Exploring the idea of automating tower cranes

An analysis of opportunities and challenges for automating tower cranes on construction sites

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If at first the idea is not absurd, then there is no hope for it.

- Albert Einstein –

Preface

This graduation thesis covers the final stage of my educational career. Coming from the University of Applied Science with the desire to further develop myself, I started the Construction Management and Engineering Master, roughly two years ago. With a strong intention to graduate on highly practical and innovative matter, I was able to connect with Witteveen+Bos. The basis they provided, made it possible to research the concept of using automated tower cranes on construction sites. During this process, I was privileged to collaborate with different companies, which enabled a steep learning curve in the overall substance. I intend that the knowledge obtained from them, really contribute to the quality of this thesis, in which I am very grateful for.

I would like to thank my supervisors L. Mazairac and A. van der Zee from the Eindhoven University of Technology and M. Veerman from Witteveen+Bos. Their guidance helped me to through this process for the duration of six months. Furthermore, I am thankful for the input and openness of Dura Vermeer, J.P. van Eesteren and van der Spek, which have provided access to highly experienced experts in the field of tower cranes. To continue, all the people of Dura Vermeer who made it possible to use their tower crane, which really advanced the product developed during this research. Finally, I would thank my family and in special, my girlfriend, as they supported me during the complete Master track.

I hope this report encourages you to assess current practice and inspires to start redefining the, currently, very traditional construction process.

Jeroen Pouw

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Summary

The traditional methods used in construction projects are highly convenient for the predominant part of the AEC industry. Although, projects in general are becoming more complex, there is a lack for the adoption of new approaches. This result is mainly caused by the sector's nature, as projects consist of a certain level of uniqueness and are realized in a relative short time-span (Shelton, Martek, & Chen, 2016). This indicates the reason why technologies are more easily implemented in the pre- and post-construction phases, as those have more similarities project-wide. For this graduation research it is endeavored to research and contribute to innovations that are useful in the process of the executional phase itself. The main objectives of this thesis are:

- Assess the possibilities for automation of tower cranes
- Find out what challenges remain before actual utilization becomes possible
- Contribute in the solution for one of the remaining challenges

First, a literature review is carried out to three interesting fields, certainly necessary in the automation of tower cranes. Starting with the current organization of the tower crane utilization process is analyzed. Subsequently, it is studied what pre-constructional data already exist and should be produced to support automated tower cranes. The remaining field addressed during the review, focuses on acquiring real-time data complementary to the pre-constructional body. Second, an example project with the objective to create an automated tower crane on a construction site in Singapore is analyzed. Third, interviews were held with four experts in the field of tower cranes. With the use of these different research strategies, a complete picture is created of possibilities as well as the obstacles in the automation of tower cranes. This picture is formalized into an exploration that indicates and combines vital necessities for this approach. This exploration is used to establish a list of challenges that certainly need to be overcome. The challenge that introduces Crane Lift Path (CLP) coordination problems due to (un)predictable variables resulting in structural deformation of tower cranes, is selected to develop a solution for. This decision is made upon the demarcated, technical scope that follows the tendency of this graduation research. It is tried to develop a prototype system that is able to measure this deformation continuously and includes this behavior in the overall path planning system installed on an automated tower crane. The prototype is developed during a process of testing, analyzing and improving the system in an iterative manner.

In order to automate tower cranes, it is important to create a central and digital process management system accessible to all stakeholders. Use of BIM to a high extend is seen as vital in the guidance of the complete project, as it has the potential to handle the large amount of data created. This data should be used as input for the tower crane. Hence, the acquisition of real-time data should adjust the crane activities to the actual situation, which is expected to differ in regard to the situation designed and established in the BIM process. Although, the exploration shows one approach to automate tower cranes, it also shows that construction workers need education to become familiar with this transition in the process. Furthermore, it is expected that automation of tower cranes is more successful in projects with a high level of pre-fabrication.

In the idea to solve the selected challenge, a sensor system is developed that measures displacement via acceleration. Because, the sensor is able to measure this, it is expected that it can measure the structural deformation of a tower crane as well. Crane deformation is seen as problematic, as it results in displacement of the object being lifted relative to its position coming from pre-constructional information. The sensor system developed, therefore, must be seen as an extension that improves the precision of the CLP. During several small-scale tests, much is learned about the sensor and it is determined that the type of sensor comes with high potential as its average error measurement is relatively small. However, it must be noted that this level of precision only is reached with the help of subsequent data processing. Because, the characteristics of the sensor used during this research it can be expected that more comprehensive sensors of the same type overcome this. To prove the usefulness of the sensor system developed, a large-scale test is arranged on an actual tower crane. In order to achieve this, the prototype is extended to three sensors. Although, the execution of the test was less successful as expected, it succeeded in measuring the deformation of the crane's tower. This made it possible to sufficiently conclude upon the usefulness of the prototype developed.

Samenvatting

De traditionele manier van bouwen blijft erg populair voor het grote deel van de bouwindustrie. Alhoewel projecten in het algemeen steeds complexer worden, ontbreekt het aan nieuwe benaderingen voor bouwmethoden en processen. Dit komt voornamelijk door het karakter van de sector, aangezien projecten een zekere mate van individualiteit hebben en in relatief korte periode worden gerealiseerd (Shelton, Martek, & Chen, 2016). Dit wordt dan ook gezien als de voornaamste reden waarom nieuwe technologieën gemakkelijker kunnen worden geïmplementeerd in de voorbereidings- en nazorgfase van een bouwproces. Deze vertonen namelijk op projectoverstijgend niveau meer overeenkomsten. In dit afstudeerproject wordt onderzoek gedaan naar een innovatieve benadering van het proces in de uitvoeringsfase van een project. De belangrijkste doelstellingen van dit onderzoek zijn als volgt:

- De mogelijkheden voor het automatiseren van torenkranen analyseren
- Bekijken welke uitdagingen resteren voordat toepassing realiteit kan worden
- Bijdragen aan een oplossing voor één van de resterende uitdagingen

Als eerste is er een literatuuronderzoek uitgevoerd naar drie verschillende belangrijke aspecten, welke zeker nodig zijn voor het automatiseren van torenkranen. Gestart is met het huidige proces voor het gebruik van torenkranen in kaart brengen en analyseren. Vervolgens is er onderzocht welke data geproduceerd wordt en moet worden in de voorbereidingsfase van een bouwproject om het gebruik van torenkranen al vroegtijdig te ondersteunen. Resterend is de aandacht gericht op methodes die bruikbaar zijn voor het verzamelen van actuele data in de uitvoeringsfase ter vervollediging. Als tweede is een voorbeeldproject, met als doel het creëren van een automatische torenkraan op een bouwplaats in Singapore, geanalyseerd. Ten derde zijn er interviews gehouden met vier experts op het gebied van torenkranen. Met behulp van deze drie verschillende onderzoeksstrategieën wordt een compleet beeld gecreëerd van zowel de mogelijkheden als de obstakels in de automatisering van torenkranen. Dit beeld is geformaliseerd in een kader dat alle kernaspecten combineert. Het kader wordt tijdens dit onderzoek gebruikt om een lijst van nog op te lossen uitdagingen op te stellen. De uitdaging gerelateerd aan de coördinatie van het hijspad, welke minder precies wordt als gevolg van (on)voorspelbare variabelen die leiden tot structurele vervorming van de torenkraan, is gekozen om een oplossing voor te ontwikkelen. Deze beslissing wordt genomen op basis van de afgebakende, technische invalshoek die de tendens van dit afstudeeronderzoek op een goede manier volgt. Er wordt geprobeerd een prototype te ontwikkelen dat deze vervorming continu kan meten en dit gedrag integreert in het totale planningsysteem voor hijsactiviteiten, geïnstalleerd op een automatische torenkraan. Het prototype ontwikkelt zich tijdens een proces van iteratief testen, analyseren en verbeteren.

Om torenkranen te kunnen automatiseren is het belangrijk om een centraal en digitaal procesmanagementsysteem te creëren dat toegankelijk is voor alle stakeholders. Het gebruik van BIM in hoge mate is essentieel voor het proces, aangezien het de potentie heeft om de grote hoeveelheid data te verwerken. Deze data moet worden gebruikt als input voor een torenkraan. Het genereren van actuele data moet de kraanactiviteiten aanpassen aan de feitelijke situatie, die naar verwachting verschilt met de in het BIM proces ontworpen en vastgestelde situatie. Ondanks dat het samengestelde kader een aanpak weergeeft voor het

automatiseren van torenkranen, laat het ook zien dat de bouwvakkers veel begeleiding nodig hebben om vertrouwd te raken met een dergelijke proces transitie. Daarnaast is het de verwachting dat automatisering een hogere kans van slagen heeft in projecten waarbij prefabricage in hoge mate wordt toegepast.

In de aanpak om de geselecteerde uitdaging op te lossen, wordt een sensorsysteem ontwikkeld dat verplaatsing meet doormiddel van het registreren van versnelling. Omdat de sensor dit kan meten, is het de verwachting dat het vervorming van de torenkraanconstructie ook zal kunnen meten. Deze vervorming wordt gezien als problematisch omdat het resulteert in een verplaatsing van het object dat door de kraan wordt opgetild ten opzichte van de positie bepaald in de voorbereidingsfase. Het ontwikkelde sensorsysteem moet dan ook worden gezien als een manier om het hijspad preciezer te maken. De eerste testen op kleine schaal resulteren dat de sensor inderdaad een redelijke nauwkeurigheid heeft waardoor er potentie zit in de getrachte toepassing. Echter is wel duidelijk dat deze precisie alleen gehaald wordt met nacalculatie van de gemeten data. Ondanks deze bevinding is het echter wel te verwachten dat betere sensoren van hetzelfde type dit probleem kunnen wegnemen. Om de bruikbaarheid van het ontwikkelde sensorsysteem te bewijzen is een grootschalige test uitgevoerd op een torenkraan. Om dit te bereiken is het prototype uitgebreid tot drie sensoren. Ondanks dat de uitvoering van de test minder succesvol was dan van te voren gedacht, is het toch gelukt om de vervorming van de mast te meten. Hierdoor is het mogelijk om goed te onderbouwen waarom het prototype bruikbaar is voor het automatiseren van torenkranen.

Abstract

There exists a difference between increasing project complexity and the shortfall in adoption of new technologies in the AEC industry. Because, the pre- and post-construction phases both are of similar nature every project, it is more straightforward to develop improvements for those. Therefore, this thesis encompasses the automation of tower cranes, as it exploits technology into the execution phase.

The research adopts a funneling method that starts with a literature review, consisting of current practices, the use of BIM and sensor technology. The statements found here, are evidenced and further examined with the help of an example project and expert interviews. Together, this basis shapes an exploration that combines every (technological) aspect necessary to automate a tower crane, operating in construction projects. Consecutively, it serves as platform for listing the remaining challenges that need solutions in order to realize the overall notion. Further depth is achieved in the development of a prototype that potentially deals with the challenge of CLP coordination problems due to (un)predictable variables resulting in structural deformation of tower cranes. Several experimental tests are used to scale up the prototype towards a functioning proof-of-concept. The findings of this thesis show that the automation of tower cranes is highly complex and involves the complete construction process. From the start, a central management platform accessible to all stakeholders is important. Furthermore, use of BIM to a high extend serves the input of data to the tower crane. However, there exists a deviation between the digital situation and reality. This deviation requires adjustment of the CLPs generated in the pre-constructional phase, making real-time data acquisition another important aspect of tower crane automation. The sensors used in the prototype show the potential of using real-time data to improve automated tower crane operations.

The findings of this research indicate that much effort remains in the development of BIM use in the entire industry. It should become possible to plan processes in more detail and compare them to the realistic situation in real-time. This, in combination with the implementation of multiple sensor technologies serves the idea of automating tower cranes.

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List of Abbreviations

ADC	Analog-to-digital converter
AEC industry	Architecture, Engineering and Construction industry
AoA	Angle of Arrival
CLP	Crane Lift Paths
DACS	Dynamic Anti Collision System
DOF	Degree of Freedom
DToA	Distance Time of Arrival
GPS	Global Positioning System
HDB	The Housing & Development Board
HS plan	Health and Safety plan
IBIS	Integrated Building Information System
IMU	Inertial Measurement Unit
IP	Intellectual property
IR	Infrared
LOD	Level of Development or Level of Detail
MEMS	Microelectromechanical system
MEP	Mechanical, Electrical and Plumbing
POC	Proof-of-Concept
POV	Proof-of-Value
RFID	Radio Frequency Identification
RI&E plan	Risk Inventory and Evaluation plan
RPI 0W	Raspberry Pi model 0W
RPI 3B	Raspberry Pi model 3B
RSSI	Received Signal Strength Indicator
RTC	Robotic Tower Crane
RTLS	Real-Time Location Systems
SICS	Smart Integrated Construction System
SN	Sensor Networks
SQL	Structured Query Language
ToA	Time of Arrival
UWB	Ultra-Wideband
VA	Vision Analysis
VLF	Vertical Line Finder
WHSQ	Work health and safety regulator in Queensland
WSN	Wireless Sensor Networks

1. Introduction

Ideally, construction projects are prepared to a high level of detail. Furthermore, the construction process is automated to a high extend and structures are erected with prefabricated components. Finally, all information captured during a project is evaluated in such that the stakeholders advance their learning curve. In order to reach this goal, numerous challenges remain to be conquered. In future, construction projects are becoming more complex and come with higher levels of risks. This is a major issue for large construction companies as they are confronted with this. Furthermore, the increase of complexity also comes with more difficulties in project management (Armstrong & Gilge, 2016; Abdou, Youn, & Othman, 2016). This results in a slow adoption process of innovative applications and keeps the companies delivering many of their projects delayed and over budget. Because of this underperformance, the construction sector remains highly traditional in regards to other sectors. Although, several governments have been doing research regarding this issue, no real improvements are made yet (Shelton, Martek, & Chen, 2016). According to the survey of Armstrong & Gilge (2016), important reasons of why the construction sector has not embraced new technologies are: the fact that perceived benefits are not in line with involved costs and risks and the issue that many companies are reluctant to use new approaches. Because, construction companies work project based, consisting of relative short periods with a certain level of uniqueness, low intention exist for long-term performance improvement (Shelton, Martek, & Chen, 2016).

1.1. Problem definition

The statements above immediately clarify why technologies that did find their way into the industry mostly appear in the pre- and post-construction phase (e.g. design, planning and maintenance). These phases are relatively similar in every project. This raises the interest for this thesis to research technologies applicable in the executional phase. Different fields of research already show theoretical examples of high-tech applications for automating the construction process. One development that is noticeable in the construction process, is the shift from labor intensive activities towards activities based on the assembly of prefabricated components. This change embraces the assumption of more automation. A challenging case that shows a high degree of automation on site presents itself in the project of Witteveen+Bos. Here, it is aimed to start using an automated tower crane with the ability to find objects and lift them into the correct position. Because, this is a new approach for using cranes on construction sites, numerous challenges appear. For example: enabling the crane to find components, enabling the components to be hoisted into the right position, monitoring the crane movement and communication between site personnel and the cranes. When looking at this approach from an overview, it remains unclear how to implement automated tower cranes in the overall construction process. Therefore, the overall objective of this research is to assess if it is possible to automate tower cranes and find out what challenges have to be dealt with before effective utilization becomes feasible. One of these challenges that need a solution is the continuous deformation of the jib and mast of tower cranes. This decreases the level of precision of the coordinate system for crane activities. Therefore, this research contributes to the overall system by the aim to develop a sensor system that resolves this issue.

1.2. Research questions

As already mentioned in the previous section, this research first aims to tackle the developments regarding automated tower cranes in construction projects and narrows the direction of research to remaining challenges. In order to really contribute in this field, a method is tested that measures the deformation of the crane in real-time to increase the level of precision in the path planning system of the crane. This study involves a literature review of possible applications and knowledge for an exploration to automating tower cranes. Furthermore, an example project and multiple interviews will be reviewed to gather practical information from industry. Ultimately, a testing phase is used to establish an answer on the main research question, which is as follows:

How can tower cranes operating on large construction sites be automated in order to improve the object assembly process with the use of sensor data?

The main question is divided into several sub-questions that provide a direction for this research:

1. How is the tower crane operating process currently organized in the construction industry?
2. Which data from the pre-construction phase serves the automated tower crane operation process?
3. Which data is needed to realize the application of automated tower cranes, complementary to pre-constructional data?
4. How can the idea of automated tower cranes be explored and what challenges remain before utilization reaches viability?
5. In pursuance of the remaining challenges, how to measure structural deformation of tower cranes with the use of sensors during lift activities?
6. Is the method for measuring structural deformation of tower cranes leading to a solution for the selected challenge?

1.3. Research design

Research can be classified as pure or applied. Pure research tries to find natural laws and discovers new theories, which ultimately results in new knowledge that contributes to the existing body. Applied research is more practical and tends to find solutions for challenges industry faces. This allows for the actual development of new solutions. Important to note is that pure research forms the basis for any applied approach (Fellows & Liu, 2003). The type of problems will determine the most logical choice for using a specific research method. Fellows and Liu (2003) state that problems can also be divided in two categories. The first category include closed problems that aim at only one possible solution. This makes the root of a problem easily identifiable and often heuristics are used to find solutions. The second category are open problems that are of a higher complexity. Open problems occur in dynamic situations and their variables are hard to grasp (Fellows & Liu, 2003). With this knowledge, it becomes clear that the problem of this research is of the open category. Furthermore, the research design is a combination of both pure and applied research.

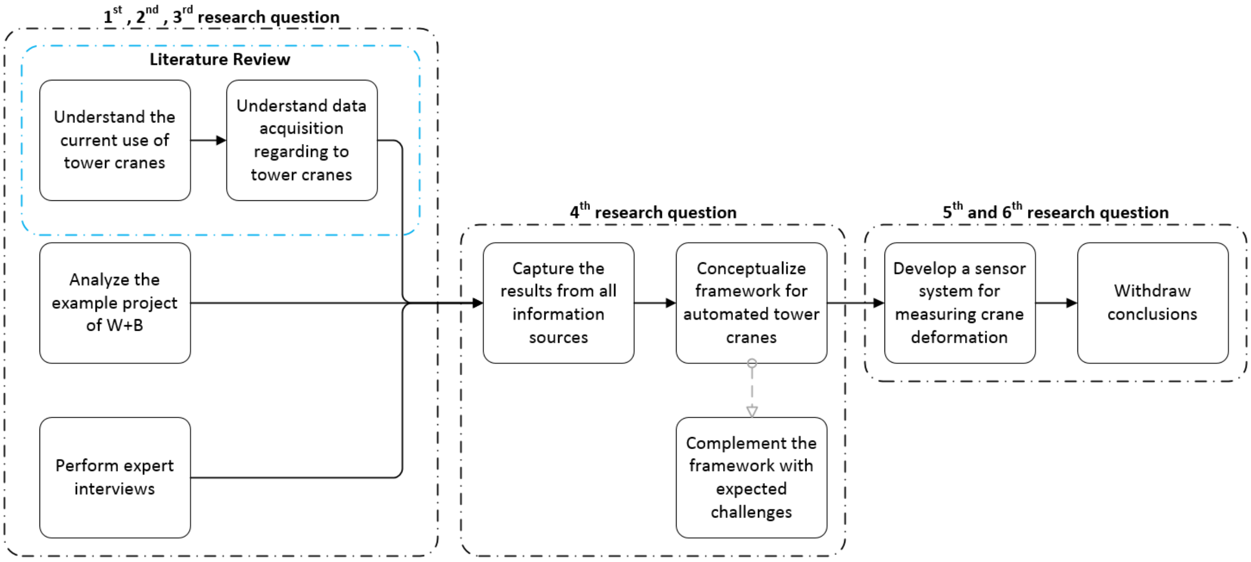

Figure 1. Research design

Figure 1 shows the division of research questions, their main objectives and the order of conduct towards conclusions and answer on the main research question. The first three questions suit the category of pure research and exist of a comprehensive literature review to three different issues related to automated tower cranes. First, the current practice and developments made in the field of tower cranes are reviewed. Second, the use and capabilities of BIM in practice are examined alongside new developments made in specific for cranes. Third, automated tower crane operations only become possible when real-time information is gathered and collaboration with pre-constructional digital data (BIM) becomes possible. Several technologies are reviewed and many different variables captured as an attempt to extend the level of knowledge in the approach of automating tower cranes. Furthermore, the knowledge examined in the literature review is extended with an example project of the attempt by the graduation company, where a project is started to develop an overall information system that is expected to result in the utilization of an automated tower crane. To complete the body of knowledge regarding automation of tower cranes, expert interviews are held with different companies working in the construction industry and are specialized in tower crane operations. The results from the pure research will help to explore automating tower cranes in the construction industry. However, in reality this is a highly complex system that will come with many challenges before actual utilization becomes possible. The formulation of these challenges mark the start for the practical part of this graduation project.

