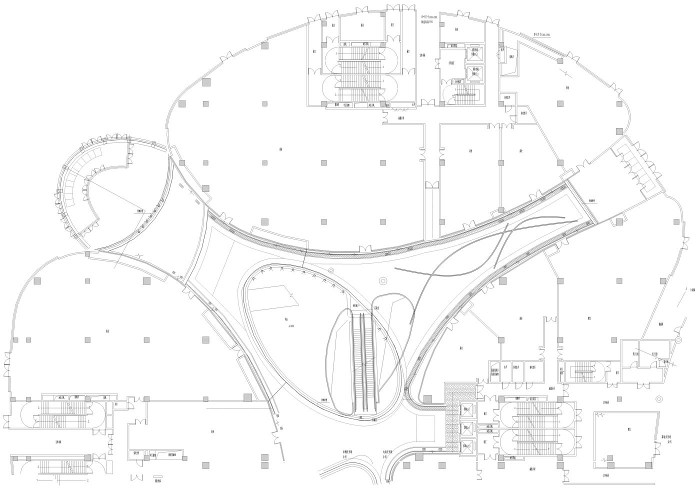


Figure 5.1: Floorplan of the construction site, 1st floor

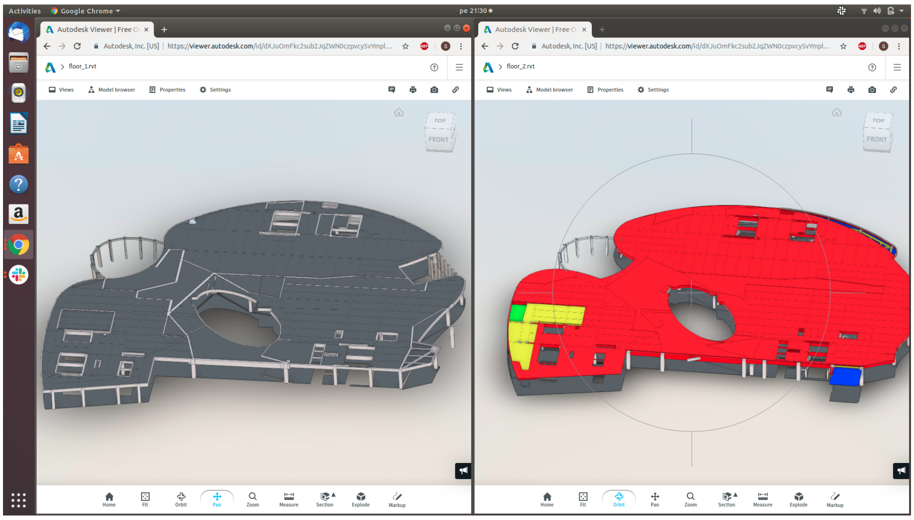


Figure 5.2: 3D structural models of the 1st and the 2nd floors

The test case was conducted during the construction phase of mechanical, electrical, and plumbing (MEP) installation, and more specifically, during the duct work at the ceilings (see 5.3). Other work was also performed, but this was the main task.

There were many practical issues that had to be considered at the construction site. As the artifact uses RasPi as Gateway, the power consumption per gateway is that of a small computer. RasPi uses mains power via USB cable. However, such power supply was not available in the construction site.

Figure 5.3: Pictures from site: MEP installation

Hence, power banks lasting for c. a day were used as power supply. The power banks had to be recharged every night. Similar challenges occurred in the previous iCONS case studies. There the on-site power sockets were used but the location of the gateways were compromised [65]. Another practical issue, as unconventional as it is, was security against theft. In this construction site, there were concerns about the theft of the RasPi devices during the night. As a counter measure, gateways were placed in locked metal boxes that were mounted onto the columns. A responsible person on-site collected the powerbanks every evening to the site office for recharging and brought them back to the boxes recharged every morning. Furthermore, there were only seven gateways available for the test case. Considering the size of the construction site, this could only cover a tiny area, as the theoretical maximum distance between two gateways is 30 meters, as mentioned in Chapter 4.2.2. In practice, 20 meters is already a big distance, considering that there were thick concrete columns carrying the wide space.

Before the metal boxes were mounted, and before deciding the locations of gateways for the actual test case, a dense test setup was built with five gateways (see Fig.5.4). Gateways were attached to the columns which were less than 20 meters apart from each other. A person carrying a beacon walked near that area from a column to another column and recorded the time stamps at each column. The positioning system now recorded both the associated gateway (corresponding to the granularity of the original positioning system), which is the nearest gateway, and a coordinate (x, y) on the same floor (the new coordinate level positioning granularity).

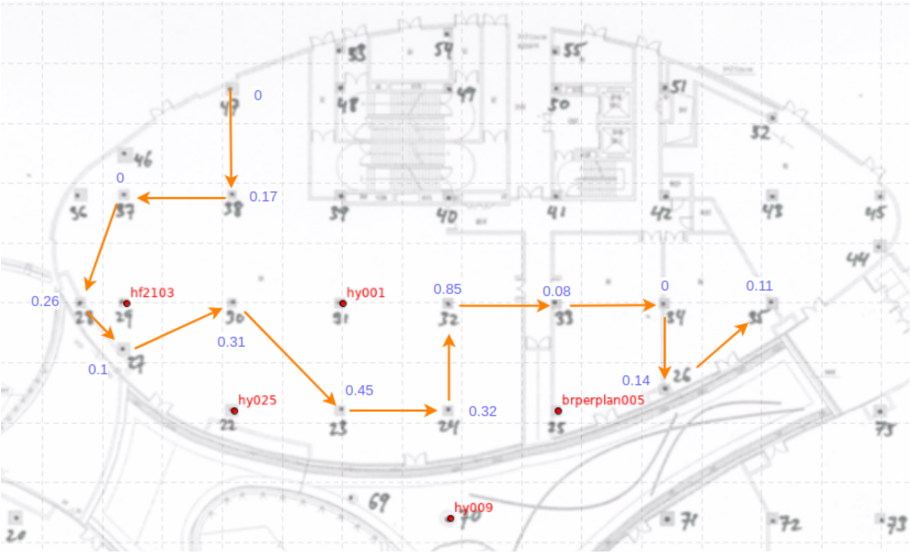


Figure 5.4: Test setup. Orange arrows show the route walked in the test round. Red points show the gateways. Violet numbers represent the coordinate output rate R_o at a measuring point (that is between two consecutive arrows). R_o tells what is the proportion of position records that had a coordinate value.

We see that the points with the best coordinate output rates are those within a polygon enclosed by the gateways. The farther from the gateways, the worse the output rate. This confirms the fact that the gateways should, as much as possible, cover the entire working area in order to produce coordinate outputs. After the test round, it was decided to enlarge the area of gateway coverage. Two more gateways were added to the set of gateways. The locations of the gateways were decided based on the location of the current work being performed. MEP installation work focused on quite a small area in the 2nd floor. Collecting data about the workers on site was conducted for another research than this thesis as part of DiCtion project. For the purpose of this thesis, which is to test the system performance of a new location tracking system in a real construction site, no data of real construction workers is used. Instead, only the validation data measuring the accuracy of the system was collected by a test personnel.

5.1.1 Validation Design and Data Collection

The purpose of validation is to check how the location data produced by the system matches the ground truth, i.e. the reality. The closer the system output is to the ground truth, the better accuracy the system has. In this case, the ground truth is the real location of the beacon, and the system output is the coordinate value recorded. In order to effectively know the ground truth, a predetermined path for beacon movement was designed. We call this the validation path. The validation path constitutes of 21 check points, each being a column, and it begins and ends at the same point. Seven gateways are placed in such a way that the path is encircled by them, and mostly the path passes the gateways. The check points were chosen to be at columns, because they are clear sign posts with known coordinates. The grid-shaped layout made it very easy to draw a path from a column to column. It was also easy for the test personnel to walk it through. This path became the ground truth against which the test results were compared; the difference of the test results to this path is the error margin of the system. See Fig. 5.5 showing the path.

Three test rounds were planned where in each round the time spent at a checkpoint varied. The times spent between each checkpoints in three rounds were two minutes, one minute, and thirty seconds. I.e, in the first round, the test person, carrying the beacon, stays almost two minutes at a checkpoint, and walks to the next checkpoint during the last 15 seconds before two minutes is full. Then he waits there again for almost two minutes, arriving to the next checkpoint when two minutes is full. This way the test person walks the entire path. Since there are 21 checkpoints, the round with two-minute intervals will last 42 minutes. The round with one-minute intervals will last 21 minutes, and the round with 30-second intervals will last 15 minutes and thirty seconds.

The positioning location tracking system will record the calculated coordinates during each test round. Since the transmission interval of the beacon is one second (recall Chapter 1.4.1), there will be at most one coordinate entry for a beacon per second. Because in reality there will always be obstacles and noise factors, the average coordinate recording frequency will in fact be less than one second. Because of the fixed schedule for walking the path, we know for each moment what is the ground truth coordinate of the beacon. However, there is the time that passes when the test person walks from a checkpoint to another, during which the exact location is unknown, but this time window will be neglected from the data records, because only the last 15 seconds are used for traveling between the checkpoints.

Data collection was performed as planned. The gateways were attached to the columns according to the plan in Fig. 5.5. The new location tracking system was running in the background throughout the validation rounds.

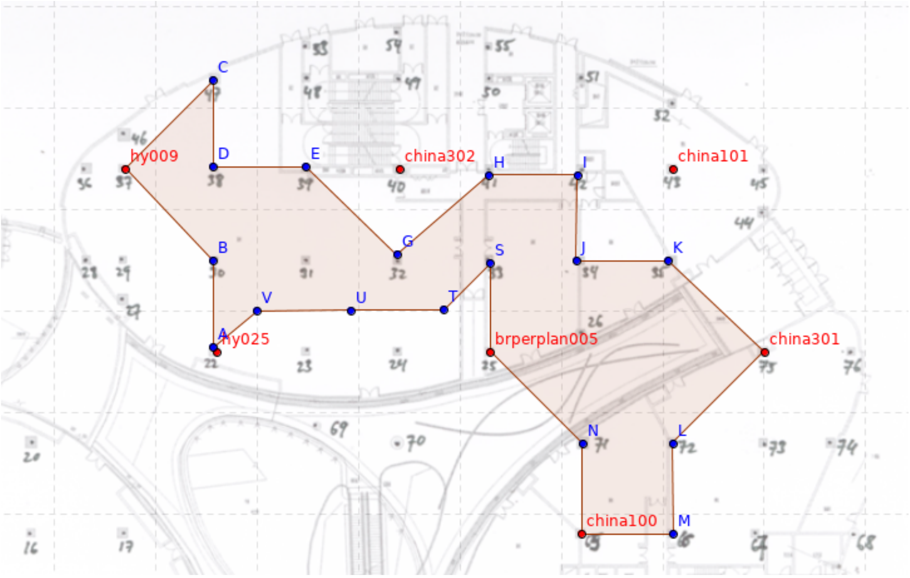


Figure 5.5: Validation path for testing the system accuracy

5.2 Data Analysis

To ease the data collection in the previous iCONS case studies where the original positioning system was used, a Python script was used for fetching the recorded location tracking data from the Database in the Cloud Instance (recall Chapter 4.1.4). The output csv-file contains the entries and exits to and from areas each determined by one gateway (recall Table 4.1). For easing the data analysis of the coordinate level location tracking system, another Python Script was written for fetching the coordinate entries. This script allows the filtering of entries by specifying the list of beacons, the areas, and the time interval. With this tool, it was easy to fetch data records for specific beacons for a specific time interval. Once the timestamps for the validation rounds were known, the data records of the three validation rounds were simply fetched afterwards when all the tests were performed. It is evident that such a tool had to be used, because the system was essentially a prototype and did not have a GUI showing the positions on the floorplan. Nevertheless, the prototype produced all the necessary positioning data, which could be visualized in a real usable application.

The enriched data record is shown in Table 5.1 below. The three rightmost columns indicating the ground truth and the deviation from it are added during data analysis, since the location tracking system itself does not know the ground truth. The ground truth was determined in advance in the validation design, and the test person followed it.

Table 5.1: Excerpt from the data records (csv-file) of the two-minute validation round. The ground truth is indicated in True X and True Y columns, and the measured error is presented in Diff column. From the unchanging values in True X and True Y we can see that all of these entries (rows) are recorded from a single checkpoint $P = (27, 54)$. it follows that the changing values in Minutes column show that the beacon stayed at point P for more than one minute, as this is taken from the two-minute validation round. The complete data records are much longer.

X-Coord (m)	Y-Coord (m)	Hours	Minutes	Seconds	True X (m)	True Y (m)	Diff (m)
34	78.13	12	1	0.155	27	54	25.1
29.25	62.28	12	1	5.155	27	54	8.6
33.12	60.01	12	1	7.155	27	54	8.6
30.15	59.47	12	1	8.155	27	54	6.3
26.69	54.62	12	1	9.155	27	54	0.7
26.78	54.44	12	1	10.155	27	54	0.5
26.78	54.44	12	1	12.155	27	54	0.5
26.78	54.44	12	1	13.155	27	54	0.5
26.78	54.44	12	1	14.155	27	54	0.5
26.43	55.15	12	1	37.155	27	54	1.3
26.43	55.15	12	1	38.155	27	54	1.3
26.43	55.15	12	1	39.155	27	54	1.3
26.76	54.48	12	2	12.155	27	54	0.5
26.76	54.48	12	2	13.155	27	54	0.5
26.76	54.48	12	2	14.155	27	54	0.5
26.83	54.33	12	2	15.155	27	54	0.4
26.83	54.33	12	2	16.155	27	54	0.4
26.41	55.18	12	2	17.155	27	54	1.3
26.41	55.18	12	2	18.155	27	54	1.3
26.41	55.18	12	2	19.155	27	54	1.3
...	...	...	...	...	...	...	...

Similar data records than that shown in Table. 5.1 were fetched and constructed for each validation round. For each of the 21 checkpoints, i.e. each location of measurement, the average deviation of the recorded coordinates from the one ground truth coordinate during the measurement interval (2 min, 1 min, and 30 sec) was calculated. Next, the results of each validation round is presented. The results show how accurate the positioning is at a particular checkpoint. In the Tables 5.2, 5.3, and 5.4, the blue arrows with an uneven pattern show the recorded path of the beacon in such a way that the tips of the arrows are the average system recorded positions of the beacon during the time when the beacon has stayed at a particular checkpoint. The red dotted lines show the positioning error of the system recorded average coordinate and the checkpoint that is the ground truth. The green point represents the recorded beginning point of the validation round, and the orange point the recorded end point.

During the construction of the validation setup, a mistake was made regarding the position of the gateway 'China301'. It was planned to be put onto the column 75, but was mistakenly put onto the column 73, a neighbor of column 75 (see Fig. 5.5 for the column numbers). Since this mistake was detected after the metal box for containing the gateway was mounted on the wall, it was decided to not correct the location of the gateway, but instead change the gateway deployment plan and the coordinate assigned to 'China301' from $P = (90, 36)$ to $P = (90, 27)$. This mistake was detected and fixed after conducting the one-minute validation round. Hence, there are errors expected in the data records near this gateway.

5.2.1 Validation Round with 2 min Intervals

Table 5.2 shows the average deviations at each checkpoint for the two-minute validation round. The rightmost column show the deviation in meters (m). The same results are visualized in Fig. 5.6 on the floorplan.

Table 5.2: Average deviations of the checkpoints, two-minute validation round.