Therefore, the fourth research question is seen as the transition between pure and applied research. One of the listed challenges, indicated early in literature and interviews, is the continuous structural deformation of tower cranes, which is expected to result in coordination problems. This behavior is tried to be measured with sensors and its potential influence is examined with several tests. In order to achieve this, a suitable sensor and data streaming and transformation network is created. Several test cases, ranging from small-scale tests to actual implementation in a tower crane establish the level of contribution to the preciseness of the overall path-planning algorithm that will be installed on automated tower cranes.

1.4. Practical importance of the thesis

Automation purposes in the executional phase of construction projects is interesting for research and development. Especially, because future construction methods are shifting towards a higher level of prefabrication. This thesis combines several fields e.g., current practice, building information modeling and real-time sensor technologies, which provide detailed insights of what is involved in the automation of tower cranes. Furthermore, the development of a measurement system for crane deformations, if useful, can be immediately implemented in practice. Currently, the fabricators of tower cranes are the only ones who make calculations regarding expected deformation in the mast of a tower crane. Whenever this is measured in real-time, contractors and leaseholders of tower cranes can analyze this information and extend their knowledge in the structural behavior of tower cranes. Especially, this is helpful in utilizing standard crane configurations on construction sites. In the long-term, this thesis is helpful, as it indicates how tower cranes can be automated and potentially provides a solution for one of the remaining challenges. Ultimately, this will bring automation of tower cranes one step closer to reality.

1.5. Reading guide

In the method of answering the research questions exemplified in section 1.2, the first three questions are handled in chapter 2 till 4. Each chapter is dedicated to one of the research strategies that all ended with a description of results. This description bundles the functionalities and challenges of practice, BIM and real-time data. Because, the literature review, analysis of example project and expert interviews all end with this description, the broad scope is narrowed down. These bundled results are used as input for the exploration of chapter 5. This chapter is a closure of the first part of the research and answers the fourth research question. Furthermore, this is the starting point for finding out, which challenge is attempted to be solved during this graduation thesis. The approach of the development for a solution is completely explained and executed in the sixth chapter, which also host the results of the developed system. Finally, both parts of the research are reviewed in the discussion and conclusion sections.

2. Literature review

Tower cranes belong to the largest type of equipment used at high-rise construction sites and organize the vertical transport of materials for all (sub-)contractors. Because, tower cranes are key in the logistical process, which constantly reforms to become more efficient, planning crane operations increase in complexity. In some cases, this results in decisions that negatively influence on-site conditions regarding safety (Al-Hussein M. , Niaz, Yu, & Kim, 2006; Kang & Miranda, 2006). In addition, high-rise construction projects are often realized in densely populated areas, such as business districts. This makes the size of tower cranes also hazardous for its direct environment. In the study of Tam & Fung (2011), it is stated that the primary reason for accidents related to tower cranes is the human factor, e.g. inadequate training and fatigue. In order to get completely acquainted within this field of tower crane research, it is important to understand what type of equipment tower cranes are and how the process of using them is structured. Additionally, pre-constructional and real-time operational data acquisition and use are identified as primary fields of interest in the automation of tower cranes. First, the pre-constructional field reviews the current capabilities and trends of Building Information Modeling (BIM), as this is expected to serve as input for the crane. Second, the possibilities of acquisition and use of real-time operational data is covered. This is expected to extend the input from BIM and enables tower cranes to operate automatically. Finally, The literature review ends with a part of the answer on the first three research questions.

2.1. Tower cranes in general

Multiple different types of tower cranes exist and there prevail interesting technologies that already are applied or will be in the near future. However, the range of technologies analyzed here, is restricted to the idea that it fits the purpose of tower crane automation. The primary source of information used here, comes from the German company Liebherr. In Kemp (2016), the sales director of Liebherr's tower crane division states that his company exceeds 50% market share, making them the largest supplier of tower cranes in the world. Furthermore, other fabricators, such as Terex, Potain, Falcon, Wolfkran and FMGru all provide similar types of cranes. The main difference with those companies is that Liebherr is leading in the development of supplementary technologies.

2.1.1. Different types of tower cranes

In total, six types of tower cranes are often used on construction sites. For small scale projects, such as dwellings and small apartment buildings, fast-erecting cranes are popular. These cranes erect themselves with a hydraulic system and therefore, no additional crane is necessary for (dis)assembly. The maximum lifting capacity of such cranes is around eight tons and their radius is maximized to 50 meters (Liebherr, 2016). Figure 2 shows a fast-erecting crane. Another type of tower crane is a mobile construction crane that is placed on a truck and operated by a single person. These trucks are equipped with multiple steering axis, so it can be maneuvered in tight positions. Other than normal mobile cranes, this type comes with a vertical tower to enable placement close to obstacles. The maximum lifting capacity of these cranes is eight tons and its maximum radius is 58.5 meters (Liebherr, 2016). Figure 3 shows a mobile construction crane.

Figure 2. Fast erecting crane (Liebherr, 2016)

Figure 3. Mobile construction crane (Liebherr, 2016)

A third type of tower crane is the top-slewing crane, which is designed to be easily (dis)assembled and transported. Most of the top-slewing cranes come with the Litronic system that is explained in the next paragraph. A special type of top-slewing cranes are the ones that erect vertical themselves. A large hydraulic system lifts up the top of the crane, while vertical sections are positioned in the tower. After each new section is positioned, the crane erects itself again until the requested height is reached. With this system, a supplementary crane is only necessary for (dis)assembling the jibs of the crane. Top-slewing cranes come with a massive range in lifting capacities and radii. A second type of crane that belongs in the top-slewing category is the luffing-jib crane. Luffing-jib cranes can lift their jib with a maximum of 70 degrees in order to reduce their turning cycle. This makes them applicable in dense areas. The largest top-slewing crane reaches a radius op 100 meter and comes with a maximum lifting capacity of 80 tons (Liebherr, 2016). Figure 4 and Figure 5 show two types of top-slewing cranes.

Figure 4. Top-slewing crane (Liebherr, 2016)

Figure 5. Luffing-jib crane (Liebherr, 2016)

The last category of tower cranes are the special cranes, which come in two types: fast-erecting or top-slewing fitted with tracks for easy repositioning in difficult terrain and so-called Derrick cranes that consist of such small components, it can be transported through elevator shafts. This makes the Derrick crane highly applicable in projects where space is unavailable on the construction site for positioning a large top-slewing crane (Liebherr, 2016). Figure 6 and Figure 7 show two types of special cranes.

Figure 6. Derrick crane (Liebherr, 2016)

Figure 7. Tower crane equipped with tracks (Liebherr, 2016)

2.1.2. Crane operation technologies

During the international trade fair for new construction and agricultural machines (ConExpo-Con/Agg, 2017th edition), Liebherr revealed their newest fast-erecting tower crane (Liebherr, n.d.). This crane, equipped with the latest technologies available, marks the starting point to applicable existing technologies that serve automation purposes. In total six technologies have been found that potentially are advantageous to crane operations and the acquisition of data. However, it must be noted that up until now some are only applied on other types of cranes.

Litronic - The Litronic system is the central crane control management system of Liebherr. This technology is modular and therefore can be connected to other supplementary technologies in hard- and software, e.g. Sycratronic and Cycoptronic that will be explained in this section (Liebherr, 2011).

Load-Plus - Increases the maximum lifting capacity with 20% by reducing the operating speed. A crane is selected mainly on its capacity to lift the heaviest elements on the construction site. However, most of the time, cranes are lifting materials below their maximum capacity. With this technology, smaller and therefore cheaper cranes can be chosen, capable of lifting the few heavy elements that were normally leading in the decision making process (Liebherr, n.d.).

Load control - Provides automated counter measures to movements of the jib that for example arise from wind or heavy loads. Furthermore, slewing movements caused by swinging loads are also compensated via a so-called oscillation damping system. Those technologies increase the level of precision and control during lifting activities (Liebherr, n.d.)

LiDAT - Collects data of around 100 parameters regarding cranes and other large equipment during operations. This helps in scheduling maintenance and off-site help. This technologies aims to decrease the suspension in processes were large equipment is in use. Supervisors and maintenance staff automatically receive a notification whenever problems emerge. Furthermore, this collection of data is used to optimize plans that can be communicated directly to the machine operator (Liebherr, 2014; Liebherr, 2016).

Cycoptronic - All crane operators move loads with a certain amount of swing, which slightly reduces the pass of every movement. Especially, in the short movements of bulk handling cranes that (un)load ships, which add up to a substantial delay. This inefficiency is reduced by Cycoptronic, as this technology only needs a loading position and an unloading position. When these are set, the crane automatically operates until new positions are required. The system optimizes the route and motion between the two positions and therefore, reduces the amount of swing. The technology calculates the motion based on gyroscopes that react immediately on environmental changes (Liebherr, 2011; Liebherr, 2014). It must be noted that this technology is used only for simple operations of bulk handling cranes.

Sycratronic - Synchronizes the crane control system with a second crane for dual crane lifting activities. One operator fully in controls the two cranes of which one is the lead crane and the other is the follower. The operator can move the load on all three axis with the help of a Dynamic Anti-Collision System (DACS) that controls the motion. The DACS reacts whenever collisions threaten to happen between the cranes themselves or with obstacles. Besides DACS, the Vertical Line Finder (VLF) system is integrated in Sycratronic. VLF prevents the cranes from pulling the load to one side by adjusting the cranes in such, the lifting cables remain vertical (Liebherr, 2011; Liebherr, 2014).

The different crane types and recent developments in operation technologies, indicate that advancements are being made in the industry. As vertical transport remains an essential activity on construction sites, which increase in complexity, it shows that tower cranes are following this trend. Tower cranes become more precise in their lifting activities, can be applied in denser environments and contribute to the increase in overall safety at construction sites. However, before a crane becomes operational, extensive analysis, design and preparation is necessary. In order to completely understand the scope of current tower crane practices, the following section describes the organization of the present tower crane deployment process.

2.2. Tower crane deployment process

In September 2016, the Dutch tower crane directive has been launched. This directive consists of safety, environmental and health aspects related to tower cranes and is created by Bouwend Nederland, which is an association representing the interests of contractors in the construction industry (Bouwend Nederland, 2017). The directive is created, because numerous risks are involved in the use of tower cranes and the present need for clarity in responsibilities during the process (Verheyen, 2016). Key to this directive is the division of the process in six phases (initiative, contracting, design sub-components, assembling, operation, disassembling and evaluation) and the allocation of staff involved:

- Project team
- Structural engineer (design)
- Structural engineer (lead)
- Structural engineer (partial)
- Coordinating engineer
- Crane (dis)assembling staff
- Controlling expert
- Crane operator
- Crane supervisor
- Crane guidance staff
- Point man
- Maintenance staff

Appendix I shows the overview for combination of phases and involved staff members, obtained from Bouwend Nederland (2017). Because, this directive guides the process instead of precisely stating what needs to be done, it is necessary to conduct a detailed analysis of how the tower crane deployment process is organized. The following paragraphs maintain the process division of the introduced directive.

2.2.1. Initiative

The initiative phase starts when the client of the project appoints a coordinating engineer. The coordinating engineer first starts with formulating a Risk Inventory & Evaluation Plan (RI&E plan), which forms the basis of the Health & Safety plan (HS plan). The HS plan includes all risks and dangers appointed with their measurers, protocols and solutions, as it is of major importance to assess the problems that possibly harm the project (Arbouw, n.d.). However, Arbouw states that in the HS plan of the initiative phase it is likely that not all problems are solvable at this point in time. Therefore, it is important to address those in the HS plan for the design phase. The advice Arbouw & Bouwend Nederland (2017) provides for this phase is the selection of a crane supervisor who is responsible for guarding the lift plans during the operation phase of the tower crane process. Appendix I shows that the first principles of the crane design are determined at this point, which enable the main contractor to find the right parties to contract for the project. Leading in this determination is the project team that is advised by structural and coordinating engineers.

2.2.2. Contracting

Most of the time, tower cranes are leased or rented from companies that own a complete stock of different types of cranes. In the research of Shin (2015) about the health and safety procedures of crane use in Korea it is stated that the main contractor contracts a leaseholder and potentially a sub-contractor that facilitates the (dis)assembly and service of the crane. From Appendix I it is clear that the contracting principles are set by the project team which is advised by the structural engineer and negotiated with the contracted companies after being controlled by the coordinating engineer.

2.2.3. Design

During the design phase, work is continued upon the first designs created earlier in the initiative phase. To create the most optimal design, it is necessary to analyze the weights of materials that have to be lifted, the dimensions of the construction, the dimensions of the construction site, presence of obstacles and soil conditions (Arbouw, n.d.). According to the Tower Crane Directive, the following reports and documents are mandatory at this stage of the process: approved building permits, structural calculations of the tower crane, soil composition report (including two ground probes and measures of the maximum and minimum groundwater levels), construction drawings, operational manual provided by the supplier, control reports and daily work schedules (Bouwend Nederland, 2017). As is described in the initiative phase, the HS plan is extended during this phase. This extension consists of emergency plans for each workplace in the operating reach of the crane and issues that were unaddressed in the initiative phase, now have to be addressed. Finally, the composition of the supplementary crane staff members is determined according to the risk assessment of the HS plan (WHSQ, 2017).

2.2.4. Assembling and Disassembling

This phase starts with an initial meeting and site inspection with the main contractor, leaseholder and sub-contractor for (dis)assembly. A risk assessment follows directly after this meeting together with a method statement, describing the protocol for (dis)assembling the crane. The responsible body that must sign off these documents is the sub-contractor for (dis)assembly (Strategic Forum for Construction, 2008; Bouwend Nederland, 2017). A second meeting is the pre-activity inspection that is required to take place within seven days prior to the start of the crane assembly. The purpose of this meeting is to ensure that conditions did not change and methods are still adequate to pursue. Furthermore, it is a check to see the progress of temporal works and required conditions that have to be met before assembly of the crane can start. On the day the crane assembly starts, a third inspection is held to check everything for the last time. This is also the moment were the coordinating engineer signs off the approval to erect, climb or dismantle the crane (Strategic Forum for Construction, 2008). Before any components of a crane are delivered to the construction site, they have to be inspected. Furthermore, manufacturer's instructions have to be present at the start of the assembly as well as the disassembly stage. As stated above, all pre-specified conditions have to be met prior to the start of works. However, unexpected conditions such as poor weather conditions are reason to stop the process. According to WHSQ (2017), it is the responsibility of the duty holder (main contractor and leaseholder) to ensure that the crane is (dis)assembled properly.

The main components of a tower crane are the foundation, mast, slewing unit, operating cabin, jib and counter-jib with its weights. The mast is placed on the crane's foundation and gives the crane its designed height. On top of the mast, the slewing unit with gears, motor and rotation system is connected. At the front of the slewing unit, the jib is attached and at the back the counter-jib with weights. Finally, the operation cabin is placed. Some cranes, as explained earlier are able to climb themselves. These types come with a hydraulic system that lifts up all components above the mast and enables a new section of the mast to be inserted in between. It is important to follow procedures as described in the method statement as the (dis)assembly stage is the most dangerous part of the process (Shin, 2015).

2.2.5. Operation

Before any lifting activities can start, the main contractor meets with the coordinating supervisor about last measures to smoothen the process. Furthermore, a coordination meeting is held between all involved contractors that need the crane for their own activities. Because the crane is a shared piece of equipment, detailed lifting plans are made. These plans and the outcome of the meeting should be documented in another extension of the HS plan. All parties involved are required to be present during this meeting (Arbouw, n.d.). Several other important aspects are the inspection of required documentation by the crane supervisor and the daily visual check of the crane operator. Whenever any defect is discovered, the crane operator decides to fix it himself or contact the maintenance staff. The crane owner (lease holder), however, must receive notifications of every defect on the crane (Arbouw, n.d.) It is possible for the crane owner to conduct site visits in order to check if the crane is used the way it should be used (WHSQ, 2017).

A second type of required meetings is the work consultation meeting that is arranged on a daily or weekly basis. Here, arrangements are made and employees are instructed about their activities and equipment that will be used. Also the methods of communication and securing materials to the crane are required to be discussed during these meetings (Arbouw, n.d.). The most important communication is between the crane operator and its point man. Hand and arm signals often form the basis for this, but on larger construction sites with multiple obstacles, a porto phone becomes important. The way of communicating between those staff members is standardized to avoid common mistakes and is only allowed at a specific frequency to prevent for any interference. Besides the porto phone, camera systems are attached to the crane, which enables the crane operator to get visuals of what is proceeding (Arbouw, n.d.; WHSQ, 2017).

The crane operator is the most important person involved during the operation phase of the tower crane. At all times the crane operator can stop the activities around the crane, even if the conditions are within operation standards. Before any lifting movements can be undertaken, the point man and crane operator must be sure that the hoist rope is vertical above the load. Whenever a (near) maximum load is lifted, the crane operator should follow a procedure of: lifting the load a few centimeters, testing the hoist brakes, check the mass on the load indicator and recheck the load chart (WHSQ, 2017). In the code of practice for safe lifting operations, applied in Singapore, a distinction is made between routine and non-routine lifting activities (National Crane Safety Taskforce, 2014). Routine activities, for example are façade or floor elements, which all have the same size and weight. In routine activities, the risk level decreases as they are already mitigated previously. Non-routine activities are more complex as they constantly should be analyzed by the staff members involved. Finally, whenever the crane operator leaves the operating cabin, it is mandatory that the crane is shut down according to the instruction manual. The most important aspect here is to set the crane in such mode, it can rotate freely because this relieves the pressure on the crane created by the weather conditions (Arbouw, n.d.).

2.2.6. Evaluation

At the end of each project, a meeting is arranged for evaluation purposes. During this meeting, the crane process should be extensively discussed. In the research of Sertyesilisik, Tunstall & McLouglin (2017), it is concluded that this positively influences the learning curve and is a good way to improve safety on construction sites.

By combining all phases, it is evident that tower cranes are not being deployed easily. A large and comprehensive process is necessary to guarantee a certain level of safety for everyone involved. At this point, it is clear what type of tower cranes exist and how they are being used in the construction industry. This provides a solid basis for understanding what challenge remains in automating tower cranes. The next section of the literature review focusses on the use and functionalities of BIM, as pre-constructional data is fundamental in the exploration to automated tower cranes.

2.3. Pre-constructional data recommended for automating tower crane operations

In order to automate tower cranes, detailed information is necessary from the pre-construction phase. Nowadays this information is generated manually e.g., construction drawings, structural calculations, analysis and contracts. However, the upcoming use of BIM is digitizing this information in a more efficient way and stores it in a single environment approachable for every stakeholder. This environment is seen as the source of information for automated tower cranes. Also, BIM enhances collaboration, better analysis and simulations. Actually, the project can be built on the computer previous to the start of a construction phase. It is expected that BIM is the starting point for automating tower cranes. However, reality often deviates from the digital models and problematic is the case that BIM models sometimes are inconsistent. Therefore, this section reviews the current level of BIM in the AEC industry and continuous with analyzing the BIM outputs that are beneficial to this case. Finally, it is described what the focus of literature is in the creation of crane lift path planning. As a result, parameters are listed to indicate what is important for crane analysis, simulations and automation.

.3.1. The current level of BIM practice

According to Turk (2016), BIM is the abbreviation for three terms in the AEC industry: Building Information Modeling (process), Building Information Model (product) and Building Information Management (process control). To remain clear, this review continuous to maintain this division, but changes the terms to BIM (process), BIM model (product) and BIM management (process control). The growing level of BIM maturity needs these different terms, as it all started with the challenge of representing buildings in 3D and evolves into a management process for complex AEC projects with a high level of interoperability during their entire life-cycle (Turk, 2016). Several recent studies provide different views on what BIM actually is. Turk (2016) state that BIM is a toolset that changes the construction processes and result in deeper knowledge and a higher level of quality. Liu, Nederveen & Hertogh (2017) see BIM as a socio-technical system that comes with the ability to combine modeling features with process management, while Ghaffarianhoseini, et al. (2017) state that BIM as a set of technologies, focusses more on the improvement of inter-organizational collaboration during project life-cycles. Figure 8 shows the timeline of these developments and indicates what is expected for the coming years.