Checkpoint	True X (m)	True Y (m)	Avg X (m)	Avg Y (m)	NOF samples	Diff (m)
hy009	27.0	54.0	27.3	55.6	20	1.64
B	36.0	45.0	50.5	37.0	27	16.60
A	36.0	36.0	38.2	32.7	46	3.93
V	40.0	40.0	48.9	35.9	84	9.77
U	49.5	40.0	65.0	38.4	75	15.55
T	58.5	40.0	57.2	31.0	44	9.09
S	63.0	45.0	84.7	31.0	6	25.79
Brperplan005	63.0	36.0	56.0	18.2	12	19.17
N	72.0	27.0	72.3	30.0	65	3.02
China100	72.0	18.0	75.6	32.6	1	15.01
M	81.0	18.0	–	–	0	–
L	81.0	27.0	65.9	27.1	26	15.14
China301	90.0	27.0	92.9	21.8	1	5.95
K	81.0	45.0	80.6	50.9	58	5.88
J	72.0	45.0	76.4	39.4	44	7.14
I	72.0	54.0	76.4	50.3	62	5.71
H	63.0	54.0	48.9	53.6	74	14.12
G	54.0	45.0	65.6	33.0	47	16.64
E	45.0	54.0	57.1	54.7	25	12.10
D	36.0	54.0	36.0	53.1	51	0.92
C	36.0	63.0	49.2	56.1	11	14.94

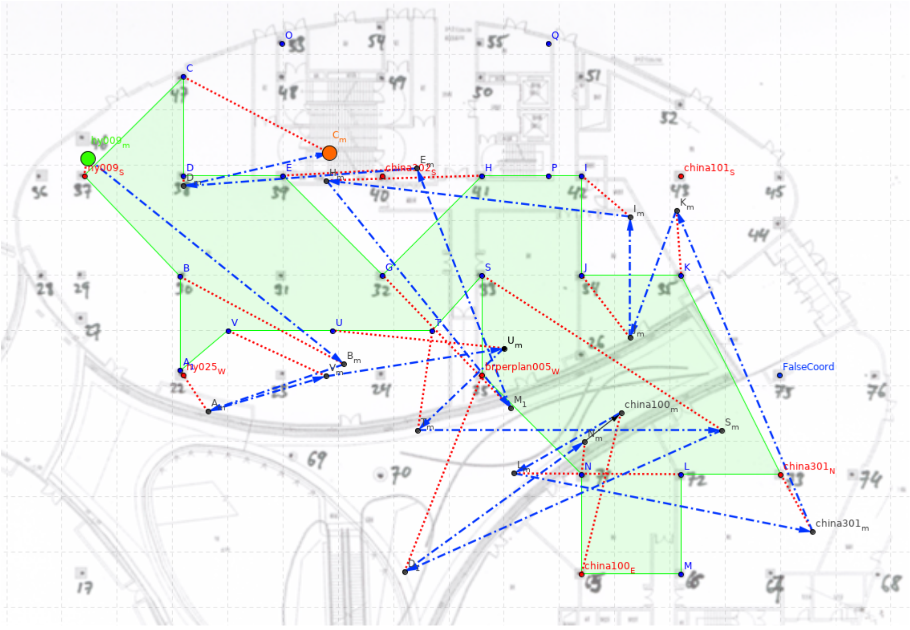


Figure 5.6: Visualization of the two-minute validation round. Blue arrows form the the recorded path of the beacon. The red dotted lines show the positioning error of the system recorded average coordinate w.r.t. the ground truth checkpoint. The green point is the recorded beginning point, while the orange point is the recorded end point.

5.2.2 Validation Round with 1 min Intervals

Table 5.3 shows the average deviations at each checkpoint for the one-minute validation round. The same results are visualized in Fig. 5.7 on the floorplan.

Table 5.3: Average deviations of the checkpoints, one-minute validation round.

Point	True X (m)	True Y (m)	Avg X (m)	Avg Y (m)	NOF samples	Diff (m)
hy009	27	54	27.41	53.79	1	0.46
B	36	45	36.26	37.95	24	7.06
A	36	36	42.35	29.55	3	9.05
V	40	40	44.73	37.65	18	5.28
U	49.5	40	59.55	44.54	23	11.03
T	58.5	40	69.28	27.60	12	16.43
S	63	45	52.07	64.07	16	21.98
Brperplan005	63	36	37.80	23.31	20	28.22
N	72	27	44.19	33.43	3	28.54
China100	72	18	–	–	0	–
M	81	18	61.20	26.04	18	21.37
L	81	27	71.81	21.33	32	10.80
China301	90	27	81.18	40.41	7	16.05
K	81	45	64.54	41.33	23	16.87
J	72	45	57.73	47.67	11	14.51
I	72	54	57.86	52.70	14	14.20
H	63	54	66.46	54.26	13	3.47
G	54	45	57.78	51.07	14	7.15
E	45	54	65.84	40.08	11	25.06
D	36	54	39.16	54.00	3	3.16
C	36	63	–	–	0	–

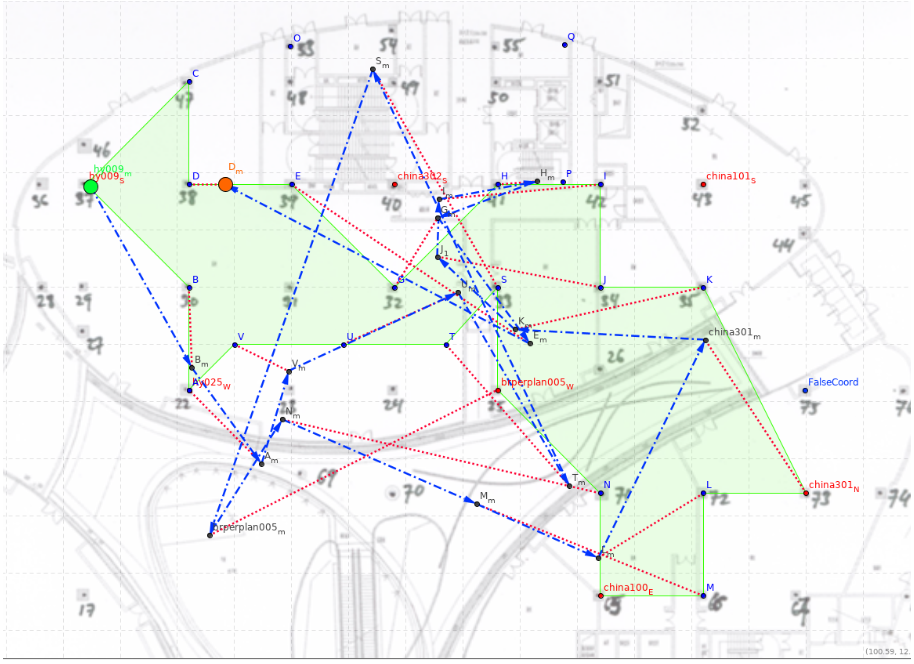


Figure 5.7: Visualization of the one-minute validation round. Blue arrows form the the recorded path of the beacon. The red dotted lines show the positioning error of the system recorded average coordinate w.r.t. the ground truth checkpoint. The green point is the recorded beginning point, while the orange point is the recorded end point.

5.2.3 Validation Round with 30 sec Intervals

Table 5.4 shows the average deviations at each checkpoint for the 30-second validation round. The same results are visualized in Fig. 5.7 on the floorplan. Note that for this validation round the starting and ending points are different from the previous two rounds. There was an unknown reason for this decision made by the test personnel.

Table 5.4: Average deviations of the checkpoints, 30-second validation round.

Checkpoint	True X (m)	True Y (m)	Avg X (m)	Avg Y (m)	NOF samples	Diff (m)
China301	90	27	–	–	0	–
K	81	45	80.96	18.59	1	26.41
J	72	45	84.31	29.30	4	19.95
I	72	54	47.62	44.22	7	26.26
H	63	54	32.84	46.05	2	31.19
G	54	45	67.61	14.94	1	33.00
E	45	54	32.94	27.43	5	29.18
D	36	54	35.35	52.08	24	2.03
C	36	63	36.48	49.26	14	13.75
hy009	27	54	23.01	52.75	11	4.18
B	36	45	27.31	37.98	21	11.17
A	36	36	25.43	36.41	22	10.58
V	40	40	37.21	39.88	21	2.80
U	49.5	40	47.93	37.43	25	3.01
T	58.5	40	77.12	34.87	22	19.32
S	63	45	50.47	29.16	3	20.19
Brperplan005	63	36	39.39	13.17	1	32.84
N	72	27	41.36	47.50	7	36.87
China100	72	18	72.40	48.43	25	30.43
M	81	18	74.89	15.68	14	6.53
L	81	27	60.85	14.19	3	23.88

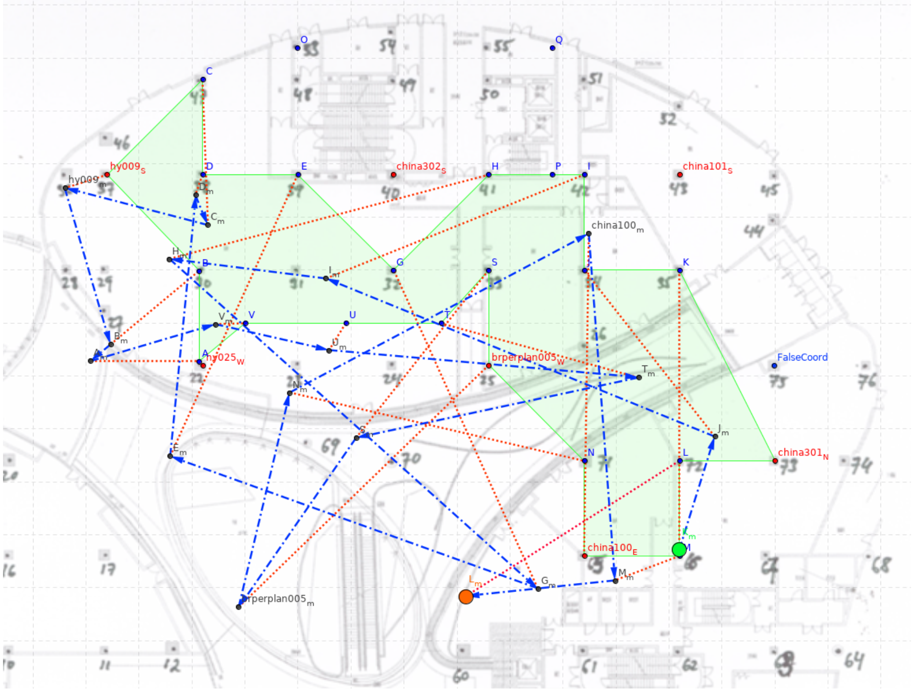


Figure 5.8: Visualization of the 30-second validation round. Blue arrows form the the recorded path of the beacon. The red dotted lines show the positioning error of the system recorded average coordinate w.r.t. the ground truth checkpoint. The green point is the recorded beginning point, while the orange point is the recorded end point.

5.2.4 Unique Points of the 30-second Validation

For the 30-second validation round, each unique point recorded during the entire validation round was drawn in Fig. 5.9. Here *uniqueness* means that the consecutive repetitive points (which are seen in Fig. 5.1) are removed. The lines with arrows show the path given by the system. The arrow indicates the direction. Note that the starting and ending points of this figure corresponds to those of Fig. 5.8, because they are representations of the same original data set. Unlike the previous figures showing the difference of the average points to the checkpoints, this figure shows the degree of fluctuations in the individual recorded points throughout the validation round. If the system was perfect, the blue arrows would follow the green polygon. The figure shows that the unique points fluctuate significantly. They do not form a clear path that even resemble the validation path, which indicates a serious instability of the coordinate level positioning system.

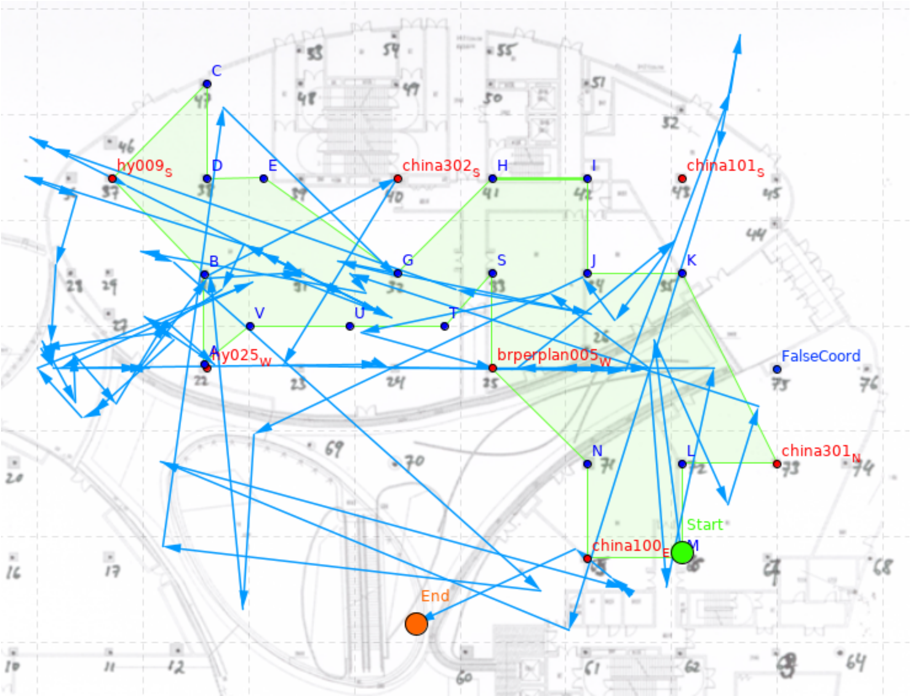


Figure 5.9: Unique points recorded during the 30-second validation. Consecutive repetitive points are removed. Arrows show the direction. The green polygon is the ground truth of the walked path.

5.2.5 Summary of the Results

The visualizations of the results of the validation rounds provide a qualitative representation of the accuracy of the system. All four figures show that there is a lot of inaccuracy, even to the degree that it hard to compare them and say which is the least inaccurate. However, quantitative results were obtained with statistical analysis. The average deviations of the average recorded points for each validation round was calculated, likewise the standard deviations and the correlations in x direction and y direction. Table 5.5 summarises the results of the validation rounds with these key values.

Table 5.5: Summary of the results of the validation rounds with 2 min, 1 min, and 30 sec measurement intervals between the checkpoints.

Validation round	x-coordinate correlation	y-coordinate correlation	AVG deviations of all recorded points (m)	Standard deviations of all recorded points (m)
2 min	0.86	0.81	10.91	6.72
1 min	0.67	0.71	14.06	9.71
30 sec	0.74	0.35	19.18	11.62

The table shows more more detailed results than one can deduce solely based on the figures. The average deviations for the validation round with two-minute intervals is 10.91 meters, which is the lowest, implying the highest accuracy. The one-minute round has the average deviation of 14.06 meters, and the 30-second round 19.19 meters. So the accuracy decreases when the beacon stays in place for shorter time. This trend makes sense, since staying longer in a point means that there is more time for the RSSI measurement history to forget the old signals received while still being at previous locations. The standard deviations and the correlations follow the same pattern, as expected.