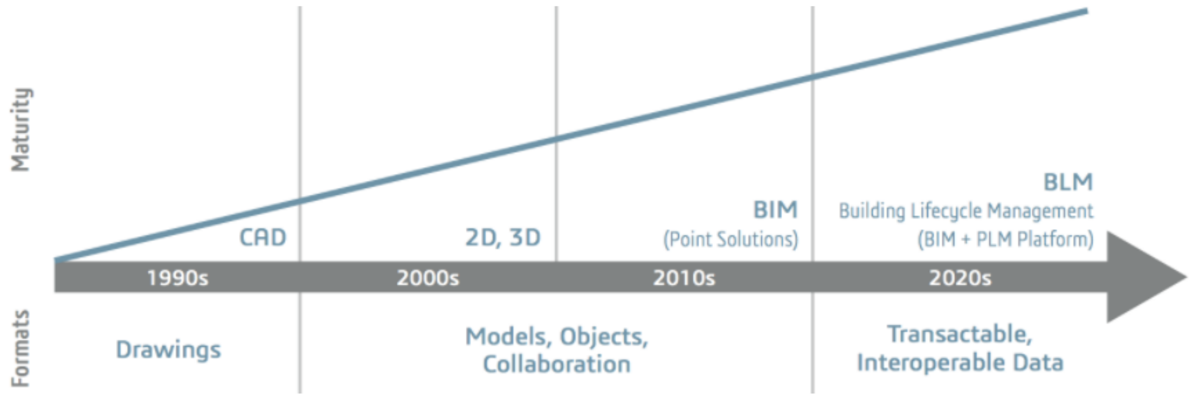

Figure 8. Timeline of BIM developments (Moriwaki, 2014)

The creation of a BIM model that grows from a conceptual design into an executional design and continuously updates alongside this process, which is the core functionality of BIM. Several disciplines e.g., architects, engineers and contractors, are working on segregate models of their own specialties that can be combined into one aggregate model (Straatman, Pel, & Hendriks, 2012). This aggregate model can be tested in order to find clashes and design failures. At the stage were the aggregate model reaches the agreed quality, quantities can be extracted. By connecting the 3D model with the time schedule, a 4D model is created that shows the progress according to the planning. This 4D model can be linked with the cost schedule, which then results in a 5D model. According to Straatman, Pel & Hendriks (2012) these models are becoming more popular as they make processes more efficient and allow for simulations and different analyses. Redmond, et al. (2012) define these models under the framework of nD BIM, which suggest that there are no limitations and allows for developments under a generic term. Research to BIM mainly focusses on the following levels: industry, company and project. This makes the possibilities of BIM even larger, while the adoption of BIM in the industry is lacking behind (Howard, Restrepo, & Chang, 2017).

In Ghaffarianhoseini, et al. (2017) the British AEC industry is analyzed and results show that 94% is aware of BIM, while only 39% currently uses it. Several reasons for this lag are: the traditional nature of the industry, untrained staff, abrupt change of current workflows, high initial investments necessary to start with BIM and interoperability issues between well-known software packages (Bouska, 2016; Howard, Restrepo, & Chang, 2017). Applying BIM entangles the relations between project stakeholders to a more complex level. Therefore, a need exists for BIM governance that is allowed to create policies for the use of BIM. It can be imagined that the process of settling contracts between project stakeholders is highly difficult, as there still is no legal framework that supports this high level of interoperability in the AEC industry (Alreshidi, Mourshed, & Rezgui, 2017; Liu, Nederveen, & Hertogh, 2017). Especially, liabilities and Intellectual Property (IP) rights are causing issues in BIM management. Architects are lacking the willingness to share their models and protect their IP, while contractors are careful in the use of models created by architects. Often, it is the case that the BIM model lacks the necessary quality and need lots of time to be adjusted, which is problematic because of the IP rights (2013). Furthermore, when BIM is outsourced to engineering companies, it is difficult for other stakeholders to access all information, unless extra fees are paid to the firm that created the model according to several participants of the expert interviews held by Liu, Nederveen & Hertogh (2017). Although, these disadvantages still remain, there is an increasing need to exchange growing amounts of information between project stakeholders. This need makes BIM to mature in an undeniable concept of which, the complete AEC industry acknowledges the existing benefits (Bouska, 2016; Ghaffarianhoseini, et al., 2017; Liu, Nederveen, & Hertogh, 2017). In addition, there are made contributions in solving this hurdle, in the form of the openBIM initiative, introduced by buildingSMART international and multiple software companies. OpenBIM should be seen as a standardized method for proper collaboration between stakeholders regardless of differences in software or data standards. IFC, BCF and other well-known standards are used in the openBIM initiative to achieve this (Berlotti, 2012).

BIM is more efficient because all project stakeholders make decisions based on exactly similar information captured from the BIM model. In the research of Liu, Nederveen & Hertogh (2017), it becomes clear that clash detection and generation of visualizations are the most used functionalities of BIM. However, as stated above, there are many other functionalities such as, taking off quantities, information exchange, project analyses and simulations (Yu, Li, & Luo, 2016; Ghaffarianhoseini, et al., 2017). In Yu, Li & Luo (2016) the reason for not using all functionalities extensively, is the fact that contractors still base their plans on personal experience. A shift in this mentality will reduce the amount of rework along the process if BIM is used correctly. The question that remains in the industry is: how to use BIM correctly? Although, there are multiple approaches in the development of BIM in a project, the industry is in need for a standard that enables correct BIM, BIM models and BIM management. According to Monteiro & Pocas Martins (2013), a general standard will be of major assistance in optimizing the performance of existing BIM functionalities. One of the latest advancements in BIM is the use of cloud technologies. In fact, research concludes that cloud technology is the future for using BIM more efficiently. The most important advantages of cloud BIM are: reduction in hardware investments, easy scalability, continuously updated BIM models, easy accessibility and real-time back-up generation. Also cloud BIM is still under development and several issues, such as data security, privacy and dependency of an internet connection remain unsolved (Alreshidi, Mourshed, & Rezgui, 2017).

2.3.2. Output of BIM as input for tower cranes

Previously, it is described that BIM generates one aggregate information model useful for the entire life-cycle of a project. This process changes the procedures for exchanging information and tries to improve collaboration between project stakeholders. A BIM model with sufficient quality provides a database that is useful for determining material quantities, clash detections, delivery times, storage area management and process analysis and simulations. The type and quality of information from the aggregate BIM model depend on the Level of Development (LOD) attached to the segregate BIM models (Getuli, Ventura, Capone, & Ciribini, 2016; Yu, Li, & Luo, 2016; Marzouk & Abubakr, 2016). BIM models mature in quality as the project progresses, which can be classified according to the concept of LOD. This specifies the accuracy and reliability of object information (model output) (BIM Forum, 2016). Furthermore, LOD means level of Detail, which reveals the amount of detail included in the elements (model input). By defining different LODs during the project, expectations are clear for the people involved in the BIM management. The concept of LOD exists of six different levels, explained in Table 1 located on the following page.

Table 1. Explanation of different levels of LOD (BIM Forum, 2016)

LOD 100	Symbols instead of geometric elements are used to represent the existence of elements. This level lacks any information of shape, size and location.
LOD 200	Generic placeholders are used to represent the needed volume of elements in space.
LOD 300	Correct representation of dimension, location, orientation and quantity of elements. Information referring to the element is placed in the model as well.
LOD 350	Continuous upon LOD 300 by adding complementary components to elements.
LOD 400	Continuous upon LOD 350 by including detail. This level is accurate enough for fabrication processes.
LOD 500	Verification of information in the modelled elements. This level does not represent elements itself.

Quantity Takeoffs

From LOD 300, it becomes effective to derive quantities automatically and use this data for determining costs, workloads and other project information. In BIM jargon this is called Quantity Takeoff (QTO). Traditionally, QTOs are created manually from 2D CAD drawings, which is highly labor intensive. Monteiro & Martins (2013) state that the quality of manual calculations is dependent on human interpretation because the quantity surveyor must understand all specifications included in the drawings. In large projects, multiple surveyors are involved and it is common that different interpretations result in deviations between final documents. QTOs derived from BIM are calculated with time and error reductions in comparison to the manual QTOs. However, BIM QTOs require a higher level of detail, earlier in the process and reach such a level of complexity, only experts use it. The current lack of standards contribute to the existence of this problem (Monteiro & Martins, 2013; Wang, et al., 2016). Another disadvantage of BIM QTOs is that specific elements, such as formwork and supplementary equipment are difficult and time-consuming to model in current BIM software (Monteiro & Martins, 2013). For this problem, two solutions are available: calculate these quantities manually or model the components with basic tools (e.g. walls, beam and roofs). The problem that rises is the pollution of data, as is stated by Monteiro & Martins (2013). Their research concludes the need of an intermediary step, which use BIM QTOs for large elements that affect the overall estimations the most and allow the quantity surveyors to derive QTOs of details manual.

Clash detection, visualization and simulation

In the creation of a 4D BIM model, milestone activities are used to simulate the process. This reduces the workload of acquiring and processing all data. However, in realistic simulations it is important to use a more detailed specification of activities. The same applies in the creation of 5D BIM models, as this improves the possibilities of BIM management for construction sites and its operational equipment. (Wang, et al., 2016; Peng & Chua, 2017). Information that is useful, complementary to the BIM model can be divided into static and dynamic data. Static data relates to the building locations, access roads, location of large equipment and workspaces. Dynamic data represents information related to material supply and construction schedules (Yu, Li, & Luo, 2016). Furthermore, project and operation data can be separated. According to Tantisevi & Akinci (2007), all construction activity and progress data belongs to the project-level, while data regarding the dynamic motion of crew, equipment and other similar resources fits in the operation-level.

Marzouk & Abubakr (2016) proposed an approach that is using QTOs for the generation of lift plans and the extraction of Cartesian coordinates of objects. Furthermore, the BIM model is used for obstacle analysis and crane selection. The researchers suggest that further research should develop a 4D BIM model simulation, which helps in understanding the sequence of the lift plan and checks for possible collision between the moving parts and the building objects (Marzouk & Abubakr, 2016). Another approach originates from the research of Peng & Chua (2017) were a BIM model is used to identify crane positions, (un)loading coordinates and constraints related to building and spatial components. According to these parameters, crane lift plans are determined. These plans exist of lifting capacity checks and obstacle analysis. The used approach is similar to the clash detection approach that is extensively being studied and already used in the industry to check for compliance with design regulations. It exists of a framework that relates the BIM model to a crane information model and parametric lifting activities. These activities should meet certain constraints before being inserted in the lift plan (Peng & Chua, 2017). Necessary input for the crane information model is obtained from manufacturer catalogues (e.g. specifications), regulations (e.g. clearance space) and project analysis (e.g. crane position), as can be seen in Figure 9. However, Pen & Chua (2017) study mobile cranes, their framework result in a decision support mechanism that serves the crane operator by pre-specifying the boom length, boom angle for swing and boom angle for (un)loading. Their research is helpful as it visions which parameters are important for automating tower cranes.

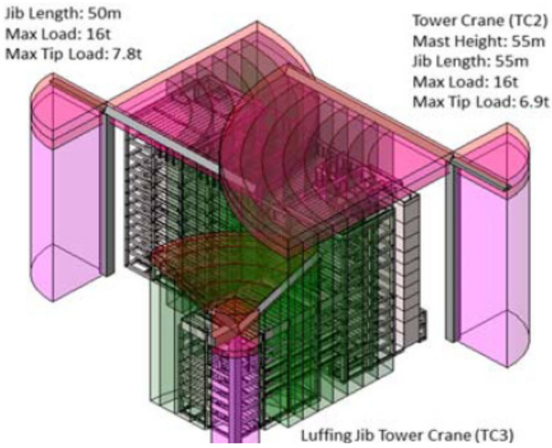

Figure 9. Implementing crane parameters in the BIM models (Peng & Chua, 2017)

Lei, Taghaddos, Hemann, & Al-Hussein (2013), state that crane analysis based on pre-constructional data is ought to result in the following variables: job requirements, crane locations, minimum and maximum radii of crane, clearances and crane capacities. In their research, a system is developed based on these variables, which enables automated generation of lift plans by pre-planning every activity related to the crane. It is concluded that successful deployment of comparable systems relate to the quality of its path checking method (Lei, Taghaddos, Hermann, & Al-Hussein, 2013). One of the most important aspects to take into account during this analysis is the highly dynamic workspace of a crane. Within the cranes workspace, conflict situations potentially result in work interruptions, production reduction, damages and dangerous working conditions (Tantisevi & Akinci, 2007; Yeoh, Wong, & Peng, 2016). Although, a detailed analysis is helpful in optimizing the construction site layout, the executional phase of projects remain dynamic. Therefore, it is difficult to introduce modifications in reality (Marzouk & Abubakr, 2016).

Simulation of equipment operations is beneficial in the communication process between project stakeholders. However, these stakeholders can only act upon the simulation if it is has been completely understood. Therefore, simulations should show a realistic view, as more abstract simulations are not sufficient enough to provide insight in the requirements and limitations of the working environment. Furthermore, abstract simulation is concluded to be more error prone, since it easily misses conflicts (Al-Hussein M. , Niaz, Yu, & Kim, 2006; Yeoh, Wong, & Peng, 2016). One important aspect of a realistic simulation is the need of an 4D BIM model that is extended with operational information (e.g., construction activities, equipment operations, motions and locations). The 4D model simulation helps in determining collision free paths, by allowing workspace analysis of the crane. The conclusion of Tantisevi & Akinci (2009) shows that a manual approach is not working well, because cranes perform hundreds of activities in their operational phase each day, although, it is noticed that many operations are of repetitive nature (Tantisevi & Akinci, 2009). Table 2 provides a complete overview of useful parameters for crane analysis, simulation and automation that could be extracted from BIM.

Table 2. Necessary parameters for crane analysis, simulation and automation

building and Spatial	crane	objects
orientation	jib length	object geometrics
building geometrics	mast height	object weight
site boundaries	lifting capacity	(un)load coordinates
site layout	rotation speed	object center point
construction schedule	trolley speed	
material supply schedule	(un)winding speed	
equipment positions	clearance limitation	
	boom clearance	
	minimum and maximum crane radii	

2.3.3. Complementary crane lift path planning characteristics

The generation of crane lift paths (CLPs) is the result of the concepts (clash detection, visualization and simulation) covered in the previous paragraph. By combining the motions performed for each lift activity a CLP of one single object appears. By combining all single CLPs, a project CLP planning is created. In reality, two major constraints must always be assured: never exceed the maximum lifting capacity and never collide with any obstacles. Generating a project CLP is highly challenging as cranes have many Degrees Of Freedom (DOF). A DOF represents a single motion of, in this case, tower cranes (Lin, Wu, Wang, Wang, & Gao, 2014). In their research, an algorithm is proposed that first plan a collision free path for a mobile crane, followed by an optimization of this path. The generation of collision free paths is concluded to be successful, but optimization remains difficult (Lin, Wu, Wang, Wang, & Gao, 2014). The actual CLP is created by a path planning algorithm, which determine collision free paths in the workspace of robotic systems. Zhang & Hammad (2012) evaluate several of the algorithms (Dijkstra, A*, Bug-based algorithm, Genetic Algorithm and D*) that are useful for CLP planning. In their study is becomes clear that some are accurate enough to be applied, while others come with limitations, regarding safety and misbehavior, when used is the massive workspace of a tower crane. The evaluation of Zhang & Hammad (2012) indicate that progress is being made in this field and relate to the concept of path smoothness, which explains the quality of the crane motion and its ability to reduce unnecessary movements. An extension of the path planning algorithms is the re-planning algorithm, which acts upon real-time information. These can be linked to the general path planning algorithm and repairs the pre-specified path whenever new obstacles instantaneously appear (Zhang & Hammad, 2012).

Another field or research that develops CLPs is robotics. Lin, et al. (2014), review several advancements made in this field. One case introduced a near real-time lift path planning method for crane erections. This approach exists of two phases, starting with the generation of a workspace and continue with the detection of collision free paths by using the probabilistic roadmap method (PRM). Another convenient algorithm for path planning is called Rapidly exploring Random Trees (RRTs). This algorithm has been successfully deployed in several robotic systems and recently found its way into studies that approach path-planning problems. Therefore, Lin, et al. (2014) describe a study that developed an RRT-based approach for monitoring and re-planning the lifting paths of cranes with the use of real-time location systems. This particular study continues with the development of a motion-planning algorithm that efficiently generates a safe path taking into account the smoothness of the lift. Lin, et al. (2014), finally describe a research that has been focusing on the CLP of tower cranes. Here, laser technology is made capable of generating lift paths instructed by a BIM and sensor-based navigation system (Lin, Wu, Wang, Wang, & Gao, 2014). Figure 10 and 11 show two examples of their proposed results.

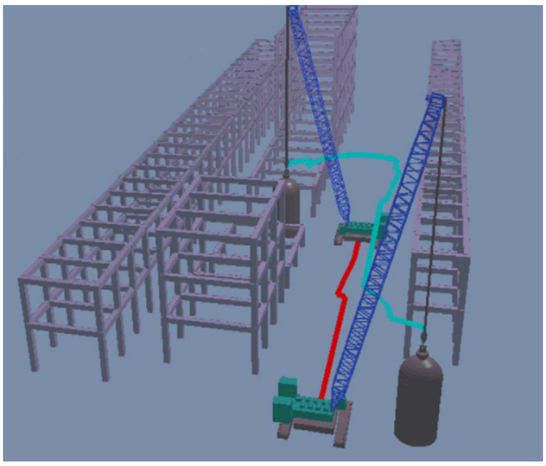

Figure 10. Path planning algorithm used on crawler crane example 1 (Lin, Wu, Wang, Wang, & Gao, 2014)

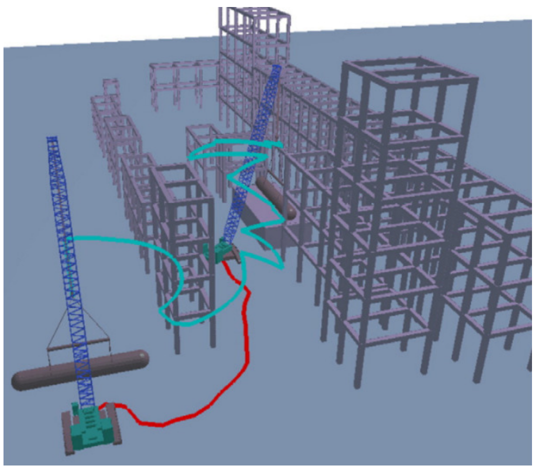

Figure 11. Path planning algorithm used on crawler crane example 2 (Lin, Wu, Wang, Wang, & Gao, 2014)

2.3.4. Overview of process by implementing operational data into BIM

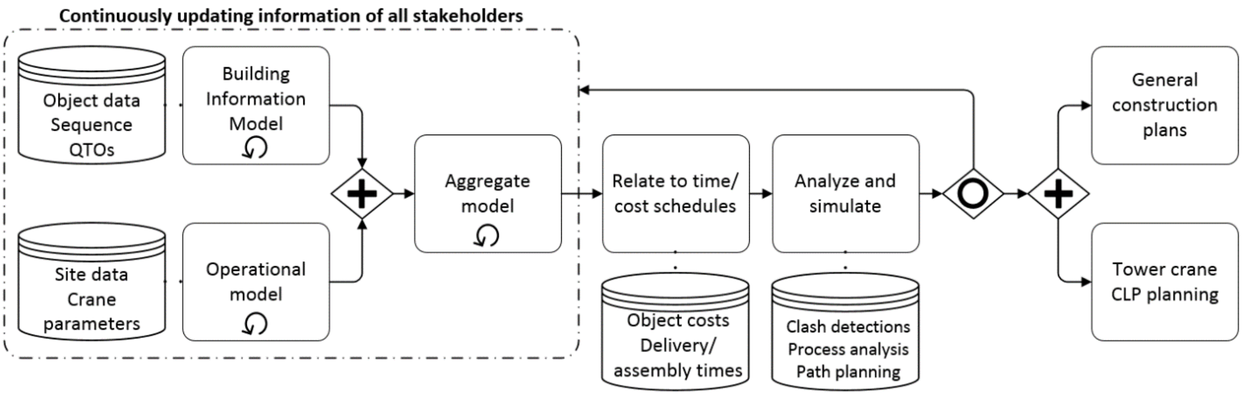

Figure 12. Pre-construction phase process overview

In order to provide a linkage between the reviewed BIM aspects from literature and show how this could be implemented in the pre-constructional process, an overview is given in Figure 12. As is stated previously, a BIM model is created of the building. Among other elements, this model includes the object data and sequence of construction. This model should be aggregated with an operational model that includes process data (e.g., site data and crane parameters). The aggregated model must function as a comprehensive overview of the project. The loop inside each model activity node indicates that the information is continuously updated during the pre-constructional phase towards a certain Level of Development. To remain within the nD framework of (Redmond, Hore, Alshawi, & West, 2012), the model shows that 4D/5D modeling starts after the aggregate 3D model is created. In the 4D/5D step, the building and operational data is linked to time and cost schedules for object costs and object assembly times. Here, QTO become an important feature as it subtracts vital information for these linkages. The following step in the process is analyzing if the strategy designed is acceptable. During analysis and simulation, the pre-constructional CLPs are generated with the help of a path planning algorithm. Sequentially, the creation of clash detection as explained in this chapter are a feature that support the used path planning algorithm. Whenever, failures are detected, the models should be adapted and the previous steps are repeated. This process continuous until the strategies are sufficient. Logically, this ends the pre-constructional phase and the overall result are the necessary construction plans and the complete tower crane CLP planning. Finally, it must be stated that the lack of a BIM standard makes the overview explained here bendable.