5.2.6 Comparison to the Original Prototype

As mentioned before in Chapter 4.2, the new location tracking system does not overwrite anything that is in the original prototype. The original prototype records the intervals spent at areas defined by individual gateways. The upgraded new prototype also records the intervals spent at areas defined by individual gateways. What is interesting and worthwhile to compare is the *intervals* data collected by the original system and the raw data collected for coordinate calculation in the upgraded system. The raw data for coordinate calculation consists of three nearest gateways and their respective distances converted from the respective RSSI values. The original prototype makes comparisons of the individual gateway RSSI values. The upgraded prototype also needs to make the same comparison in order to sort the detectable gateways by distance. Consequently, when an interval is opened or closed, that is when the nearest detectable gateway has changed, the nearest gateway in the array of the nearest three gateways should also change. However, because there is a hysteresis threshold that controls the change of intervals, but there is not such a control mechanism in the nearest gateways array. This results in the fact that the intervals change less often than the nearest gateway in the nearest gateways array. In practice, the system will not record a change of an interval if the gateway with the strongest RSSI takes the first

Table 5.6: Interval records of the 2-minute validation round, that is the output of the original prototype. Off-site rows correspond to the gaps when the beacon is not associated to any gateway and is thus considered to be off-site.

GW	Start			End			Duration (min)
	Hour	Min	Sec	Hour	Min	Sec	
hy009	7	2	29.2	7	3	53.2	1.40
hy025	7	3	53.2	7	9	46.2	5.88
brperplan005	7	9	46.2	7	17	40.2	7.90
china100	7	17	40.2	7	25	25.2	7.75
Off-site	7	25	25.2	7	25	26.2	0.02
china301	7	25	26.2	7	29	59.2	4.55
Off-site	7	29	59.2	7	30	1.2	0.03
china101	7	30	1.2	7	31	3.2	1.03
Off-site	7	31	3.2	7	31	4.2	0.02
china101	7	31	4.2	7	34	59.2	3.92
Off-site	7	34	59.2	7	35	0.2	0.02
hy009	7	35	0.2	7	35	3.2	0.05
china302	7	35	3.2	7	35	34.2	0.52
brperplan005	7	35	34.2	7	38	5.2	2.52
chian302	7	38	5.2	7	40	7.2	2.03
Off-site	7	40	7.2	7	40	7.2	0.00
hy009	7	40	7.2	7	44	27.2	4.33

place in the nearest gateways array for only a short time or with a margin smaller than the hysteresis threshold.

Table 5.7 shows a comparison of the nearest gateways array (from the new prototype) to the associated gateway (from the original prototype) from the 2-minute validation round. The expected match between the nearest gateway and the associated gateway is marked by green text. Note that on three occasions the associated gateway does not correspond to the nearest gateway (1st GW). These are marked with orange text color. This may be caused by the hysteresis condition or other random errors. Notice that the order of gateway listing in 'Assoc. GW' column follows that in Table 5.6, as they represent the same set of data. Entries where the associated gateway stays the same are omitted from the table, which is represented as three dots. This comparison shows how the coordinate level accuracy extends the cell of origin accuracy by collecting more data and in a continuous stream. There is a significant increase in the data density of the collected data with the upgraded positioning system.

Table 5.7: Comparison of the nearest gateways array to the associated gateway from the 2-minute validation round. All three nearest gateways and their respective recorded distances are listed in columns. Green texts represent the expected results, while orange text shows the unexpected results. The rightmost 'Assoc. GW' column shows the associated gateway for each moment that is calculated by the original prototype.

X-coord.	Y-coord.	Nearest GW array						min	sec	Assoc. GW
		1st GW	1st dist.	2nd GW	2nd dist.	3rd GW	3rd dist.			
34	78.1	hy009	25.1	hy025	42.2	brperplan005	75.0	1	0.2	hy009
29.3	62.3	hy009	8.6	hy025	27.1	brperplan005	85.8	1	5.2	
					...					
29.	43.4	hy025	43	hy009	48.3	china-302	73.5	3	33.2	
20.4	36	hy025	36.9	brperplan005	54.1	china-302	96.3	4	12.2	hy025
53.8	36	brperplan005	54.1	hy025	56.2	china-302	96.3	4	13.2	
					...					
66.6	39.8	brperplan005	20.0	china-302	29.3	hy009	44.7	9	45.2	
66.6	39.8	brperplan005	20.0	china-302	29.3	hy009	44.7	9	46.2	brperplan005
66.5	37.2	brperplan005	15.3	china-302	29.3	hy009	44.7	9	47.2	
					...					
75.3	31.2	china100	25.1	china-101	31.6	china-301	56.2	17	38.2	
86.8	40.8	china-301	14.1	china100	27.1	brperplan005	79.4	17	58.2	china100
86.8	40.7	china-301	14.1	china100	27.1	brperplan005	79.4	17	59.2	
					...					
92.9	21.8	china-301	39.8	china100	50.1	china-101	79.4	25	13.2	
96.8	21.9	china-301	19.2	china-302	56.2	china100	84.1	27	0.2	china301
81.6	36.0	china-101	25.1	china-301	27.1	china100	32.9	27	6.2	
					...					
78.0	63.2	china-101	28.2	china-301	46.4	brperplan005	79.4	29	30.2	
46.5	46.8	china-302	60.7	china-101	70.8	china-301	79.4	30	4.2	china101
59.5	28.7	china-302	60.7	china-301	63.1	china-101	70.8	30	5.2	
					...					
80.3	71.8	china-302	15.8	brperplan005	39.8	hy009	56.23	35	2.2	hy009
34.2	56.8	china-302	20.0	brperplan005	35.5	hy009	108.0	35	3.2	china302
34.2	56.8	china-302	20.0	brperplan005	35.5	hy009	108.0	35	4.2	
					...					
86.7	24.2	brperplan005	36.0	china-302	56.2	hy009	70.8	35	33.2	
85.2	36.7	brperplan005	48.3	china-302	56.2	hy009	70.8	35	35.2	brperplan005
74.8	30.1	brperplan005	48.3	hy009	70.8	hy025	84.1	35	36.2	
					...					
87.2	72.9	china-302	17.1	hy025	63.1	hy009	63.1	37	38.2	
41.6	54	china-302	13.6	china-101	39.8	brperplan005	79.4	38	5.2	china302
41.6	54	china-302	13.6	china-101	39.8	hy009	76.5	38	6.2	
					...					
16.7	36.8	hy025	56.2	hy009	58.4	china-302	60.7	39	53.2	
40.5	54	china-302	35.5	hy009	35.5	hy025	56.2	40	15.2	hy009
40.5	54	china-302	35.5	hy009	35.5	hy025	56.2	40	16.2	

Chapter 6

Evaluation

The previous chapter presented the test case in which the new artifact was tested and the results obtained from it presented. In this chapter those results will be evaluated both as such and with respect to the existing literature on BLE trilateration based indoor location tracking system. The artifact will be assessed in terms of the criteria typical for Design Science Research presented in Chapter 3 by [49]. The assessment criteria and the proposed use cases given for the artifact stand as the horizon against which the criteria are viewed. We will also evaluate how well the new prototype fulfills the expectations set by DiCtion research project. This set of evaluations will answer RQ1.

Then we will evaluate the prototype in a larger context by comparing the results to other research publications. This extension will lead to the discussions that aim at answering the second research question. The implications of a coordinate level real-time indoor location tracking system on lean construction management will be discussed more extensively. Finally, the potentials of a commercial product will be explored in light of the lessons learned during this research process. This set of evaluations will answer RQ2.

6.1 Utility, Quality, and Efficiency of the Artifact

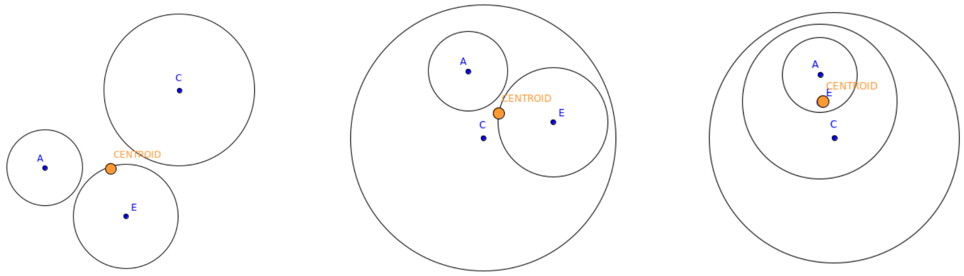
The three criteria of utility, quality, and efficiency mentioned in [49] together provide a basic rubric for evaluating whether an artifact is successful. In Chapter 3, the RQ1 was reformulated as ”How does the new prototype affect the *utility, quality, and efficiency* of location tracking compared to the original system?” Here we first evaluate the positioning feature of the system, focusing on the output of the system, while excluding the practical steps required to achieve it.

The utility brought by the BLE trilateration on top of the original indoor location tracking system in construction site is the coordinate level precision of location data. This was the purpose of trilateration in the first place. The accuracy (distinguished from precision) of the location coordinates given by the trilateration algorithm turned out to be very low. Table 5.5 summarized the acquired deviation of the output coordinates in relation to the ground truth. At best, the accuracy was slightly below eleven meters in average, and that was when the beacon stayed unmoved for almost two minutes per checkpoint. At worst, the average deviation was double of that (19.18 m) for 30 second stays per checkpoint. As we are talking about *real-time* location tracking, the former result resembles the situation when the beacon is not moving in the building, while the latter result the situation where a beacon is moving.

The practical usefulness of real-time coordinate of a beacon depends on the extent to which this real-time information can be visualized or otherwise codified into an understandable form for human. In this prototype the data visualization and representation are not implemented. The location data remains available only in the sense that it is accessible from the database. Data analysis in Chapter 5 is essentially done manually. In other words, an application layer that gives the prototype a true user interface is still missing. This is a critical shortcoming that restricts the utility of the prototype. It must be mentioned that the scope of this research could not include such development work. Nevertheless, this shortcoming does not make a difference to the data itself. The results were manually visualized and represented in the result analysis in the previous chapter.

In terms of utility, we can summarize that this prototype meets the basic utility of what it was designed for, i.e. the coordinate level location tracking. However, here we do not consider the utility, in the meaning of *usability*, from the point of view of an ordinary user, as this prototype does not simulate a product but a concept. It is primarily meant to be used by DiCtion research personnel who are few and who will receive first hand instructions for it.

The quality of the coordinate level tracking system is poor because of its weak accuracy and high sensitivity to movement. The flickering of many individual RSSI signals accumulate many fold to produce coordinates with much of noise. This can be seen from Fig. 5.9 that shows the consecutive unique points recorded by the system. Another basis for claiming the poor quality is the fact that very often the system does not output a coordinate at all. This is major problem whose source was afterwards found in the trilateration algorithm: the trilateration algorithm does not consider the situation when the three circles do not meet at all! Those cases are depicted in Fig. 6.1 below. See that the previous Fig. 4.8 considers only the cases when there is at least one intersection of the circles formed by the RSSI signal received by a gateway.



(a) (b) (c)

Figure 6.1: Omitted scenarios in Centroid algorithm where no intersections occur. Yellow point represents the centroid of the triangle AEC.

The omission of the cases where no intersections occur is a serious flaw in the trilateration algorithm. The random error caused by the fluctuations in RSSI signals could alone cause situations where the circles representing the measured distances to the nearest gateways do not intersect with each other (see Fig. 6.1a). In addition, the metal boxes that were used for protecting the gateways from theft weakened the RSSI signals to a slight extend. A layer of thin metal can already attenuate the signal. Random error can also easily cause the more special cases illustrated in Figs. 6.1b and 6.1c where the beacon is not spatially determined by gateways with intersecting circles, or in other words, when a beacon does not belong inside any triangle formed by the centers of the gateways. Such positions are at least the checkpoints D and M in the validation route in drawn in Fig. 5.5, but in reality there can be more positions causing those cases, since the columns, the metal bozes, and other obstacles attenuate RSSI signal.

To improve the Centroid algorithm, the method of calculating an estimated coordinate for those situations must be specified. For those already considered cases with intersections, the idea was the use the Centroid of the intersections (hence, the name *Centroid* algorithm). In cases where there are no intersections (Fig. 6.1), there should be a way to determine the point that is nearest to all three circles. As seen in the figures, the centroid of the centers of the circles do not necessarily give a correct hunch, especially in 4.8b and 4.8c. In theory, the LSE trilateration algorithm that was also implemented should produce a point very close to that point. However, this was not realised before hand. In hindsight, this shortcoming in the trilateration algorithm, the omitting of the cases without intersections, could be easily

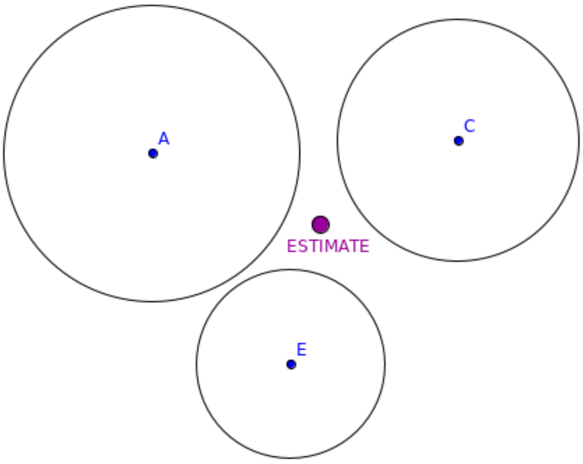


Figure 6.2: Example: a coordinate estimate computed by LSE algorithm when none of the circles intersect. There centers of the circles are $A = (8.9, 9.8)$, $C = (6.3, 6.4)$, and $E = (12.8, 3.8)$, and their radius are $r_A = 4.24$, $r_C = 3.46$, and $r_E = 2.71$, respectively. The LSE algorithms gives the coordinate estimate $E = (13.7, 7.8)$, marked as a purple point.

fixed by choosing to use the LSE algorithm whenever the centroid algorithm does not find any intersections among the three circles formed by the three nearest gateways. An example in Fig. 6.2 shows how LSE would produce an estimate even when there are no intersections.

Now, one could argue why not to use only LSE in the first place, if it considers all the cases in theory. This is a valid question. The reason for not using LSE was because of its low output rate of coordinate estimates observed from the initial tests comparing LSE and Centroid algorithm (see Chapter 4.2.3). This contradicts the theoretical behavior of LSE. The reason for such behavior was not analyzed in detail, and the choice of using Centroid algorithm was pragmatic at that time.

Independent from the trilateration algorithm itself, the instability of the RSSI signals is a great source of random error. This was mentioned in many reviewed studies [47] [62]. This instability increases as the movement increases, which means that during movement the output is less reliable. This is also what the validation results speak for (see Fig. 5.5). In the prototype, this varying degree of instability was not considered in the calculation of the coordinate estimates. All the calculated gateway distances that were based on average RSSI values received by gateways were treated as equally. In reality, the reliability of the calculated gateway distance is not constant but depends on the variance of the latest three measured RSSI values. The more variance, the more the beacon has moved during the corresponding time interval, and consequently, the less reliable the determined gateway distance (to a beacon) is. Since the gateway distances of the three nearest gateways in relation to a beacon are used as the input for trilateration algorithm giving the final position estimate, the unchecked reliability status inherits to the trilateration algorithm itself.

Another way to tackle this problem with the existing available tools is to keep track of the statistical variance in the latest ten measured RSSI values, which are recorded in the *RSSI-history* array (recall Fig. 4.4). The variance of this array containing RSSI values from a fixed time interval can serve as an indicator of the degree of "trustworthiness" of the gateway distance data, which is calculated from the average RSSI value obtained from this array. This way the knowledge of the degree of reliability for the coordinate estimates recorded by the system could be maintained. It could be defined as a *trustworthiness indicator*. In practice, the knowledge of reliability could be represented in various ways. E.g., if the coordinate of a beacon is to be visualized on a floorplan not as a point but rather as a circle, the *trustworthiness indicator* could affect the radius of the circle: if the trust is high, the circle marking the position would be small, and if the trust is low, that circle would be large. So the size of the circle would correlate to the inverse of the trustworthiness of the coordinate estimate. This kind of a visualization could give more than a hint to tell when a beacon is moving and when it is not.