The use of BIM in general seems inseparable in attempts to automate tower cranes. Although, current capabilities of BIM are sufficient enough to serve as source of pre-constructional data, challenges remain in the implementation of the proposed concepts. Also, in the first part of this section it becomes clear that BIM developments are more focusing on the organization of BIM itself. At this point, it is understood which functionalities are beneficial to automating tower cranes, what parameters are vital to include and how path planning problems are approached. However, as is indicated, the pre-constructional data should collaborate with real-time data. This is important because construction sites are dynamic and many deviations arise from the pre-construction phase. Therefore, the following section of the literature review examines different technologies capable of acquiring of real-time data.

2.4. Real-time data acquisition for automating tower crane operations

Among others, a major obstacle that prevent for the utilization of automated tower cranes is the manual tracking of materials and equipment. Because construction projects increase in complexity, manual tracking activities become more and more difficult to manage. Furthermore, the changing positions of objects on site require reliable data acquisition (Pradhananga & Teizer, 2013). Therefore, technologies capable of acquiring such information provide opportunities for managing construction processes. Extensive research effort has been taken into the subject of advanced computing and information technologies in the field of construction (Jang & Skibniewski, 2009). The researchers state that the ultimate goal of analyzing construction site data is real-time construction management. Many technologies, such as RFID and GPS provide an imperfect solution capable of automated resource tracking on construction sites. Their performance is limited due to the characteristics of construction sites, e.g., large dimensions, dynamic and filled with obstacles (Jang & Skibniewski, 2009).

It is evident that the importance of tracking technologies is growing during the operational phase of construction projects. This is beneficial for the automation of tower cranes, as their support cannot be derived only from the planning and pre-constructional analyses. Real-time process data of on-site information is complementary to this. The dynamic nature and unexpected situations, which are typical on construction sites must be taken into account in order to reduce the risks of any collision between the crane and its surrounding (Zhang & Hammad, 2012). Options for automated data acquisition, other than mentioned above are: laser scanners, flash LADAR, video analysis, WLAN and UWB (Hwang, 2012; Carbonari, Giretti, & Naticchia, 2011). All of them potentially improve the project control and have been tested in research. However, they provide the capacity to track resources on construction sites (e.g., workers, equipment and materials), their reliability remains relatively unknown. According to Yang, Cheng, Teizer, Vela & Shi (2011), prove of reliability is necessary to enable large scale adoption at construction sites. By combining the pre-constructional data coming from the BIM process with real-time data acquisition is expected to result in an automated crane system with higher knowledge. Therefore, this section describes and compares multiple sensor technologies that help in operating tower cranes.

2.4.1. Real-time location and hoisting path data

As is described earlier, path planning is an activity performed in the pre-construction phase. However, the hoist path should be adaptive to its environment and therefore path-planning is extended in the cranes operational phase to compensate for unexpected events (Zhang & Hammad, 2012). A system of different types of sensors can be used to automate the tower crane. This paragraph introduces a number of examples found in literature.

The research of Ghang, et al. (2009) proposed an automated tower crane that uses lasers, an encoder and accelerometer to become operational. Its feasibility is tested under several conditions (indoor, outdoor and swinging). It is expected that the use of an automated tower crane results in reduction of construction time, loans, material costs and improves the level of safety. Their concept starts with an identifier indicating the start of a lift activity. These identifiers come from a central database, which stores information regarding the planning and the 3D BIM model. Secondly, the point man is instructed to find the material that needs to be lifted with the help of GPS and RFID. Third, a lifting path is created based upon the location were the point man scans the RFID tag and the final position of the object coming from the database. Once the lifting path is created, the crane moves accordingly. However, Ghang, et al. included dynamic variables related to the construction site, helping the actual lift path to adapt itself to the actual situation (Ghang, et al., 2009). Another attempt is derived from the study of Lee, et al. (2012). Here, a hybrid system is developed as navigation for tower cranes, by combining the BIM model with a video camera and anti-collision system. Also in this system, lasers and an encoder are used to measure the rotation of the jib, the distance of the trolley from the zero-point and the distance between the trolley and the hook. Furthermore, a laser counts the number of windings the cable is lowered or lifted. Both implementations of lasers come with disadvantages, according to the researchers. The laser counting the number of windings is not ideal as the crane tends to slip when lifting heavy objects. The laser measuring the distance from the trolley to the hook, potentially misses its reflector when the load swings in windy conditions (Lee, et al., 2012). This statement is different in regard to findings of Ghang, et al. (2009). Here, on-site experiments reveal that loads do not swing much, as they are heavy and the hook is supported by at least two wires. The researchers also conclude that dust and other normal weather conditions are not affecting the preciseness of the lasers (Ghang, et al., 2009). Although, this difference lee, et al. (2012) use both approaches to prevent for any failures. Furthermore, the anti-collision system monitors the crane by checking its slewing angle, trolley position, maximum load and length of the hoisting cable. The BIM model is used as an extension of the sensors and provide a visualization and coordinate information of the object and tower crane, which is helpful for the crane operator. During their research, the BIM model was not updated automatically, although, it is concluded that a 4D functionality of the BIM model linked to the crane process would be ideal in their application (Lee, et al., 2012).

The most recent example is found in the research of Maghzi (2014). In this study the BIM 4D model is attached to a safety monitoring and GPS system. The overall goal of this development is improving the level of safety on construction sites. The system alerts the crane operator by sending a warning whenever a load is within a certain perimeter of any obstacle. According to the researcher, GPS fits best for such applications as it is functional outdoor and a minimal system infrastructure is necessary (Maghzi, 2014). By reviewing these examples it can be suggested that automating a tower crane only becomes possible if a hybrid system is developed, which is able to include layout changes and unknown obstacles in real-time, complementary to the data output of BIM. This real-time information must be fed into the re-planning algorithm to improve the overall level of path planning and communication (Zhang & Hammad, 2012). The upcoming paragraphs provide a more detailed explanation of what real-time location systems (RTLS) useful for automating tower cranes are.

2.4.2. Real-Time Locating Systems

According to Li, Chan, Wong & Skitmore (2016), RTLS is useful for locating the geographic positions of humans, materials and equipment, consisting of a combination of software (algorithm) and hardware (sensors) applications capable of finding these coordinates in real time. Pradhananga & Teizer (2013) state that chances to react upon potential dangers increase when data is updated more rapidly or ultimately in real-time. Furthermore, collected data serves other purposes as it helps in many different process analyses (Li, Chan, Wong, & Skitmore, 2016). Currently, RTLS is used in many other industries, such as handling containers in port terminals and in the security management of hospitals. most RTLS work similar by attaching tags to all traceable objects. Despite its introduction in the construction industry, its capabilities are lacking behind. Mainly, this is the result of the vast dimensions of construction sites and the occurrence of false alarms regarding collisions. This results from the note that RTLS sensors have a particular accuracy error (Park, Koch, & Brilakis, 2012; Li, Chan, Wong, & Skitmore, 2016). As a result of the interviews, Ghang, et al. (2009) held with robot experts, the following factors are seen as important in the determination of an RTLS application. Together, with an extension of the characteristics coming from Cheng, Venugopal, Teizer & Vela (2011) the list becomes more complete, as can be seen in Table 3.

Table 3. Characteristics of RTLS systems obtained from:

Ghang, et al. (2009)	Cheng, et al. (2016)
maximum measurable distance	dependence of line of sight
error range	required signal strength
laser safety	data output
durability	calibration requirements
compatibility with other equipment	
dimensions of the system	
weight and price	

RTLS applications can be categorized within (wireless) sensor networks. Both consist of a number of nodes (sensors) of which their position is calculated via several triangulation methods that locate coordinates from three known positions (antennas). One of them is the use of the received-signal-strength-indicator (RSSI), which use the strength of a transmitted signal to determine the distance travelled of that signal. Another method is the angle-of-arrival (AoA), which measures the location based on the angle from where the signal is originated. Two other methods are the time-of-arrival (ToA) and time-distance-of-arrival (TDoA), which both measure the time necessary for the signal to arrive at a sensor, transposed into a distance. To note, the speeds of the signal must be known upfront. All four methods enable location via geometric relationships brought together by triangulation. To illustrate, ToA is used in GPS applications, while DToA is used in active RFID systems (Cheng, Venugopal, Teizer, & Vela, 2011). Specific insight in the possible RTLS applications are created in the following paragraphs that describe and compare a number of such technologies.

2.4.3. Different RTLS sensor technologies

In Li, Chan, Wong & Skitmore (2016), a critical review is provided of existing RTLS technologies. Their selection include: GPS, Infrared, Ultrasound, RFID, WLAN, Bluetooth, UWB, magnetic signals, vision analysis and audible sound. Furthermore, they indicate future research directions (Li, Chan, Wong, & Skitmore, 2016). The literature used in their review is analyzed to establish an understanding of the possible RTLS technologies, potentially applicable on automated tower cranes. For this specific purpose, some technologies could be withdrawn immediately from the selection. The remaining interesting RTLS technologies described in this section are: RFID, GPS, UWB, Vision analysis, Ultrasound and Infrared. According to Hwang (2012), the use of such technologies grow in importance and the selection of appropriate technologies should satisfy the following requirements: equipment locations should be collected within short time intervals, reliable and accurate collision detection and the system should not be influenced by line-of-sight problems.

Radio Frequency Identification (RFID)

In the AEC/FM industry, RFID has grown to an automated data collection and information storage technology. On construction sites, it is often applied as inventory tracking method. To explain, RFID tags are attached to all building elements throughout the life-cycle of a project and capture information that serves as input or output for BIM models (Park, Chen, & Cho, 2017; Motamedi, Soltani, Setayeshgar, & Hammad, 2016). Park, Chen & Cho (2017), state that RFID technology is not meeting the requirements for accurate tracking of real-time dynamic objects on construction sites. One reason for this, is the fact that RFID is not a real sensor technology, as its components miss the characteristics and functionalities of sensors. RFID is not generating physical measurements. However, if RFID is connected to a sensor system, its network can be used to transmit sensor readings (Park, Chen, & Cho, 2017; Motamedi, Soltani, Setayeshgar, & Hammad, 2016). Examples of RFID applications are: indoor object location tagging, asset tracking, inventory management, equipment tool tracking, material management, facility management and quality control (Motamedi, Soltani, Setayeshgar, & Hammad, 2016; Razavi & Moselhi, 2012). RFID communication is based on electromagnetic transmission and radio frequency circuits. In large open areas, RFID can be combined with other technologies, such as GPS. This increases the accuracy of localization. Furthermore, RFID systems can be classified in two categories: active systems that use receivers to locate tags and passive systems that use fixed tag positions to locate the receivers (Li, Chan, Wong, & Skitmore, 2016). From the research of Razavi and Moselhi (2012), it becomes clear that an error of 1.3 meter is average in areas comparable to construction sites.

Global Positioning System (GPS)

GPS consist of three elements: The space segment, which defines the satellites orbiting around the earth, the control segment, which is the monitoring system of the satellite positions and the user segment, which is the GPS tag that locates the objects (Pradhananga & Teizer, 2013). According to Pradhananga & Teizer (2013), GPS is useful for outdoor application and provide relatively accurate position measurements. The major disadvantage of applying GPS are the costs involved for implementation, which are higher than many other technologies. One example of using GPS on construction sites is the analysis of dynamic equipment operations. This is possible because GPS does not require any other infrastructure than GPS tags, which are wireless (Pradhananga & Teizer, 2013). GPS finds the position of a tag with the use of triangulation methods, as explained in the previous section. The distance between the satellites and the tags, the travel time of the signal and the speed of light is important for this type of triangulation. Field tests in an open area resulted in an average measurement error of 1.1 meter. However, this error increased significantly (2.15 - 4.36 meter) in the urban area tests (Li, Chan, Wong, & Skitmore, 2016). According to the researchers, the error measurement reduces when GPS is combined with other technologies.

Ultra-Wideband (UWB)

UWB is a radio frequency technology, used for tracking resources with the help of sensor tags. The tags used in UWB applications, are wearable and enable 2D as well as 3D trajectory sensing. Receivers placed at the outer boundaries of construction sites calculate the positions of tags with triangulation methods. 2D positions require three receivers, while a 3D position need at least four. Ensuring adequate positioning requires many tags and receivers on construction sites that form a certain overlapping environment (Yang, Cheng, Teizer, Vela, & Shi, 2011). According to the Yang, et al. (2011), UWB should be further researched in order to completely understand and evaluate its potential. Furthermore, it is stated that UWB is similar as RFID, however, it comes with the benefits of a higher data transmitting capacity and its ability to track multiple tags in a wide area, both indoor and outdoor. Hwang (2012), added the following: higher reliability and response times than RFID, the ability to communicate with less interference and better performance in dense environments with metal objects, such as construction sites. UWB signals are sent with a short pulse and therefore, can be filtered from other interfering signals. This is useful in multi-path distortion in indoor environments and is concluded to provide accurate results. The average error is below 0.5 meter, however, this error increases as the system is used in large areas and in cases were obstacles are involved to around 1.25 meter (Li, Chan, Wong, & Skitmore, 2016). UWB can be applied for tracking people and equipment and is also deployed in safety and training purposes of construction workers. One other example of UWB deployment in construction sites is the safety and monitoring system that prevent for collisions by monitoring tower crane movements and other equipment. Simultaneously, the system tracks the real-time location of construction workers. A limitation of UWB is the requirement of connection with a local area network (LAN), which can be problematic at initial stage of a construction project (Li, Chan, Wong, & Skitmore, 2016).

The paper of (Cheng, Venugopal, Teizer, & Vela, 2011) focusses on the performance of UWB on construction sites. it is stated many barriers exist for contractors that disable the employment of data acquisition technologies: risks of failure during initial implementation, high implementation costs, lack of demonstrated benefits and inability of the user to understand and exploit the collected data. Compared to technologies like RFID and ultrasound, UWB shows unique advantages: longer range, higher measurement rate, more accurate, immune to interference from rain or clutter (Cheng, Venugopal, Teizer, & Vela, 2011). Their study concludes that UWB reaches sufficient accuracy to be of practical use for many construction sites in a less dense environment. Furthermore, UWB assists in the safety and productivity management of construction sites (Cheng, Venugopal, Teizer, & Vela, 2011).

The study of Hwang (2012) state that many studies concerning UWB, mainly focus on locating materials and workers. Furthermore, it is concluded that the developments already made in this technology are not yet sufficient enough to monitor equipment operations and collision detection. The concept of Hwang (2012) acquires real-time process data and proves that UWB can do more than just locate objects. In addition it is expected that UWB performs much better when combined into a hybrid system (Hwang, 2012).

Vision Analysis (VA)

Analysis based on camera vision and its attached technology mostly is used to compare the as-built structure with the as-planned 3D model, detection of defects and virtual reality purposes. According to Yang, et al. (2011), VA is shifting towards a resource and material identification and tracking technology. This is an interesting development, as it allows for tracking objects in large-scale dynamic environments without the use of a tagging system. In order to use VA for this specific goal, 3D ranging video cameras are implemented on the construction site (Park, Koch, & Brilakis, 2012). In the research of Li, Chan, Wong & Skitmore (2016), it is described that VA is affected by many environmental characteristics, such as: lighting, background colors and dynamics of the environment. Nevertheless, VA is being used in research concerning construction site analysis. One study, traced a worker, a concrete bucket, a dozer and a wheel loader to examine errors under several conditions, such as illumination and occlusion. A second study extended the VA system for tracking the position of a tower crane and estimated its location during operations (Li, Chan, Wong, & Skitmore, 2016). It must be noted that VA only works when there is a direct line-of-sight. Otherwise, the video cameras cannot detect any object. This often cannot be assured, due to the dynamics of construction sites (Hwang, 2012).

Ultrasound

Ultrasound technology is derived from studying bats that make use of ultrasound to navigate when flying around. With the use of transmitters and receivers, the location of an object is calculated via triangulation. Ultrasound does have one major limitation, as it is highly affected by metal surfaces. This makes it difficult to apply on construction sites (Li, Chan, Wong, & Skitmore, 2016). Furthermore, ultrasound signals have a ranging distance of maximal 15 meters and communication between transmitter and receiver requires a line-of-sight. Only if the signal has a reasonable strength, it can go through obstacles (Hwang, 2012; Jang & Skibniewski, 2009).

Infrared (IR)

IR is similar to ultrasound as transmitters and receivers communicate between each other with a direct signal. One example of an IR application is the remote control for televisions. One of the reviewed studies used a 3D range camera for tracking resources, workers and equipment. In the experiments, the dimensional error was less than 0.12 m. This is highly accurate, but it must be noticed that the range camera is only able to obtain positioning data of objects at a distance of 7.5 meter (Li, Chan, Wong, & Skitmore, 2016). According to (Hwang, 2012) Infrared is limited to its short distance of communication and detection of objects, as this results in a very short time to react upon the sensed data. Furthermore, infrared is influenced by natural light. In different studies concerning IR, it is noticed that a wide range of measurement errors exist.

2.4.4. Overall characteristics of RTLS systems

Obtained from Li, Chan, Wong & Skitmore (2016), several characteristics can be specified to support the decision of a particular RTLS technology for deployment on construction sites:

- GPS only works in outdoor environments and its accuracy is dependent on the density of the area it is deployed in.
- Ultrasound is the most accurate technology when a direct line-of-sight is possible. Otherwise, its signal strength is strongly reduced when it has to go through objects.
- Vision analysis loses track of objects when in environments with shadows and blind spots.
- UWB and RFID, both using radio frequencies and need access to a LAN connection to provide accurate location properties. Both technologies are affected by the presence of (metal) objects, which surely are present on construction sites.

Besides the overall characteristics, the most important characteristic is expected to be the average error measurement. This indicates how precise all RTLS technologies are and can be a primary decision parameter. Table 4 shows the reviewed technologies and their average measurement error based on field experiments in similar environments as construction sites.

Table 4: Average measurement errors per technology in similar environments as construction sites

Technology	Average error	Environment	Source
RFID	1.3 m	construction site/laboratory	Razavi and Moselhi (2012)
GPS	1.1 m	open area	Pradhanaga and Teizer (2013)
	2.15 – 4.36 m	urban area with obstacles	Li, et al. (2016)
UWB	0.41 m	construction pit (2.400 m^2)	Cheng, et al. (2011)
	1.26 m	lay down yard (65.000 m^2)	Lee, et al. (2016)
VA	< 1.0 m	simulation with actors	Yang, et al. (2011)
Ultrasound	0.97 m	outdoor environment	Jang and Skibniewski (2009)
Infrared	0.12 m	distance < 7.5 m	Li, et al (2016)

2.5. Results from the literature review

The body of literature reviews the overall scope of aspects necessary in the research to automated tower cranes. Existing types of tower cranes and available technologies in this particular field are described. Furthermore, the current tower crane process is analyzed according to the Dutch tower crane directive and other relevant literature. These three aspects are fundamental to understanding the current situation in the field of tower crane operations. Another important part is the collection and usage of data, starting with a review of the existing level of BIM and its barriers. Continuing with BIM, it is studied what type of functionalities contribute to automation of equipment and the different variables that should be captured in the pre-constructional phase of the process. Finally, an overview of numerous technologies is provided to indicate what the possibilities are, as this extends and completes the data generated in BIM. In the exploration that shows what is involved in the automation of tower cranes, the literature review is the first source of information and its results are located in this section.

2.5.1. Functionalities and challenges from current practice

A central control management system (Litronic for Liebherr cranes) is expected to be vital for automation. Because, Litronic is modular and Liebherr is the only crane manufacturer that currently develops additional technologies, the system is extendable with interesting other technologies. In particular, Load Plus (reduces the operating speed of the crane during heavy loads), Load Control (provides counter measures of crane movements via an oscillation damping system) and LiDAT (a data analysis software regarding crane usage). LiDAT benefits from automation of tower cranes as project analyses can be a useful source of information for upcoming projects. A major challenge in automating tower cranes is the communication between the point man and the crane. Standardized hand signals and use of porto phone are not applicable anymore, as there is no crane operator. New methods for communication are important in the collaboration between equipment and humans.

2.5.2. Functionalities and challenges from BIM

BIM is expected to be a highly important aspect in the automation of tower cranes. However, it is obvious that more detailed analyses and developments are necessary. As an example, every lifted objects should precisely be modelled, in such their dimensions and weights can be analyzed to help in the selection of a specific crane type. BIM will help in speeding up the process and increases accuracy as opposed to the traditional approach. Furthermore, simulations, visualizations and clash detections between crane and objects ought to become possible. However, this comprehensive part of the process requires capturing many parameters, as can be seen in Table 2. These functionalities help in the creation of CLPs that can be generated in a digital environment with the help of a path-planning algorithm and object coordinates. CLPs are seen as the basis for crane operations in reality and should be extended with real-time information. Furthermore, planning these operations helps in tracking material and equipment activities and reduce the need of manual tracking, which is seen as a major obstacle for automation purposes.

Establishing CLPs in BIM is only tested during experimental research, however, it is concluded that these plans come with many benefits compared to the ones manually established and made on short notice during the operational phase. The applied level of BIM and understanding in the industry is facing several barriers in its current practice. Defining responsibilities and IP rights in the BIM model seems difficult and these will not be solved in the utilization of automated cranes. However, the exploration being established in this research is expected to contribute to the overall maturity process of BIM.

2.5.3. Functionalities and challenges from real-time data

In the handling of loads, it is important to maintain a vertical line between load and trolley. This can be measured by laser sensors. Furthermore, the weight and of each load is important information as well. Besides the path planning algorithm used in the pre-construction phase, the dynamics of construction sites require an additional re-planning algorithm that act on real-time information. One note on the use of algorithms is the fact that the operational reach of a crane is large and therefore long computation times are expected. This indicates the necessity of developing optimized algorithms. Although, it is possible to determine collision free paths, dangerous situations can still appear. The concept of path smoothness, therefore, should extend the CLPs even further. Path smoothness relates to the quality of the lift path, the cranes motions and the ability to reduce unnecessary movements. In addition, RTLS technologies, such as the examples mentioned in section 2.4.2. review enable tracking of objects and the overall progress. In the application of RTLS on construction sites, wireless capabilities are important as the network is of temporary nature and employed in a dynamic environment. However, there are many RTLS systems, all of them have an average error in location objects that is simply too large for applications such as automated tower cranes. They are useful for tracking resources and project management.

the control system of the crane can be based on lasers and encoder. By subtracting the lift plan from a central database structure the crane knows what actions to perform. The encoder measures the rotation of the jib and the laser sensors measure the distance of the trolley and position of the hook. However, it can be imagined that when the hook swings, the laser sensor is not able to measure anything. According to some researchers, the amount of swing often is negligible when the load is heavy and the hook is supported by at least two wires. Nevertheless, at all times the weather conditions have to be taken into account. By acquiring a massive amount of data in real-time, inefficiencies can be captured and better process analyses and evaluation becomes possible. This will also be beneficial for upcoming projects that use automated tower cranes.

3. Example project – Automated Tower Cranes

The client of the project, used as a practical example for this graduation research, is the Housing & Development Board (HDB). This is the public housing authority of Singapore, which develops real estate projects and tries to increase the quality of the living environment. In total, more than 80% of the Singaporean population lives in apartments of the HDB (The Housing & Development Board, 2016; 2017). Because, HDB is a large company, it is valuable for them to increase productivity. Effort is made to adopt a higher level of prefabrication and implement design standardizations. Clearly, HDB takes an active approach in adopting new technologies. However, HDB faces some major issues such as, lack of process standardization and progress tracking, communication, data sharing and transferring between the construction phases (The Housing & Development Board, 2016). To address these challenges, the project they commissioned should result in a Smart Integrated Construction System (SICS). The goal of this system is a centralized platform that synergizes the different inputs by improving the data and information sharing processes. The development of this system is divided into three areas: (1) Integrated Building Information System, (2) Smart Production, Logistic and Materials Managements System, (3) Smart and Automated Crane/Hoisting System (The Housing & Development Board, 2016). HDB brought the project to the market by starting a tender, requesting for proposals. A team existing of three companies (Nanyang Technological University, Hope Technik and Witteveen+Bos) have won this tender.

3.1. Project outlines stated by the Housing & Development Board

The duration of the project is set at three years for research and development of the SICS and two years for testing the developments in all areas. The first phase is expected to result in a proof-of-concept (POC) and a proof-of-value (POV) and the second part of the project is concerning the test-phase. In the POC stage, feasible technologies and software packages must be analyzed and compared on allowance for digitization, import and export of building designs and modeling capabilities. Furthermore, analysis is requested upon different data types and flows in the supply chain. During the POV stage, the conceptual design is developed further into a prototype that can be demonstrated in reality. Highly important during this stage is the development of a fail-safe system that guarantees a high level of safety. This fail-safe system must sent alerts automatically and an operator is committed to take over the crane control system if necessary. Finally, testing is only possible whenever HDB approves upon the progress made. Here, the system is installed at a construction project of one of the standardized HDB apartment buildings. Five floors, which host approximately up to 30 apartments and consist of about 850 prefabricated components must be realized with the SICS. This section continuous with the explanation of the three areas, the SICS system should exist of according to HDB.

3.1.1. Integrated Building Information System

The development of the Integrated Building Information System (IBIS) should result in a comprehensive platform that serves the purpose for communication between the project stakeholders. IBIS must include the ability to track, monitor and exchange information about the construction project and contract management. During the research of this area, current construction processes of HDB must be analyzed to address gaps in the communication and data transferring process. IBIS should come with the following features:

- All project stakeholders are included and granted access to the system and data located on IBIS is allowed to be updated and retrieved in an interoperable manner for construction and supply chain processes.
- IBIS should feature the export of digital building data to the smart crane system to facilitate lifting activities. Integration with Geographical Information System (GIS) should also be part of the of the system.
- A standard design protocol should be created that is useful to all project stakeholders
- IBIS allows the project stakeholders to update the BIM, based on actual construction site conditions, to improve prefabrication efficiency.
- The interface of IBIS can be approached via an application for access through mobile devices.
- The data security and protection system prevents IBIS from being hacked and should include a complete back-up functionality.

In the R&D stage of the first area, a sensing and mapping system should be proposed, which maps the construction site and is integrated with the 3D model with a high level of precision. This is reached with advanced technologies such as, 3D laser scanning and/or cameras mounted on construction machines. The combination of actual site information and the 3D BIM model should help in the creation of the smart crane system.

3.1.2. Smart Production and Material Management System

The production, logistics and materials management system is approached as extension of IBIS. This system should allow for efficient production, logistic and inventory management. Here, the development of a tracking technology system is core to the success and ability of its integration within IBIS. The tracking technology system is equipped with a cost effective tagging system (e.g. RFID or GPS) and provides information of the prefabricated components and their predetermined assembly location. The tracking technology comes with a certain level of intelligence, so it is able to detect missing or incorrectly delivered components. The system is integrated in the data sensing system of the automated crane in order to facilitate the intelligent logistic and hoisting process.

3.1.3. Automated Crane and Hoisting system

To improve construction site productivity, research needs to be done to a smart crane system that optimizes the current way of performing lifting activities. The system consists of a complementary hoisting path system, which is able to generate hoist paths that guide the process and is integrated within the IBIS. Furthermore, an automated control device to enhance the existing crane system needs to be developed with a semi-autonomous function and integrated with remote control capabilities to improve the work process. A vertical hoist platform operates in collaboration with the smart crane system to transfer materials efficiently. The setup stated in the proposal request document of HDB can be seen in Figure 13 and Figure 14.

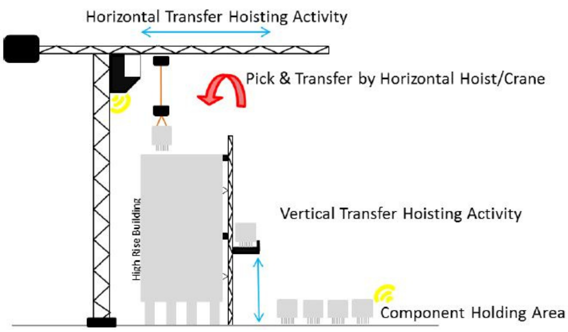

Figure 13. Elevation view of HDB concept (The Housing & Development Board, 2016)

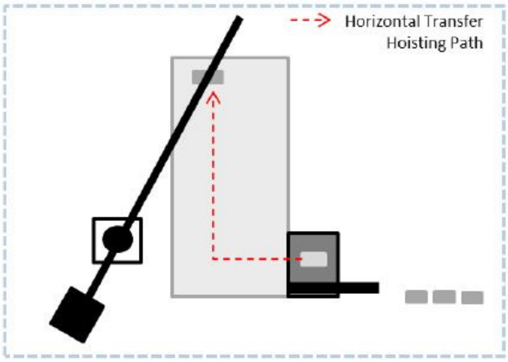

Figure 14. Plan view of HDB concept (The Housing & Development Board, 2016)

The smart crane system should be equipped with enhanced safety functions, anti-collision system, smart sensors, wind sensor, tracking system and imaging technologies (e.g. HD camera and LiDAR), speed control and anti-sway technologies, all capable of integration with IBIS. It is the intention to leave the crane operator out of the cabin. However, the operator should remain present on site and have the ability to take over control if necessary.

3.2. Approach of the project team

The previous section made clear what the HDB tries to accomplish with their project in the coming five years. Because, prefabrication processes and technologies are rapidly evolving, the next step in prefabrication is the integration of MEP services and dry joint connections between elements. Ultimately, prefabrication results in fully-integrated prefabricated prefinished volumetric construction (PPVC) (Hai, Tech, & Yaowen, 2016). This transition creates opportunities to automate certain processes on construction sites such as, the project of HDB. However, this only becomes possible through extensive collaboration and use of high level BIM practices. The approach of the project team and their ideas regarding the creation of a smart construction process are described in this section.

3.2.1. Composition of project solution

For the POC an extensive literature review is conducted about current practices, in the field of building information systems, automated construction techniques and information and communication processes. This review focusses on all different stakeholders of a project and it is tried to create a conceptual framework that is useful for the POV. During the creation of the POV, the SICS will be developed and tested using a mock-up version that is equal to one-third of the tests in the actual testing phase. The SICS itself is compiled of the three areas defined by HDB. The platform that automates the communication and information sharing and collection between the project community (IBIS) will compete with similar other platforms such as, Autodesk 360 and the BIMserver. However, IBIS tries to stand out as it focusses on data exchange in the entire construction chain and is built for the purpose of construction automation. The smart tracking system that uses RFID tags placed on the prefab elements. This enables tracking elements in the on-site storage area. In the current situation, prefab elements are attached to information by simple and cheap methods such as, barcodes and stickers. Whenever an element is placed on the building, the RFID tag updates the information in IBIS. The RFID tags are detected by several antennas that are installed at the construction site. Furthermore, these antennas are placed on different levels, as this creates a 3D space that combined with a 3D location sensing algorithm will result in a not yet available 3D tracking system.

The automated tower crane enables lifting prefab elements from the hoisting area to the designated location on the building. Currently, tower cranes are manually operated and used for transporting elements around the construction site and vertically to the right story of the project. Whenever, a tower crane is robotized, a design is necessary comprising of both soft- and hardware components that collaborate. The automated tower crane is assisted by the point man and can be controlled by an operator from the ground. The system makes use of the 3D and 4D BIM models that are uploaded to IBIS. Especially, the 4D BIM model determines the sequence of the prefab element assembly process. IBIS and a path planning algorithm instruct the crane, which then follows an optimized collision-free path. The elements are picked up by the automated crane from a vertical lifting platform. The crane itself is equipped with laser distance sensors placed in the trajectory of the trolley. It is noted that automation of the tower crane is a key factor in optimizing the construction process. Complementary to the predetermined information flow, real-time obstacle avoidance technologies are implemented. The movements of the automated crane are activated by placing a system to override the joysticks. By overriding the control system, it is important to calibrate the control parameters such as: sensitivity, offset errors and response time. During the execution of the construction process, the building is mapped into a GIS model with the use of 3D laser scanning techniques and drone surveys. This as-built information (e.g. point clouds and solid surfaces) is compared to the 3D model for deviation detection. Finally, safety is of major importance and therefore, the crane is provided with tracking information on the hook and load. In case a sensor malfunctions, the system automatically stops and only remote control can move the crane again. Also, multiple emergency stop controllers will be placed for the people working at the pick-up and drop-off locations.

3.2.2. BIM management

In order to optimize the building design for construction automation and sequence simulation, a 3D BIM model is necessary. This model defines all building elements and objects. The objects are needed for tracking and tracing using tags during the complete process. The Level of Development required for the project is 300. Complementary to the 3D BIM model, a protocol will be developed for automated construction practices. The elements (e.g. walls, columns, beams and foundation) are exactly defined as in reality and included with an unique identifier, 3D geometry and volumetric data. When the 3D model reaches the desired quality, it is attached to the time schedule (4D BIM model). This model is expected to help in specifying and verifying the construction sequence based on separate elements. All the information related to the prefabricated elements such as, construction planning, object ID numbers, element design and placement dates will be stored in IBIS.

3.2.3 Development of a Smart Production and Material Management System

It becomes increasingly important to gather the overall progress of building elements in real-time. A central system will be developed that allows full data exchange at all times and aims for active collaboration. Therefore, the required functionalities of IBIS are its ability to create, read, update and delete data regarding (BIM) objects. In order to accurately track all objects in the supply chain, RFID tags will be used. First, the functional and technical requirements for automatic site tracking are determined. Second, an appropriate RFID technology is selected. Third, a methodology is developed to automate the identification and localization of construction components. Fourth, the system must be integrated within IBIS. The 3D RFID location sensing system exists of RFID tags, receivers, data storage and display device that reads the information once the components arrive and tracks their movements around the construction site. The 3D location sensing algorithm operates based upon the trilateration method that calculates the target object location using distances from the RFID antennas to the target object by using Received Signal Strength Indication (RSSI). Within the 3D space, the distance is calculated according to radius of the sensed distance. Multiple antennas result in intersections of spheres. Using this concept the location can be narrowed when more antennas are being used. In the example project, it is expected that four antennas pin-point the specific location of each RFID tag. The interface that is built for the workers enable them to locate the objects on the construction site including the positioning and browsing diagrams. In the positioning diagram the user selects the prefab element to be installed. The system then calculates the object location in the 3D space. In the browsing diagram the system displays additional information about the selected object.

3.2.4. Development of Smart and Automated Crane and Hoisting system

Before a tower crane can be automated, it is expected that the first step is the development of an accurate mathematical model of the tower crane and its operating environment. This model should allow for analyses and visualizations. Kinematic and dynamic analyses of crane movements under different loading combinations and controls schemes are expected to be of value. Also, offline generation of optimal lifting trajectories for a set of constraints in combination with updated real-time constraints can be tested. Furthermore, visualizations can be made of system behavior and trajectories of hoisted objects in relation to the construction environment. The model of a tower crane is based on kinematic approach of Denavit-Hartenberg (DH). The tower crane is represented as a nine degrees of freedom (DOF). With each DOF, one motion is represented as a variable. In total there are nine variables. With the use of the DH notation, each motion can be determined by the construction of a transformation matrix. The overall transformation can be obtained by multiplying all respective transformation functions to determine the motion of the hook. Finally, tower cranes are seen as under-actuated controlled systems as they have fewer actuators than DOF. In the actual system, the geometric information of the BIM model will serve as primary source of information for environmental modeling. Furthermore, the hoisting movements and geometric data of each object are extracted from the digital models. Finally, the disturbance of the construction environment e.g., wind, rain and human intervention are modeled as additional control input parameter. However, there is some research necessary to model external forces under different loading scenarios. It is stated that a mathematical formula provides the description of the path planning problem for the tower crane. In theory, performing hoisting activities with a tower crane is a non-linear problem of multiple variables and constraints. One important feature of the problem is the detection of collisions between the environment and the crane components. It is planned to study recent applications of collision detection strategies and techniques for efficient path planning. According to the project team, this can be achieved by extending the automatic path planning of mobile crane lifting. The algorithm that will be used is of the Genetic Algorithm (GA) family and includes four functional modules (selection, mutation, crossover and fitness evaluation). Because intensive computations are expected, it will be tried to explore fast GA optimization with the use of high performance computing.

Complementary to the previous, attachment of sensor systems to the crane is highly important. The angular displacement of the slewing unit can be measured by installing an encoder box with an input measured by the drive gear. For the trolley and hook block, which are both cable driven, displacement will be measured with laser distance sensors installed on the trolley. On the bottom of the operators cabin, a stereo camera bar with a two 4K UHD cameras and depth sensors are mounted. These cameras maintain a line of sight to the hook block, which is fitted with at least 12 markers allowing the stereo cameras to perform 3D tracking of the hook block and its orientation. The cameras also check the load and determine a safety volume for real-time obstacle avoidance. Finally, a wireless camera with a wide angle lens is attached to the hook block for the same purpose as the stereo cameras. In the operators cabin, the manual control interface consisting of two panels located at the armrest positions of the operators chair are foreseen with a manipulating system, as can be seen in Figure 15.

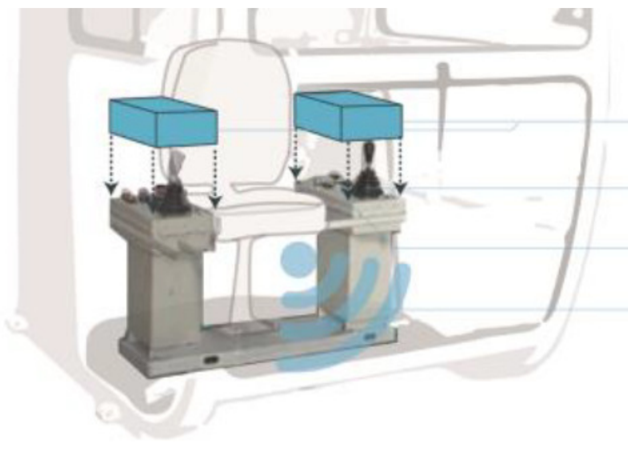

Figure 15. Overriding control system in the operators cabin (Hai, Tech, & Yaowen, 2016)

3.3. Results from the example project

The example project reveals the potential opportunities for deploying automated tower cranes. The clients of the project aims for a relatively large increase in efficiency and productivity. Therefore, it is necessary to develop several new applications that are beneficial to the overall construction process. By analyzing this project, important aspects are found regarding the possibilities and important functionalities of automated tower cranes on construction sites.

3.3.1. Functionalities and challenges coming from practice

The example project shows that it is expected, cranes can be automated by manufacturing a hardware control device that is place on top of the manual steering system. This indicates that automation is possible on all type of tower cranes. Encoder and laser sensors are used to measure the rotation and displacement of trolley and hook, as those are steered by the overriding system. However, the lack of standardization, manual progress tracking, communication and data-sharing in the current approach of construction projects are major barriers to such developments. Because, the client of the project is a very large housing corporation with a massive volume of real estate, an opportunity appears to approach these challenges. Therefore, they request for an integrated supply chain system that can be used by the industry on a global level. As this project is focusing on Singaporean contexts, it is expected that prefab construction will evolve towards PPVC. This is positive for automated tower cranes as PPVC is a highly standardized construction method.