Ideas for improvement do not end here. As Fig. 5.9 shows, often the consecutive coordinates of a the beacon jumped drastically. This obviously cannot be true. Workers do not run on site and most probably move slower than the normal human walking speed $1.4ms^{-1}$. Knowing this fact, there could a rule set into the system that limits the maximum speed of a beacon, for example to $1.4ms^{-1}$; if the next calculated coordinate is farther than where it is possible to move with this maximum speed, the system could cut the distance to the maximum distance that could be reached with the maximum speed. With this rule, the Fig. 5.6 would look much neater than it now is.

Considering other than the existing hardware and tools, there are many more options for improvement. For example, a beacon with an accelerometer that reports the xyz-acceleration in every transmission message could be used to determine when the beacon is moving and when it is not. Accelerometer together with gyroscope was used in [47], so this type of an implementation is possible, although such a beacon will cost more than the ones we have used.

To summarize the quality aspect, the quality of the coordinate level location tracking prototype is poor due to the shortcomings in the Centroid trilateration algorithm and the neglect of consideration for unstable RSSI measurements. Nevertheless, ideas to fix these shortcomings and improving the overall system have been presented here.

The efficiency of the prototype can be discussed at different levels. There is the computational complexity of the algorithm and then there is the device efficiency of the system. The computational complexity of both the Centroid algorithm and the LSE algorithm is constant, as the number of the nearest gateways considered for trilateration is fixed to three. For a single computation, the Centroid algorithm can have a varying number of operations that depends on the amount of intersections among the three circles. The LSE algorithm has a constant number of operations, as it is computed with a fixed matrix formula (4.2.3.1). An educated guess would be that LSE has more operations than Centroid. However, this time a rigorous complexity analysis will be skipped. It is enough to know that the complexity is constant for the purposes of this thesis.

The other aspect of efficiency is the usage of devices. The hardware consists of the gateways and the beacons. The gateways are RasPi single-board computers. The computational power that is used is a fraction of what RasPi offers, since the gateway only passes on the message of the beacons to the cloud where the main computation happens. Of course, the number of beacons on the field has a straight impact on the amount of data passing through the gateways, but even so the RasPi gateways are an overkill in terms of the technical specifications. The need for power supply is a significant limitation. In the test case, an ad hoc solution of using power banks was applied, but that required significant investment of time and effort that are unrealistic in a real construction project.

Another significant shortcoming in the computational efficiency of the Data Analyzer algorithm was found only afterwards: the algorithm updates the position of *all beacons* whenever the signal from *any beacon* is received. This is computationally very expensive. With minor changes in the source code, this could have been easily avoided.

In fact, the real-time location tracking prototype remains relatively inefficient. Although the desired feature (coordinate level positioning) was to some extent implemented, the costs of effort for operating the system remains way higher than necessary. It is pity to realise how much more this new prototype could have achieved if only these improvement ideas were realised before hand. For now, these improvements have to wait for the future.

6.2 Comparison to the Literature

As the literature review already demonstrates, BLE trilateration is not a particularly new topic, and neither is the idea of using it in construction site. Given the wide research interest over this topic, this thesis provides one more concrete example among others, and thus contributing by gaining flesh around the bones for the BLE trilateration based location tracking in construction environment. The second research question, RQ2: *What additional values can the trilateration of BLE beacons bring to the production control of construction?* gets beyond the artifacts itself. To answer this question, the perspective has to be widened to examine specific use cases that could be made possible with such a location tracking system. These use cases will be next discussed with reference to literature.

6.2.1 Accuracy

Park et al. (2016b) achieved an excellent accuracy of less than 2 meters error with probability based algorithms with BLE combined with motion sensors. However, the beacon density was not specified [45]. Wang et al. (2013) conducted the positioning experiments in a 6 m x 8 m room with four beacons at the corners and reached an accuracy of less than 40 cm of error. Here mobile phone was used as the tracked object, whereas the beacons had the same role as the gateways in our system [62]. Wang et al (2013) also uses six latest measured RSSI values for obtaining the reference RSSI value (also through averaging) that is converted into a distance before trilateration. We used only the three most recent RSSI records. In our test setting, unlike in [62], the beacons were expected to move a lot, which was the reason why we only used three most recent measured RSSI values for obtaining the reference value. In hindsight, it would have been better to stick with this literature example and use more data records for obtaining more accurate trilateration.

Bose et al. (2007) reached the accuracy of less than 3 meters of error with WiFi in an ordinary indoor environment with walls [10]. Rusli et al (2016) reaches the accuracy of less that 2 meters of error with similar setting [53]. Compared to these results, our results seem poor and inaccurate. However, the technology and the environments in these studies were quite different from this research. Among the reference studies, Park et al. (2016b) stands out as the most comparable to our research as it shares the same type of environment and technology, although it uses additional motion sensors.

Determining the accuracy of a location tracking system is more complicated than what might be expected. Saying that a system has an accuracy of

2 meters does not yet tell under which circumstances such result is achieved. Many factors influence the accuracy: it matters how many signal receivers there are, how closely they are located, and whether there are obstacles between them etc. The density of the deployed gateways has probably the most direct impact on accuracy. In this research, we placed gateways 15 to 20 meters apart due to a limited amount of gateways in use. Park (2016a) has a test setup where the fixed position sensor density (beacons in this case) is five times higher than that in our test case (gateways in our case) [47]. Park (2015) also uses significantly higher densities of fixed position sensors for computing the position [46], although the algorithm is very similar to that of our prototype. Accuracy also depends on whether the tracked object is moving and in what kind of a trajectory. In most of the previously mentioned papers, the positioning was carried out for stationary objects, unlike in this thesis. Hence, the poor accuracy obtained with our prototype is not directly comparable to those systems and setups used in the existing studies.

As our test case had relatively scarce deployment of fixed sensors (gateways), more accurate results will be expected if gateways are deployed more densely. In practice, the requirement for the accuracy of the coordinates is subject to the degree of movement to be tracked. The location tracking system developed in this design science research can be beneficiary for tracking big tools and machinery on construction sites where the error in meters can be neglected. After carrying out the improvement ideas, our prototype will serve more use cases.

6.2.2 Value for Production Control

So, *what additional values can the trilateration of BLE beacons bring to the production control of construction?* The manifold potentials are discussed in various studies [65] [47] [45] [46] [11] [12], but now let us portray the results of our test case to Zhao et al (2018a) and Cheng and Teizer (2013. These two papers deal with real-time location tracking at construction site on a very practical level, as is the objective of our artifact.

As mentioned in Chapter 4.1.5, Zhao et al (2018b) distinguishes four classes of use cases for location tracking: *Task status monitoring*, which compares the actual activities with planned activities, *BIM integration for onsite condition check*, which visualize the work processes for ensuring the fulfillment of dependencies in the work flow at each location, *Safety control*, which can be used for monitoring dangerous zones with alarm triggers, and *Resource searching*, which decreases the time wasted for searching for tools and materials on site. [66] For all these four use case classes, the coordinate level location tracking system brings more or less advantage over the original proximity-based location tracking system. For safety control, the coordinate level location tracking brings perhaps the most crucial advantage. If the border of the danger zone is to be determined exactly, the coordinate level of precision is necessary, as shown in [47]. For resource searching, the coordinate level precision also brings significant advantage. For these use cases to benefit from coordinate level precision, obviously the accuracy must be sufficiently high. Because of the inherent instability of RSSI signals, which has been shown in this and other studies, it seems very hard if not impossible to reach high positioning accuracy for moving objects with BLE trilateration alone. For reaching higher accuracy, other methods such as the usage of accelerometer should be added on top of trilateration, which has been shown in [46]. For the other two use case classes, the coordinate level precision brings relatively small additional value, as long as the proximity-based accuracy is granular enough, e.g. room precision, apartment precision, or floor precision depending on the required accuracy.