3.3.2. Functionalities and challenges coming from BIM and real-time data acquisition

Similar as stated in the literature, many parameters are necessary to define all prefabricated objects and link them to the construction process. Among others: ID numbers, element dimensions, placement dates and coordinates are relevant. In the example project, a 4D BIM model that is developed to a LOD 300 level, establishes the construction sequence of prefab elements and generates lift plans. The core of the automated tower crane is a system that generates save hoist paths with the use of a GA algorithm, which uses the lift plans as input and reacts on the dynamic environment of the construction site. This system generates information from measurements of different sensor technologies to detect possible collisions. This is challenging as all the different sub-systems must collaborate. Furthermore, a progress and material tracking system will be developed with the use of RFID. This enables the tracing of elements from the precast yard to their final position in the structure. The overall system is classified as hybrid, as it remains possible for humans to interact with the crane. A crane operator is able to take over the control system in hazardous situations and emergency stops are installed at the construction site. Because, there should be an operator constantly monitoring the movements of the crane, the same number of people will be involved in the overall process. The hybrid system should furthermore check for deviations from the pre-planned structure. In order to do this, GIS is combined with 3D laser scanning techniques and drones to form as-built models. These models will be compared to the as-planned BIM models to detect and react upon deviations. Complementary to this, a stereo camera bar with two 4K UHD cameras and depth sensors are mounted. These cameras check the load and determine an additional safety volume for real-time obstacle avoidance.

4. Expert interviews

In the exploratory stage of this graduation project, multiple interviews are held. The purpose of these interviews is to verify the findings from the literature and the example project. It is chosen to maintain the characteristics of semi-structured interviews, as this provides the freedom to cover unspecified subjects. For the interviews, two different contractors, each with their own tower cranes, one international (construction) equipment supplier specialized in Liebherr tower cranes and one consultant of the graduation company with many different backgrounds are selected to capture a broad view upon the idea of automating tower cranes. The interview strategy and results useful for automating tower cranes are described in the following paragraphs. Furthermore, the elaborated interviews are placed in Appendix II.

4.1. Interview strategy

The interviewing strategy ranges from structured to unstructured. Structured interviews are mostly adopted by researchers that perform surveys and unstructured interviews are used in more qualitative approaches. The interviews performed in this research are of an unstructured nature, because the lack of structure increases the level of flexibility and allows for a broader approach of the different subjects (Edwards & Holland, 2013). According to Edwards & Holland (2013), three characteristics always have to be present in unstructured interviews:

1. interaction between interviewer and interviewee coming from both sides
2. one or more predetermined themes that guide the interview without fixed structure
3. relevant contextual information brought by the interviewer to further elaborate the capturing of knowledge

Each performed interview used these characteristics as a basis. Before the start of an interview, questions were prepared as guidance of the conversation. First, an elaborated introduction of both the interviewer and interviewee are set to start the actual conversation and establish the level of expertise. Second, all aspects that are presented in the literature review are discussed. Third, the interview ends with personal opinions to know what the interviewee thinks of the concept and to establish a larger collaboration for potential other related questions in future. All interviews are recorded to help in the precise reporting of the conversation. The next section describes all interesting aspects that can be useful for automating tower cranes.

4.2. Results from the interview

The interviews reveal additional opportunities and challenges for automating tower cranes. All interviewees were interested in the matter, but remained skeptical about real implementation and increase in efficiency of automated cranes. This skepticism makes the interviews very useful in determining if the automation of tower cranes is a logical step to make and potentially lead to knowledge about possible unknown challenges.

4.2.1. Functionalities and challenges coming from practice

Cranes owned by the interviewees are sometimes equipped with the Litronic system. This shows that Litronic is not standard on tower cranes. The reason for this are the costs involved for implementation. Therefore, one interviewee stated that only their heavy cranes have Litronic. A newer technology that is equipped on the cranes sold by one interviewee after 2013 is LiDAT, but this is not used to its full potential yet, as the Dutch construction industry simply is not using this system. All of the interviewees agree that data acquisition systems (LiDAT) are vital in future crane operations. One method that is used in tower cranes is called the 'Arbeids Bereik Begrenzing' (ABB). Before crane operations start, the computer is pre-programmed to certain non-working zones in the reach of the crane.

The function of a crane operator is very stressful according to one of the interviewees. This person works according tight schedules that generally result in working overtimes. Furthermore, the lift plans are created manually and on short notice by the workers involved in the process management. The function of point man has become more important recently, as dangerous situations often appeared due to mistakes they make. Education and experience now are very important to ensure safe attachment of the load to the hook. Furthermore, accidents related to the use of tower cranes often are the result of an accumulation of mistakes and errors. Another outcome of the interviews is the fact that evaluation is not part of the process as much as it should be, according to the tower crane directive and to be of any help in upcoming projects. Also, the crane supplier is not aware of the actual use of the tower crane, which makes it easy for contractors to rent a crane for eight hours a day and use it for twelve hours. However, the supplier and user of the crane strongly collaborate, there is a lack of transparency. This lack could be solved when the crane is automated or at least equipped with the LiDAT system.

In the discussion about the setup of an automated crane, one interviewee expects that it is more likely that there is a demand for hybrid systems were the crane operator is responsible for the precise handlings and the crane itself for the large and general sections of the lift path. Furthermore, crane configurations often exceed the most efficient dimensions. This comes due to the fact that loans of workers are very high, while the rental price of a crane is low. Over dimensioning a crane relieves work pressure and the benefits are worth-while the difference in crane rent. One interviewee is reserved about the overall effectiveness of the automated tower crane, as he suggested that time loss mainly comes from the construction method and waiting times of (sub)-contractors that need the crane for their activities.

4.2.2 Functionalities and challenges coming from BIM

It is expected that BIM processes become the new standard in the construction industry, and it certainly serves simulation and planning activities as well as automation purposes. According to the interviewed BIM expert, it is possible to generate automated hoist plans with a 4D BIM model. Especially, when steel frame and prefab construction methods are being used. One important aspect to take into account is the hinder that result from activities that are not modeled. The generation of such plans is expected to optimize the operational phase, as the lift plans currently are created manually and on short notice by the staff responsible for site management.

The method for attaching loads to the crane are determined by the point man. One of the interviewees state that this should be determined by the fabricators of the object, as this is expected to increase the level of safety and can be captured in BIM as well. Imaginable, the BIM model needs to be perfect and complete with information. Furthermore, tolerances implemented in the construction method should be captured already in the BIM model and measured in real-time. However, a question from one of the interviewees rises about how the crane can react to this. Finally, one of the most important difficulties in the deployment of BIM on construction sites is the fact that many aged people work in this part of the process and lack the computational knowledge. However, younger people that have this skill, lack the practical knowledge. It remains unknown how to defeat this gap, which is increasing as technological developments appear very fast.

4.2.3. Functionalities and challenges coming from real-time data acquisition

According to most of the interviewees, deploying camera systems on tower cranes seems useful. However, a camera system alone is not enough to capture all relevant data for automating a tower crane. Therefore, different sensor systems should collaborate to make safe automation possible. The interviewees mention that the crane is constantly bending due to the force of wind and lift activities. It remains unknown by the interviewees how to measure this exactly and with what type of sensors. Especially, the forces of wind are unpredictable in the work space of the crane, as it is influenced by surrounding obstacles. According to all interviewees, this shows the importance of the human factor in the operations of tower cranes. This person is able to sense the behavior of the crane and takes countermeasures to remain in control over the load. When automating a tower crane, this high level of sensitivity ensures the level of safety in lifting activities. Furthermore, exact measurement is necessary to know the coordinates of the object in the work space of the crane during the lift activity. Different from the findings in the literature review, some of the interviewees state that swing certainly is present during lifting activities. Also, the hook can freely rotate instead of the hoisting cable, which allows objects to turn around. The point man on the ground often guides the load with a set of ropes. This indicates the importance of sensors that detect swing and the necessary communication between the point man and the automated crane. Actually, crane operators do not only perform lifting activities, but also have to be aware of every person, machine and object within the work space of the crane. This characteristic should be copied to the automated tower crane.

5. Exploring tower crane automation

This chapter describes an exploration to the automation of tower cranes that results from the combination of research strategies described previously. The literature review, first treated a general introduction to what sort of equipment tower cranes are and how their process of deployment is shaped. Second, the possibilities regarding pre-constructional data in relation to the automation of tower cranes are studied. The use of BIM is emphasized here, as this is seen as the base of the overall process. One of the most important activities of the pre-constructional phase is crane lift path planning, hence it is examined how this works. Third, the use of RTLS technologies is considered as helpful in the control of the crane and allows for real-time adjustments during operations. Therefore, the functionalities and disadvantages of numerous RTLS technologies are analyzed. Additionally, an example project of the graduation company is analyzed. This helped in finding out the expectations of the industry and shows which concepts from the academic field will be transferred into practice. Finally, expert interviews are held to obtain practical knowledge of tower cranes and understand existing opportunities for automation. The combination of several research strategies helps in understanding the (dis)advantages of the overall notion to automate tower cranes. In order to provide guidance and be able to combine all findings, this exploration is assembled.

5.1. Outlines of the exploration to tower crane automation

This exploration merges the aspects found to be relevant in the automation of tower cranes and contributes to the determination of remaining challenges that certainly need a solution. Although, this is helpful, it must be recognized that this exploration is not the only valuable strategy. The automation of tower cranes only becomes possible when the operational construction process is renewed. Starting with a central and digital process management system that is accessible for all project stakeholders. The use of BIM and integration of the complete supply chain is mandatory in this system. It must be able to track every object pre-defined in the BIM models and updates its information in real-time. Furthermore, the BIM model is upgraded to 4D standards early in the process and enables pre-constructional analysis and the creation of CLPs. This data serves as input for the automated tower crane.

Actual crane operations are difficult to produce from pre-defined information, as there are many deviations in structures, objects and people on construction sites. Furthermore, the tower crane is very dynamic and reacts upon numerous variables that are difficult to model precisely, indicating that real-time information is necessary to adjust crane operations in reality. This can be accomplished by combining multiple sensor systems that measures crane behavior and controls its movements. Furthermore, instantaneous gains can be achieved by the use of already existing technologies that increase the level of control over the load and make it possible to collect information about crane operations. Finally, the deviations of the structure under construction and the environment itself in comparison to BIM models must be captured. This can be achieved with the creation of as-built models that can be related to the BIM models.

Because the automated crane construction process comes with a high level of digitization, a misfit is expected with the people that must use the system. Because many people that work in the executional phase are of a certain age, they lack the knowledge of using digital systems to the required level. Education is important for the transition towards understanding and adopting the new system. Finally, current building methods in Europe are not beneficial for automated tower cranes. A shift towards more prefabrication is expected to be useful for the deployment of automated cranes. Figure 16 shows the comprehensiveness of the exploration introduced above. The following sections explain the included features in more detail.

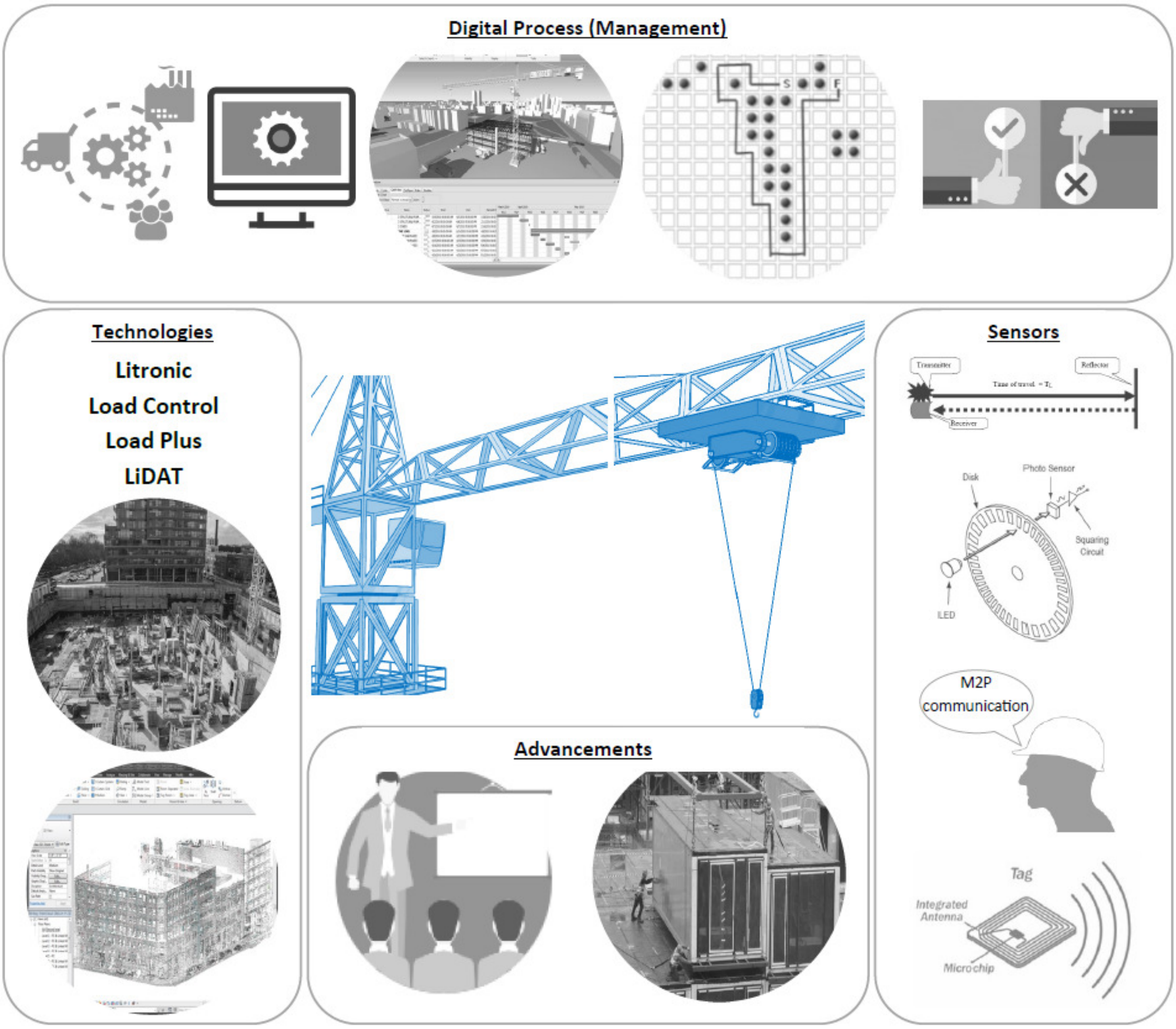

Figure 16. Overall visualization of the exploration indicating aspects for tower crane automation

5.2. Central management and crane control

Digital process (management)

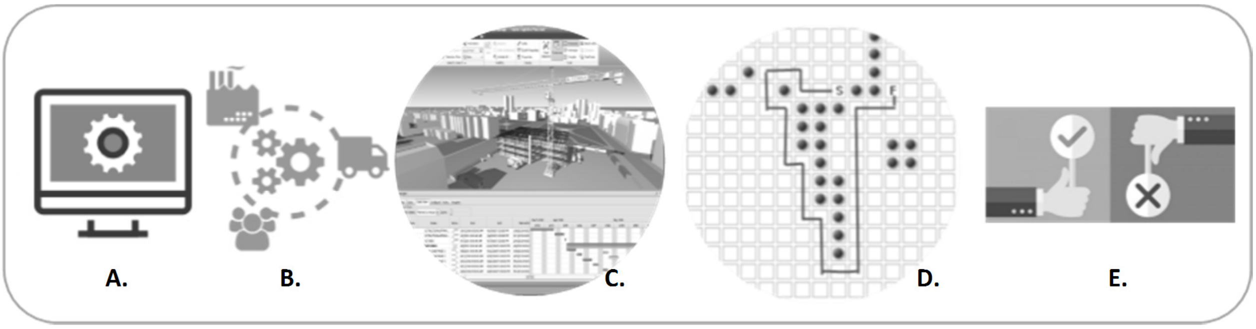

Figure 17. Digital process aspects of the overall exploration of tower crane automation

Figure 17 shows the digital process (management) category of the exploration. Starting with (**A**), a need exists for a process management system that captures the complete process in a digital environment and is accessible for all project stakeholders. It becomes important that all information is stored at one location and can be traced throughout the process. This increases the level of transparency between project stakeholders. For example, this is important for the leaseholder of a crane that is currently unaware of the actual use of the crane. This is problematic in the determination of rental prices and scheduling of maintenance. Furthermore, an integration of the total supply chain is necessary, as continuously updated information about object statuses and locations must be known at all times (**B**). Whenever track of objects is lost, the whole system is expected to stagnate and production will come to a standstill.

Storing information at one single location for the purpose of construction processes, enhances the use of BIM from the start of the project (**C**). As indicated in the literature review, many variables exists that capture the structure under construction, spatial characteristics and the tower crane itself. The information defined in the BIM models is required to obtain at least a quality of LOD 300. After the 3D BIM models are complete, a combination can be made with the time schedule. This will result in 4D BIM models that are useful for visualizing and simulating specific situations. These situations can be analyzed in order to improve the process in advance. It is important to know that it remains impossible to model every object and activity in BIM. However, including the concept of hinder times overcomes many of these elements. After the construction sequence is established with the 4D BIM model, CLPs can be generated. CLPs result when geometric boundaries are combined with a path planning algorithm (**D**). This thesis is not stepping into detail about the differences in available path planning techniques, however, it is clear that path planning is vital in automatic generation of hoist paths. Furthermore, the large radius of a crane causes extensive processing times and therefore, optimization of a chosen path planning algorithm is expected to reduce these computation times. Also, the current use of reach limitations (ABB) can already be integrated in the defined CLPs instead of programming these after the crane is installed on site. 4D models and simulations allow for detection of clashes. However, this concept is already recognized widely in the construction industry, clash detection rulesets specific for the execution of CLPs need to be developed. From the process management system, these controlled CLPs are sent in the correct sequence to the automated crane.

Another improvement related to BIM is the determination of attachment method of objects to the crane as responsibility for the fabricator. Currently, the point man is deciding upon this at the start of each lifting activity. However, there often are multiple available methods and time is lost in choosing one. It is expected that this information can be included in the objects defined in the 3D BIM model and instruct the point man. An increase in the level of safety and efficiency is expected, as many crane related accidents and time losses occur due to the wrong method of attachment and lack of experience.

In the creation of a central and digital construction management system, it is clear that multiple activities shift towards the pre-construction phase. However, this increase of work before the start of the construction phase is expected to relieve pressure from the on site management team, which currently make many decision at the moment of occurrence. Furthermore, detailed preparations are necessary to guarantee safe use of automated equipment. Finally, the digitization and information storage at one single platform enables the possibilities for process evaluation (**E**). Currently, this is not being used much, while efficiency is gained more easily with a steeper learning curve. The next step in the exploration is the adoption of technologies and sensors necessary in the automation tower cranes.

5.3. Enabling safe crane operations with technology and sensors

Technologies and Sensors

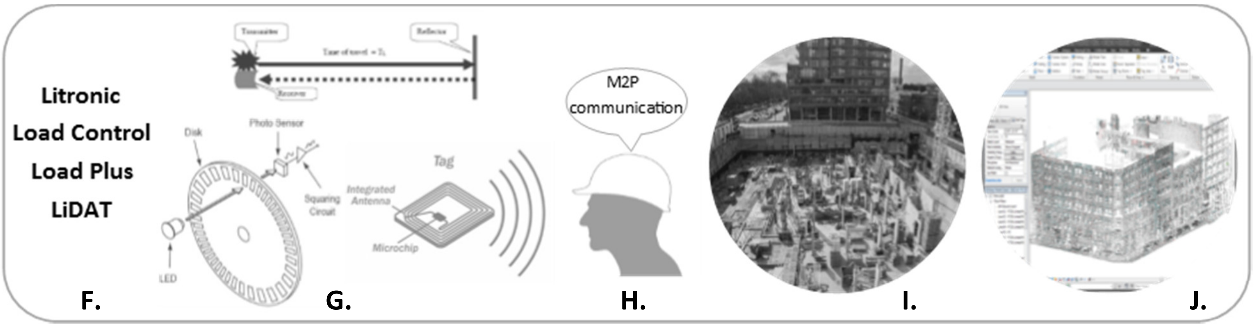

Figure 18. technologies and sensor aspects of the overall exploration of tower crane automation

The previous section explained every component necessary to serve as basis for automated tower cranes. Although, this is quite broad, it does not enable actual crane operations. This mainly comes due to the dynamic characteristics of construction sites. These dynamics should be monitored and measured with the use of sensor systems and other technologies that collaboratively guide the overall crane operations in real-time. Therefore, this section explains the <u>Technologies and Sensors</u> parts (Figure 18) of the exploration. Currently, several technologies exists that increase the level of control during crane operations (**F**). At least, the central control management system (Litronic), the system that provides countermeasures to unexpected movements (Load Control), the system that increases the lifting capacity by reducing the operating speed (Load Plus) and the data analysis system that enables analysis numerous parameters during (LiDAT) are compulsory and generate prompt improvements.