Chang and Taizer (2013) provides an extensive conceptual model for safety and activity monitoring in construction site, which supplements the ideas presented in Zhao et al (2018a). Here the positioning technology is UWB instead of BLE, but the use case of monitoring is otherwise very similar. [11]. The unique contribution of Zheng and Taizer (2013) is the comprehensive system designed for visualizing the position data of the resources in construction site and giving meanings to their mutual relationships. E.g., a use case is presented where a danger zone under the arm of a tower crane is geometrically determined, and whenever a worker gets close to the danger zone, an alarm is fired. Here the crane hand and the workers are both construction site resources with known locations. Their locations are visualized in a virtual reality that represent the construction site, as if there is a video game representing the reality in real-time. [11] Based on this example, other relationships between resources could be defined with such a system, e.g., when a worker needs a certain tool (which is a resource with a known location), he could request for its location and availability, and the system would then tell him the location of the tool. This kind of a system would enhance the bottom-up self-organization of the workers. As discussed in Chapter 2.1.1, self-organization is a favorable activity in the complex context of construction production. When subcontractors self-organize fluently and coherently with respect to each other, the top-down production control will also be easier. This would naturally lead to the reduction of overall construction waste. These hypothesis from literature were not really tested in our test case. Our artifact was not mature enough for such tests.

What our prototype could bring to these use cases presented by Zhao et al (2018b) and Zheng and Taizer (2013) is very little in practice. The artifact developed in this thesis remains incapable for directly benefiting any real production control process. However, but it does give some insight of what could be achieved once a comprehensive real-time location tracking system for construction site is developed. The improvement ideas mentioned previously are already a tiny step towards that goal. At that time, there will be a lot to achieve. The more or less predictive use cases presented in these two research papers could then become reality, after which they would become real ways of improving production control. The exact mechanisms of how that will happen remains beyond what could be concluded in this thesis. What could be said is that the usage of real-time location tracking on site will be a means to practice effective management on site. It will not take away human responsibility from site, but instead make it more transparent and potentially more distributed.

As we have discussed the value of a coordinate level location tracking system for construction site resources, it must be said that the exact technology used for achieving such a system is less important than the outcome of the technology, i.e., the performance of the system. Cheng and Taizer (2013) did not use BLE [11]. BLE trilateration was just a starting point for this particular thesis, and although it has many benefits such as cheapness, simplicity, and privacy (compared to using personal phones), there is no reason why it could not be replaced by some other technology that gives a better overall performance. In the end, the value of real-time location tracking comes from how to apply it. Alone it gives very little, but once appropriately visualized and smoothly integrated to other systems, the prospects are plentiful.

6.3 Product Aspects

The artifact created in this work a proof of concept, and as such, it has very modest limits. Nevertheless, it is interesting to project the proven concept towards a product that would be ready for delivery. Before concluding this work, let us consider what are the aspects that should be considered and what problems needs to be solved in order for this concept to mature into a ready product.

Scalability and resilience is a basic product requirement. For setting up a location tracking system, there must be a network of fixed sensors (e.g., gateways in our prototype) that cooperate with each other to get the position of the tracked sensors. The network of fixed sensors should be easily extended and easily reduced. In the frame and structures phase of construction, the number of areas keep increasing until all the areas are created. It should be easy to add and remove sensors in such a way that the functionality of the sensor network stays valid. Resilience is needed, because construction site is a harsh environment and it is highly likely that sometimes one or two sensors get damaged unintentionally. In our prototype, the scalability is limited by the need for mains power. In theory, more gateways can always be added to suitable locations, but a construction site rarely has constantly available power sockets at the desired locations. In some cases in [65], gateways had been unplugged from a power source, because a worker needed the socket for accomplishing his work. Hence, the positioning network of gateways would have to be battery powered in order to be scalable and resilient.

Once battery is involved, the battery life cycle becomes a relevant question. The battery should last long and be replaceable or rechargeable. A thing that needs to be balanced is the battery duration vs. the density of the time interval of location tracking. The more frequently the position of a tracked sensor will be updated, the more battery the system will consume and the shorter will be the life cycle of the positioning system. Also, the amount of computation in the battery powered sensors should be kept minimal to save battery. In our prototype, all computation happens in the cloud. The task of the fixed sensors should only be to transport the raw data that will be used for computing the locations in the cloud backend, like in our prototype. A part of the system that worked flawlessly in our prototype was the internet connection via mobile broadband. It proved to be a suitable connection method for construction site, since by default there are neither WiFi nor cable networks. Of course, problems arise if there is no coverage of mobile network in the construction site.

Visualization is an aspect whose importance cannot be overstated, as is shown in [11]. To have a positioning system product that could be widely used, there must be a user interface that provides the access to control the positioning system. This should include setting up the positioning network containing fixed sensors in a map of the construction site (i.e., floorplan) and adding and removing resources that are to be tracked. These should be the minimal requirements in order for a system to be useful for a wide audience. Furthermore, the integration of a location tracking system with BIM would be a next big step to further advance the applicability of the real-time location information in construction project, with all the potential semantics incorporated in both the location tracking system and BIM itself. Lean construction management will take a giant leap forward once such a system is successfully created and spread among construction practitioners.

At the heart of lean construction and the improving of production control, there is a yearning to reform construction into more productive, more transparent, and more sustainable. Resource positioning contributes to all of these perspectives. Productivity improves with better decision making in all levels of management, including the bottom-up self-organization. Having the real-time location information of the resources in a construction site increases the capability of making correct decisions. Transparency increases as knowledge increases, as long as the knowledge stays accessible fairly for all relevant parties. Sustainability comes from the synthesis of keeping the building standards high and keeping the construction waste low. The contribution of resource positioning to sustainability is not trivial, but there are many indirect ways in which it supports sustainable building. Logistics optimization, which benefits from real-time resource location information, enhances quantity optimization, which can reduce material waste. Construction material production is a significant source of energy consumption in developing countries [37], where production control can have even greater impact on the overall quality of construction. From a larger perspective, a building that is built well will not need reparation or be demolished before due time.

Chapter 7

Conclusions

In this thesis we have implemented a prototype that uses BLE trilateration for coordinate level indoor location tracking in construction site. The purpose of creating this artifact was two fold: first, to upgrade the positioning precision level for indoor positioning of a previous prototype, and second, to explore the ways to utilize the location information of resources for improving production control in construction. In simple terms, the thesis tried to answer *how* and *why* to develop indoor positioning technology for construction site. The theoretical impetus behind such a quest is the lean construction philosophy emphasizing the reduction of *waste* in construction. This aspiration embodies itself in engineering that create the tools and means for achieving it. This thesis was a little piece of engineering that takes small steps towards this goal.

7.1 Future Research

Considering the two objectives of this work, there are lots of room for further development and research on both fronts. One is to develop the technology to achieve a better overall performance for the location tracking system, including but not limited to higher accuracy. The aspects of system suitability for construction context and affordability are not less important. There can be systems that are very accurate but are impossible to deploy in a construction site, or that are simply too expensive. Bluetooth 5.1 was published in January 2019 by Bluetooth SIG, which means that the techniques of *Angle of Arrival* (AoA) and *Angle of Departure* (AoD) will now be able to reach unprecedented accuracy for positioning calculations [63]. This is with similar technology than that of our prototype, which means that such a system could be built with similar devices than those used in our prototype.

The other front is to develop more use cases for location tracking system as tactics for lean construction management. This will require an exploring mind set to capture the relevant links between resource location information and different aspects of construction production. Integration of location tracking with BIM and even VR [11] can have a transforming impact on construction production control. The future of real-time location tracking in construction production will be very interesting. Technology is advancing, and so is the understanding of lean construction management. Ideas and concepts will eventually become products and services, although there will be no lack of challenges and difficulties. Many great product and business potentials are waiting to be discovered and fulfilled.

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