Because, tower cranes are expensive pieces of equipment and come with long depreciation times, it is preferred to automate existing tower cranes instead of developing a new type. In order to accomplish this, a hardware device that overrides the manual control system, located in the operators cabin, is necessary. This hardware device is capable of moving the joysticks into the right directions and collaborates with sensors that coordinate the crane movements. The rotation of the jib is measured with the placement of an encoder sensor in the turning mechanism of the crane. The movement of the trolley is coordinated with laser sensors capable of measuring distance. The same yields for the movement of the crane hook. The conjunction of these three sensors, enable allocation of every point in the workspace of the crane. For example, the crane is at position A and should move towards position B. In order to do so, the jib needs to rotate a certain degrees, the trolley moves to a certain position on the jib and the hook is lowered to a certain level. This main body of information comes from the pre-determined CLPs, however, the CLP must be adjusted to the real situation with the help of supplementary (RTLS) systems and a path re-planning algorithm (**G**). Helpful systems for these adjustments are: camera systems such as, the 4K UHD cameras described in the example project. These cameras will be placed underneath the operators cabin and monitor the hoisted object and create an additional safety boundary to reduce the chance of collisions. It must be noted that the use of cameras require a line of sight and do not work in case of blind lifts. The use of cameras can be referred to the RTLS system of Vision Analysis. Laser sensors are another option to control the load, however, these only work to a certain amount of swing, as the laser is sent back via relatively small reflectors. It remains challenging, though highly important to guarantee the desired level of path smoothness.

Besides, the dynamics on the construction site, there are other variables that need attention. Actual weather conditions and deformation of the tower crane are always present and only can be measured in real-time, as these are influenced by many variables. These variables are difficult or even impossible to predict and model. Weather conditions change at different positions in the workspace of the crane, especially when it is stationed in dense urban areas. The deformation of a tower crane is influenced by the momentum of the load and weather conditions. Measuring these aspects and adjust the actual CLP accordingly, is challenging. Therefore, some interviews propose the idea of an hybrid system, were detailed handlings are done by a crane operator and generic movements are done by the crane itself, as intermediary step before full automation becomes possible. To assure safe crane operations, a crane operator must be available on site to take over control if necessary. Furthermore, a new communication protocol needs to be developed for the point man in order to develop a system that enables the crane to know what the point man is doing and establishes a signal for the crane to start its CLP (**H**). Currently, it is not possible to use an RTLS system for the coordination of objects around the construction site. However, it is expected that developments in this field rapidly evolve and therefore, systems as RFID and GPS will become very helpful in the overall system. Without the use of these systems, it is necessary to create fixed load positions on the construction site. It must not be forgotten that RTLS systems are useful to keep track of objects in the entire supply chain and progress management (**I**).

The differences in reality compared to the BIM environment need to be captured during crane operations. Dimensional tolerances and a lower level of preciseness on site are normal. However, these differences decrease the precision of the tower crane's operating and coordination system. A solution for measuring the adjustments necessary, is the creation of as-built models (**J**). Modeling real situations can be done with laser scanners that create a point cloud. Manual scanners based on the ground or scanners hanging underneath drones periodically make an as-built model that can be compared to the BIM models. Deviations measured in this comparison are another source of input for the path re-planning algorithm mentioned earlier. By grasping real-time information that differs from the pre-construction phase, automation of tower cranes heads into the right direction. However, it is expected that this combination of collaboratively operating systems is not sufficient enough to result in the potential deployment of automated tower cranes. The following section describes the last two aspects that need attention to complete an overall and detailed impression of the exploration.

5.4. Advancements to increase the success of utilizing automated tower cranes

Advancements

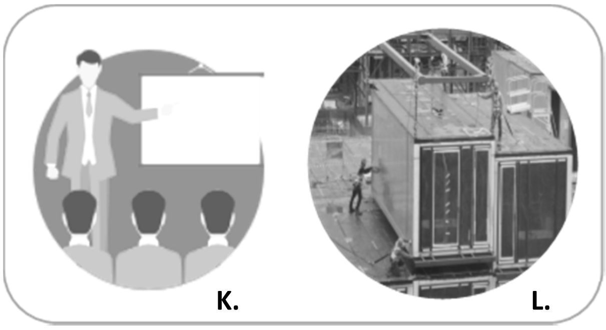

Figure 19. Advancements of the overall exploration of tower crane automation

The combination of pre-construction and real-time data acquisition is expected to overcome many issues in the automation of tower cranes. However, there are some aspects that certainly need attention, as can be seen in Figure 19. The <u>Advancements</u> are the last part of the exploration. From the interviews it became clear that many aged people work in the executional phase of construction projects. Often, those people lack the knowledge to work according a digital process and prefer more traditional approaches. In fact, this has been mentioned as one of the main reasons that prevent successful innovation in construction projects. In order to overcome this situation, people who do have the required knowledge should educate the others to become familiar with the use of automated tower cranes (**K**). Furthermore, transition to a high level of prefabrication of components is expected to result in opportunities for automation on construction sites. As mentioned earlier, one of the most advanced prefabrication methods is PPVC, which already becomes more and more adopted in Asian countries. This simplification of building method on the construction site, is beneficial to the operation of an automated tower crane (**L**). During this exploration, it is tried to explain how everything comes together and provides an indication upon the complexity that is expected in the automation of tower cranes. The last step is the description of remaining challenges that certainly need a solution before such cranes become reality. This description is given in the last section of this chapter.

5.5. Challenges to solve before actual utilization

The exploration shows that automation of tower cranes is highly challenging. A combination of different fields is necessary to develop a functioning system. Although, this provides a detailed insight in the mix of possibilities, there remain multiple challenges that certainly need solutions. Some of these are already indicated previously, but many others exist. The challenges that appeared during this research are listed in this section (Table 5). Because this thesis research is bounded by a timeframe of six months, it is decided to select one of the remaining challenges that have the potential to be solved within this scope. The explanation of which challenge is selected is described below the table.

Table 5: remaining challenges

#	Challenges (management)
1.	Developing a highly standardized and prefabricated construction method
2.	BIM adoption to a high degree in the complete chain of stakeholders
3.	Establishing a standardized BIM protocol, which enables construction process modeling
4.	The transition of CLP development and creation from research to the industry
5.	Data-driven construction site management based on real-time information processing
6.	Creating an easy-to-use system for the traditionally educated construction workers
7.	Maintaining a high certainty of the automated crane being a safe piece of equipment

#	Challenges (practice)
8.	Development of an RTLS system that comes with more precision in managing the supply chain and pinpoint (off)load locations of objects
9.	Development of a collision detection system that is not influenced by LOS problems
10.	Including parameters to designed objects regarding the construction process
11.	Handling material and measurement tolerances during object placement
12.	**CLP coordination problems due to (un)predictable variables resulting in deformation of a tower crane's structure**
13.	Communication between an automated crane and construction workers (point man)
14.	Automated and recent (near real-time) comparison with as-built situations

As can be seen in Table 5, challenge twelve is highlighted and is expected to have the highest potential for a solution during this research for multiple reasons. However, the time scope is seen as an important factor for selection, multiple other reasons exists. First, the challenge has a technical focus, which continuous upon the result of the pre-constructional process and is very critical in the adaption of the previously modeled CLP to the real situation. Second, this challenge has a limited scope that enables a clear development process for a solution. Third, every challenge placed in the management category are all stand-alone large research or development questions. On the other hand, some challenges from the practice section do not fit personal interests (challenge 8 and 9) or lack the necessary depth demanded in this thesis (challenges 10, 11 and 13). Therefore, it is determined that measuring the displacement of the crane's structure (challenge 12) follows the technical trend of this thesis and is a logical in-depth extend of the exploration presented in this chapter. The next chapter, therefore, continuous with the explanation of how this specific challenge is approached.

6. Methodology

As introduced at the end of the previous section, this research alters from a broad scope of approaching the automation of tower cranes in general and indicating which aspects are found to be essential, towards a more specific experimental study. Among others, a result of the exploration is the list of remaining challenges, which is helpful in determining future research directions. As is explained earlier, it is chosen to focus on challenge 12 of Table 5, in order to contribute to the automation of tower cranes. Therefore, this chapter is dedicated to the attempt of resolving the problem of the crane's structural deformation. First, an introduction to the structure of the development process is given, explaining what steps are important in order to find a suitable solution to the challenge. Second, the actual problem is explained in detail to really understand the challenge. Third, the prototype developed during this research is proposed in terms of used hardware and software. Fourth, the test setup and test results alternate as the development grows from small-scale to large-scale testing. Finally, the results of this developmental approach are explained and discussed.

6.1. Introduction

Continuous deformation in the crane's structure results in a displacement of the object being lifted relative to its position coming from pre-constructional information. This introduces the problem of an obscurity in the level of precision of the path planning system that locates the (un)loading positions and determines lift paths for every hoist activity. Because deformations reside of the standard structural behavior of a tower crane, this attempt tries to find a method that includes this behavior in the path planning system. Currently, there is no method with the ability to measure these unpredictable deformations in real-time. Therefore, the fifth research question is committed to developing a reliable measurement method that complements the system with real-time data to increase the overall efficiency and safety of an automated tower crane. The last research question is continuing this development and explores to what degree the integration of crane deformation is contributing to the overall process. For answering these research questions, the following structure is used to propose a prototype system based on data collection via sensors and empirical validation of the contributing value when installed as component in the overall sensor network necessary for the automation of tower cranes.

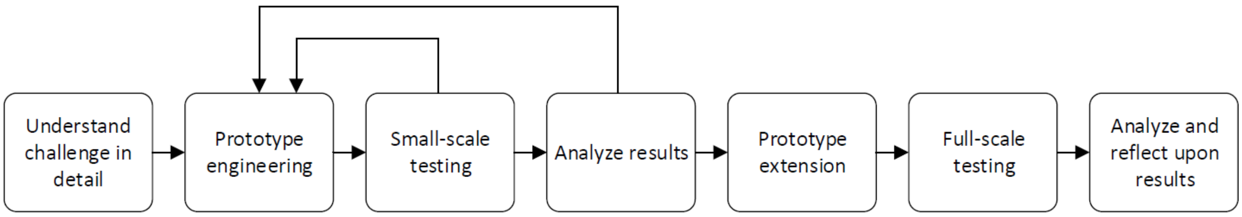

Figure 20. Development process of prototype

The development process is visualized in Figure 20 and with the in-depth analysis to the challenge of structural deformation and the displacement problem arising from this. Thereafter, a sensor is selected that expectedly comes with the ability to measure the amount of deformation in the crane's structure. The sensor is made working in a prototype system that is tested with three different small-scale tests. The first tests accommodates a straight horizontal movement that aims to result in the distance covered by the sensor. The second test aims to result in the measurement of the circumference of a circle by rotating the sensor along a fixed radius. The third test aims to result in the measurement of distance travelled in a pendulum movement, also with a fixed radius. Whenever the output is determined to be sufficient, the prototype system is extended with multiple sensors in order to capture every deformation of the crane. The finished prototype is tested in a full-scale test on a tower crane. In this approach, it is expected that loops are necessary at two points in time. This will improve the quality of the prototype and therefore the results. The complete explanation of every test is placed in the impending sections.

The approach comes with several strengths as well as weaknesses. The distinction between small-scale and large-scale tests is seen as a strength, as this enables quick generation of data that indicates upon the robustness of the chosen sensor. Furthermore, starting small and growing towards a complete prototype system allows for a natural learning curve in the use and understanding of sensors, data gathering and storage systems. Important weaknesses are the use of low-priced sensors that are expected to perform below an applicable standard. The reason for using these sensors is twofold. At this particular stage in the development, it is less important to realize a very precise system and more about the potential of the selected system. Additionally, more sophisticated sensors are simply too expensive for this graduation research. Another weakness is that, at this point, it is assumed that a path planning system already exists for automated cranes and that the use of the developed system in this research is making that system more precise. However, a path planning system only exist in theory and needs to be developed as well, before automated tower cranes become reality. Although, it is expected that this system can be implemented in a coordination system for objects in hybrid systems as indicated in the theoretical part of this research. It must be made clear that this research has a clear experimental focus, as it follows a path of trial-and-error in developing a working prototype that increases the precision of automated tower cranes. Because, it is only expected that the output of the sensor system will be of any use, the greatest challenge is to process the data in such, it can be used to measure distances in deformation movements of the crane. Another challenging aspect is the setup of a wireless network for the sensors to push their measurements into a database. The explanation of the working sensor system is described in detail in the following section.

6.2. Method

This section starts with the in-depth analysis of the challenge and explains which deformations exists in tower cranes and introduces a simplified calculation method that results in the amount of deformation that can be expected during the large-scale test. Secondly, the used hardware (sensor and microcontrollers) and software (python codes, communication and database structure) components are explained. This can be seen as the complete structure of the prototype developed during this research. Finally, it is explained how the measured values of the prototype are processed in order to derive the right information.

6.2.1. Structural deformation analysis of tower cranes

The existence of structural deformation in tower cranes is evident. However, the consideration that it exists by oneself lacks competence as starting point in the development of a solution for this challenge. Therefore, this section further analyzes the challenge and delineates the qualitative approach of this research. First, an individual workshop with a highly experienced structural engineer specialized in tower crane foundations is arranged to acquire the knowledge about which deformations are generally present during crane operations and how industry is handling this behavior. Second, specific information of tower cranes is collected from the technical manager of the Dutch importer of Liebherr tower cranes. From these experts, it becomes clear that the fabricator itself is the only stakeholder in the process, capable of calculating deformation in detail. The standard structural information of crane elements is sufficient enough in most cases and therefore, these type of calculations are not mandatory. However, it can be the case that a crane is close to surrounding structures, for example, cranes placed inside an elevator shaft. Here, it is important to know the maximum deformation of the mast exactly on beforehand. In such utilizations the fabricator is informed and provides the required calculations. In the research of Ju & Choo (2005), a visualization is made of the types of deformation in tower cranes. Although, the deformation in the visualization is little overdone, it does show what the content of the challenge is and divides the deformation into four modes. The visualization obtained is presented in Figure 21.

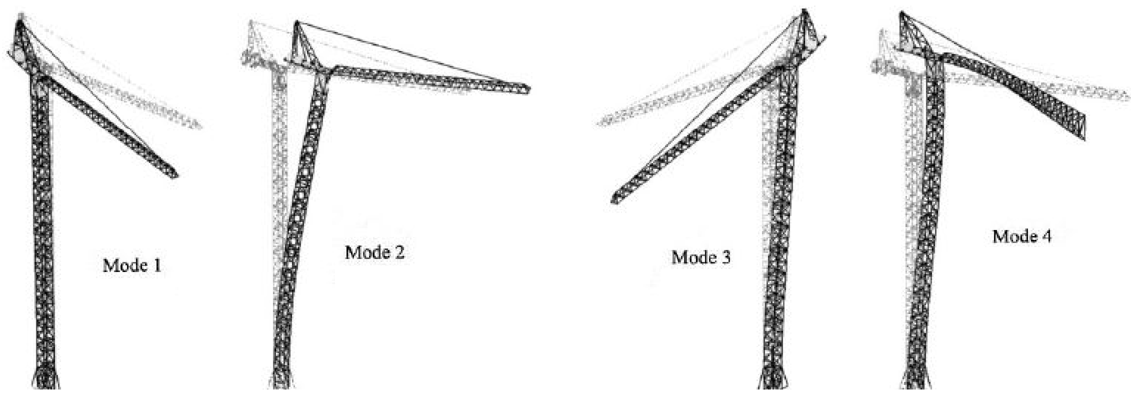

Figure 21. Different modes of structural deformation obtained from: (Ju & Choo, 2005)

It must also be noted that figure 21 shows a luffing-jib crane with a tie rod that reaches till the front of the main jib. This tie rod minimizes bending of the jib during lifting activities. Top-slewing cranes also have a tie rod, however, it does not reach the end of the jib. Therefore, the jib of top-slewing cranes deforms slightly different than visualized above. Mode three is a combination of mode one and two and is the most natural mode for a tower crane. Mode four represents the twisting motion of the main jib and a normal deformation of the mast, which can occur when the load is swaying under the main jib. This makes clear what type of deformation should be measured in theory. The need for measuring this is made stronger with the remark of the consulted experts, which explains that the user of the crane is not aware of the actual amount of deformation and does not need to know either. It is stated that the crane operator is feeling the deformation and acts accordingly. However, when the crane is automated, there appears a clear need to take countermeasures for successful crane coordination. Although, the crane is built up from standardized elements, structural deformations during crane operations are unpredictable, making the objects displacement unpredictable as well. Variables that contribute to the amount of deformation are: wear of elements, weather conditions, the exact weight and sway of objects and the position of the trolley over the length of the main jib. In order to measure structural deformation during lifting activities, constant monitoring is necessary to be useful in crane coordination.

Helpful in measuring deformation of a tower crane's structure and development of a sensor system are values that can be expected. Especially, in the full-scale testing phase of this research. Therefore, the challenge is made more abstract in the sense of approaching deformation analytically. Together, with a structural engineer from the graduation company, specialized in steel structures, the challenge is simplified in such, it becomes approachable with rules of thumb. These rules are often used by structural engineers to provide an indication of what can be expected from the steel structure selected in the design phase. Figure 22 shows the deformation of a crane's mast and main jib. Although, rules of thumb are used, real information is collected and the structure of the full-scale crane is used to provide measurements and weights for this indication. The question marks in the figure below visualizes what is tried to be measured in this research, which ultimately results in the object displacement during lift activities.

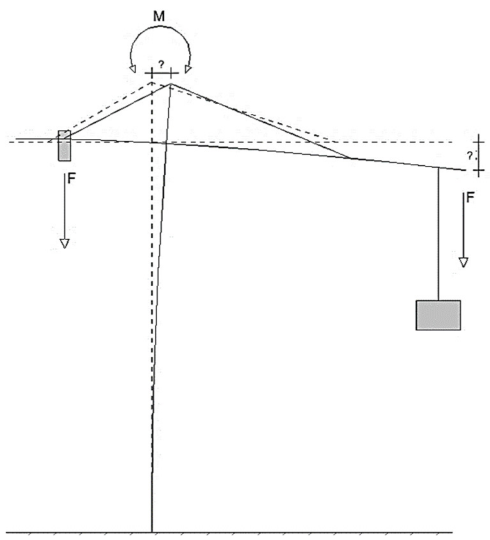

Figure 22. simplified model for tower crane deformation

6.2.2. Structural deformation calculation of tower cranes

In addition, Figure 22 shows that deformation is the result of forces applied on the jib, the counterweight hanging in the counter-jib and the momentum generated by these forces in the mast of the crane. According to (Blok, 2006), there are rules of thumb for bending and angular displacement of steel structures. Required for creating a suitable indication, bending of the structure after applying forces and momentums, Equation 1 and 2 are of interest.

$$w = \frac{1}{3} * \frac{F*L^3}{E*I} \qquad \text{(bending of jib)} \qquad (1)$$

$$w = \frac{1}{2} * \frac{M*L^2}{E*I} \qquad \text{(bending of mast)} \qquad (2)$$

As can be seen, four unknown variables are required serve as input for these formulas. The momentum variable can easily be calculated by multiplying the force in Newton with the length variable of the structure in millimeters. For the crane used in the large-scale test, the length (L) is 24,5 meters and the momentum (M) is quantified as (647 kNm). The elasticity modulus (E), 2,1 * 10^5 N/mm^2, is a fixed value for steel structures. The quadratic surface momentum variable is more difficult to calculate, as the structure of the jib and mast are built up with multiple steel profiles connected with girders. The equations required to calculate the quadratic surface momentum of the jib and mast are Equation 3 and 4. The quadratic surface momentums (I) of the steel profiles used in the crane's structure are 1,968*10^6 cm^4 . Furthermore, the sectional surface (A) of the profiles is 50,2 cm^2. Finally, the arm (a) of the profiles in regards to the center of gravity is 990 mm for the mast and 920 mm for two profiles of the jib and 1310 mm for the third one.

$$I_{ms} = 4 * I_p + 4 * A_p * a^2 \qquad \text{(quadratic surface momentum mast)} \qquad (3)$$

$$I_{js} = \left(2 * I_p + 2 * A_p * a^2\right) + (I_p + A_p * a^2) \qquad \text{(quadratic surface momentum jib)} \qquad (4)$$

After filling in the equations explained above, it becomes clear that the expected bending of the jib is approximately 31 mm and the expected bending of the mast is approximately 230 mm. This indication is helpful in the determination if the sensor system is able to overcome the investigated challenge. The next section describes the developed prototype for this research, starting with the design principle used to guide the process.

6.2.3. Prototype engineering: design principles

The prototype that expectedly measures the structural deformation of a tower crane exists of small computational controllers and sensors. With the help of a Wi-Fi network, these controllers are able to communicate with each other and process data into a database. The strength of the prototype developed during this research, is the possibility of combining different applications and therefore multiple data sources to derive interesting information. A weakness of devices, such as this prototype is the wireless connectivity that can cause problems. However, this is a weakness of every system that sends data wirelessly. According to Dr. J. Barrett from TEDx (2012), applications such as this prototype should have the following features: a wireless internet connection, a unique identifier, the ability to sense its environment with sensors, controlled and monitored from everywhere. The output of the prototype exists of a dataflow, coming from multiple sensor measurements. All these measurements are stored in a single database. This database structure allows for analysis and, in this case calculation of object displacement during lifting activities. The major difference with the design principles provided, is the fact that the prototype will communicate over a standalone internet connection. However, in real application of these technologies on construction sites, a wireless internet connection is required. In contrast to the network used here, this network is capable of controlling and monitoring the system from everywhere.

6.2.4. Prototype engineering: inertial measurement unit

The selection of a suitable sensor that can be used in such, it measures the structural deformations, starts with two categories. In fact, the sensor should generate a travelled distance in a certain direction, which can only be measured with motion and proximity sensors. As can be seen in Figure 22, the crane deforms in multiple directions at the same time. This makes it impossible to use proximity sensors (e.g., IR distance sensor). Although, their high level of precision, they need a fixed reference point. This directs the selection procedure to the category of motion sensors (e.g., gyroscopes, accelerometers and magnetometers). A very specific type of motion sensors are Inertial Measurement Units (IMUs). Extensive explanations of IMUs can be found on multiple platforms. However, a more formal one comes from Kok, Hol, & Schön (2017). An IMU combines a three-axis accelerometer with a three-axis gyroscope. IMUs are widely being used in, for example: the tilt function of a smartphone, the levelling of drones during flight modus and the headset of a virtual reality system. IMUs thank their popularity to the development of microelectromechanical system (MEMS) technology.

MEMS allow accelerometers and gyroscopes to be manufactured at low costs and decreased the sizes of necessary components, making them highly efficient. Although, the accuracy of IMUs is lower than traditional gyroscopes and accelerometers, it is stated that large improvements are made and expected in the coming years (Kok, Hol, & Schön, 2017). Because, the output of MEMS IMUs can be integrated to position and orientation information, this sensor is expected to perform best.

However, IMUs are available in different types of measurement ranges, the most generic ones come with an accelerometer range of ±2g, ±4g, ±8g and ±16g. This means that the sensor can handle accelerations up to 157 m/s^2 (16 g * 9,81 m/s^2). The gyroscope range of such sensors is ±250°/s, ±500°/s, ±1000°/s and ±2000°/s, indicating the sensor handles up to an angular velocity of 5,6 rotations per second (2000° / 360°). Each sensor has one to several different ranges, as the level of precision decreases when the range is larger. For each of the four ranges, a scale factor is determined by the factory that generates the maximum accuracy of the sensor output. Another selection parameter for IMUs are the Degrees of Freedom (DOF). Different than the DOF discussed in section 2.3.3, the DOF of an IMU specifies the number of accelerometers, gyroscopes and magnetometers. For example, a 9 DOF IMU sensor is equipped with three accelerometers (3 DOF), three gyroscopes (3 DOF) and three magnetometers (3 DOF). The direction of the jib of the crane does not need to be determined and therefore, magnetometers are not necessary.

Therefore, an IMU with 6 DOF is determined to fit this research best. As, many of them come with very similar characteristics, sensor availability was the last selection parameter. This process has led to selecting the MPU-6050 sensor from InvenSense. The MPU-6050 is an MEMS IMU sensor and as explained above measures acceleration and angular velocity in three orthogonal directions, referenced to the Cartesian coordinate system. Figure 23 show the sensor and Figure 24 shows the different directions in which the MPU-6050 is retrieving measurements.

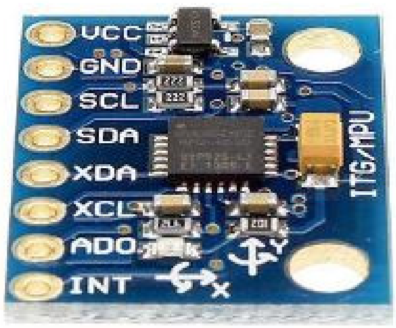

Figure 23. MPU-6050 IMU sensor (Op, 2017)

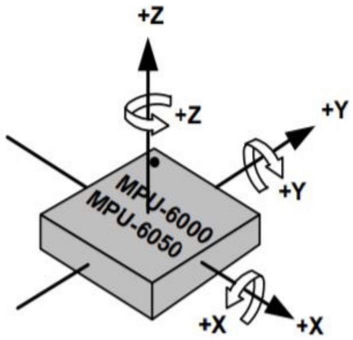

Figure 24. DOFs of MPU-6050 (InvenSense, 2013)

In order to use the MPU-6050 output in real-world applications, several coordinate frames need an introduction. According to Kok, Hol, & Schön (2017), there are four different frames available when using IMUs: the body frame (frame of the sensor itself), the navigation frame (local geographical frame), the inertial frame (coordination frame at starting point of the sensor) and the earth frame (geographical frame that rotates with the earth). These frames clear up the actual sensor measurements, as gyroscopes measure angular velocity (°/s) of the body frame in reference to the inertial frame and accelerometers measure the specific force (g) on the body frame itself. It must be noted that the accelerometers specific force of 1g is equivalent to 9,81 m/s^2 (Kok, Hol, & Schön, 2017). Each of the six sensor output signals is converted from analog to digital with the onboard 16-bits analog-to-digital converters (ADC), this transforms measured voltages into digital values. Because the real IMU is very small (4x4x0,9 mm), additional chips are added to increase the number of functionalities. One of the most important on-chips is the FIFO buffer, which lowers the systems power consumption allowing the systems processor to read a collection of sensor data similarly, as the MPU-6050 collects more data at the same time. This contributes to the high output data rate of 1000 Hz (InvenSense, 2013). The registers, which host all the functionalities of the sensor and other chips communicate with the I^2C communication protocol. According to (NXP, 2011), this protocol allows for communication with only two electrical signals, while sensor registers can be added or removed out of the loop. This reduces space and increases speed. For example, a signal is destined for a single register, but there are ten registers connected to the communication pipeline, it is no problem for the I^2C protocol. This makes it a very popular standard and contributes as well to the output data rate of the sensors measurements (InvenSense, 2013).

Although, many advantages are explained and it becomes clear that IMUs and in specific the MPU-6050 is useful for this research, there exist some major disadvantages, in the form of measurement errors. Woodman (2007), state that the most important errors of MEMS IMUs are noise (random walk error) and uncorrected bias errors (change in temperature and initial bias). Noise is seen as restless fluctuations around the real value. According to Woodman (2007), the standard deviation of noise grows over time, for both the gyroscope and accelerometer measurements. Bias errors are the difference between the actual value and the measured value. This error grows linear over time for the gyroscope measurements after integration and quadratic over time for the accelerometer measurement after double integration (Woodman, 2007). Both errors are found in the test results and will be explained more extensive in section 6.4.

6.2.5. Prototype engineering: microcontrollers

The previous section explained the selection procedure and characteristics of the MPU-6050. However, controlling the sensor is another important aspect of the overall system and made available with a combination of hardware and software. This section describes the hardware part of the system being in service of the sensor. Potential platforms that are often used in such developments are the microcontrollers of Arduino and Raspberry Pi. According to McEwen & Cassimally (2014), the Arduino controllers are the most basic of the two and adding more functionalities is only possible by combining multiple modules (systems-on-chips) together. This feature allows for the development of a highly specialized microcontroller for specific purposes.

The Raspberry Pi, however, is a more advanced microcontroller and fills the gap between the ones from Arduino and fully functioning computers. Because, the latest Raspberry Pi model (Third generation model B) comes with a standard Wi-Fi functionality, while the Arduino requires an additional module, otherwise it will cost as much as the Raspberry Pi 3B (RPI 3B). this makes the extra performance features of the Raspberry Pi beneficial to reading of sensors and allowing a database to run (e.g., larger CPU speed, larger RAM, extendable data storage). Furthermore, extending the sensor network from one to multiple sensors, requires multiple microcontrollers, as the sensors will be placed with a large distance between each other on the crane’s jib and mast. Because, these microcontrollers only control one MPU-6050 each and are in need of a Wi-Fi functionality to send their data to the RPI 3B, it is logical to remain with similar microcontrollers. Therefore, the Raspberry Pi Zero W (RPI 0W) is selected, as this is the smaller and simpler version of the RPI 3B. Both microcontrollers can be seen in Figure 25 and 26.

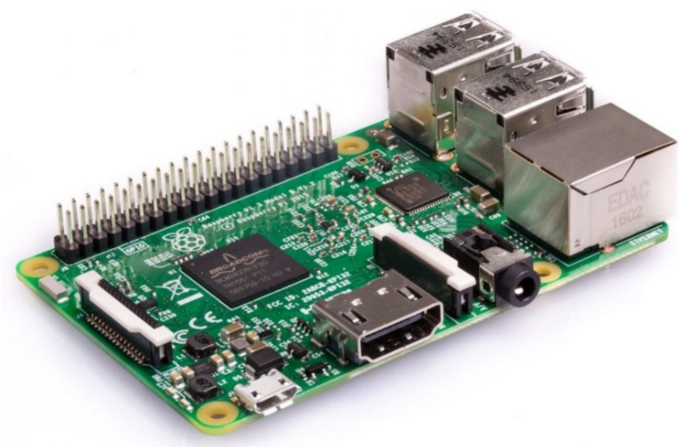

Figure 25: Raspberry Pi model 3B (Raspberry Pi Foundation)

Figure 26: Raspberry Pi model 0W (Raspberry Pi Foundation)

6.2.6. Prototype engineering: software components

Both Raspberry Pi's are designed to be small, inexpensive and especially for experimental purposes. Both controllers come with the ability of running on various operating system, of which the Linux variant 'Raspbian' is the default option (McEwen & Cassimally, 2014). According to the official website of Raspbian, the operating system is optimized for the RPI and combines some basic programs and utilities that make it able to use the RPI. Furthermore, Raspbian has a collection of more than 35.000 software packages that are useful in the setup of many applications. Also, there is a Raspbian Lite version, especially for the RPI 0W, which shows that operating system is tuned to the hardware and makes the modules more efficient. Another important aspect of the RPI is the programming language Python that is necessary for programming features, such as using the MPU-6050. For each functionality (e.g., retrieving sensor data, pushing this data to the database and exporting the dataset to excel if necessary). Every piece of Python code created is placed in Appendix III. Beneficial to the use of RPI and Python is the fact that many projects and there source codes are published on the internet. Furthermore, An extensive amount of forums are available to help programming and use code sections from others to realize new and potentially improved features.

In order to store the data created with the MPU-6050 sensors, the MySQL open source database system is used. MySQL allows the creation of databases with the use of Structured Query Language (SQL). For this research a very simple database is assembled, consisting of a single table with nine columns, as is visualized in Figure 27.

id	serial_numb	timestamp	acc_x	acc_y	acc_z	gyro_x	gyro_y	gyro_z
1	Sensor-rpi	2017-12-15 17:29:15.686212	-0.696713	-3.96959	9.00699	-0.557252	1.03053	-0.969466
2	Sensor-rpi	2017-12-15 17:29:15.692622	-0.706289	-3.95043	8.97107	-0.442748	1.10687	-0.824427
3	Sensor-rpi	2017-12-15 17:29:15.698977	-0.742203	-4.00311	9.01656	-0.496183	1.16031	-0.717557
4	Sensor-rpi	2017-12-15 17:29:15.705315	-0.730232	-3.90973	9.00699	-0.412214	1.25954	-0.931298
5	Sensor-rpi	2017-12-15 17:29:15.711653	-0.708684	-3.93128	9.01896	-0.648855	1.25954	-0.832061
6	Sensor-rpi	2017-12-15 17:29:15.718055	-0.699107	-3.92649	9.05487	-0.572519	1.21374	-0.763359
7	Sensor-rpi	2017-12-15 17:29:15.724411	-0.730232	-3.881	9.05727	-0.526718	0.984733	-0.679389
8	Sensor-rpi	2017-12-15 17:29:15.730786	-0.782904	-3.9217	8.90882	-0.496183	1.0916	-1.0229

Figure 27. Snapshot of MySQL database table used for storage of sensor values

Because, the RPI 3B is running the database, and efficient working with this in the Raspbian command program is difficult with an insufficient level of experience. However, the use of phpMyAdmin allows the database to be accessed via an internet browser. The use of phpMyAdmin also creates a visual representation of the database and comes with graph and export functionalities. This is highly convenient in the experimental phase, this research starts with (Bell, 2013). The remaining gap between sensor measurements and data storage in a database is filled with the use of a messaging protocol that transfers the data. For this research the Message Queue Telemetry Transport (MQTT) protocol is used. This protocol is lightweight and useful in scenarios where small network bandwidth is required. MQTT makes use of the mechanism where senders publish a message with a pre-specified topic and interested recipients can subscribe to this message in order to receive the data. A so-called message broker in between connects the publisher and subscriber, which makes it very easy to facilitate a one-to-many or many-to-one communication strategy (McEwen & Cassimally, 2014).

6.3. Data transformation

Although, the MPU-6050 comes with 6 DOF, the small-scale tests made clear that many of these DOF are meaningless. This can be clearly explained, as the purpose of this sensor is measuring a pre-defined movement of the crane's structure. Through, positioning the sensor with one of the axis aligned with the jib or mast, it is possible to specify the particular DOF in advance. This is different to most of its generic implementations (e.g., video stabilization, wearables and dead reckoning), where it is unknown what DOF are needed on beforehand (InvenSense, 2013). After analyzing the output of the sensor, it is determined that the gyroscope measurements are not useful in the determination of distance travelled. This decision is the result of implementing the concept of sensor fusion to obtain a higher quality of measurement results. In order to combine the accelerometer and gyroscope sensor output, a filter is implemented.

Among others, the Complementary filter and Kalman filter are popular in numerous sensor development projects. The Kalman filter comes with a high degree of complexity, while similar results appear in the implementation of the, much easier to implement Complementary filter (van de Maele, 2013). However, the filter was implemented successfully and resulted in a representation of sensor output without any noise, the filter could not be included in the data processing method. All test results were less precise than without the implementation of a filter. An explanation of this occurrence, again is the use of the sensor. The article of van de Maele (2013), is part of his development to using a MPU-6050 as stabilizer in a quadcopter. In this case, distance travelled is not interesting and noise need to be removed out of the sensor readings, otherwise the quadcopter is expected to vibrate heavily. To conclude, using a filter for IMU sensor fusion can be discarded out of the data processing method of this research, although it is an often used method in many development projects. This being stated, it is clear that in particular accelerometer measurements need attention. The sequence of processing the raw values to distance travelled (for small-scale testing) and crane deformation (for large-scale testing) is explained in this section.

6.3.1. Acceleration measurement of the MPU-6050

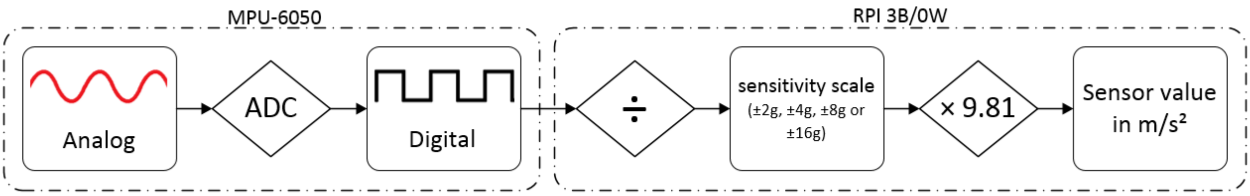

Figure 28. Processing sensor readings to understandable values

Figure 28 shows how the sensor readings are processed through the sensors and RPI 3B/0W, before they are being stored in the database. The MPU-6050 measures analog signals in voltage, which are converted to digital signals via the on board ADC component. This is an important feature, as both RPIs only handle digital signals as input. The second group in the Figure above shows the process that is programmed in Python. Here, the sensor output is processed as follows: digital values for the x- , y- and z-plane acceleration are divided by an selectable sensitivity scale. The sensitivity scale is a ratio that represents the relation between the sensors input (mechanical) and output (electrical). For the MPU-6050, the selectable ranges are: ±2g (16384.0 LSB/g), ±4g (8192.0 LSB/g), ±8g (4096.0 LSB/g) and ±16g (2048.0

LSB/g). With this transformation, the sensor values indicate acceleration in g-forces. In order to change this to a more practical unit for further processing, these values are multiplied with a singular g-force (9,80665 m/s²). At this point, All sensor values are transformed into the SI unit for acceleration, which is beneficial for integration into velocity and distance. In this form, the values of each test run are stored into the database. The database enables export of a complete dataset for each test run to Microsoft Excel. Although, it is clear that further processing of data could be programmed on the RPIs or in the database, trial-and-error was necessary to find out which method and what type of calculations are needed to generate the most optimal output of the whole system. The sequence of steps in processing the data is successfully found and will be explained in this chapter. In order to understand this process in detail, the expected output is first analyzed from literature. These expectations are shown in the next section.

6.3.2. Expected output of data processing method

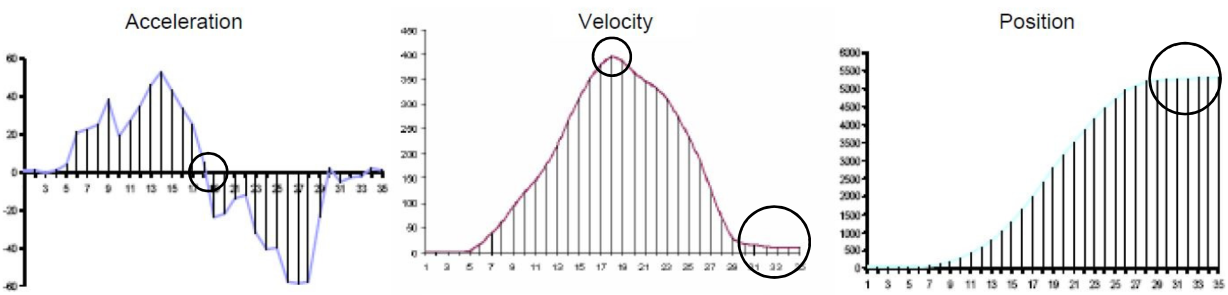

Figure 29. expected output of data processing to positional outcome of IMUs obtained from: (Seifert & Camacho, 2007)

Seifert and Camacho (2007), describe the use of an algorithm with the ability to find positions, by using an accelerometer. Figure 29 is obtained from this report and shows a movement of an accelerometer over a straight path. It is important to look at the trends of all graphs, starting with the graph for acceleration that shows positive values when the sensor accelerates and negative values when the sensor decelerates. In the second graph, which represents the sensor's velocity, a parabolic shape shows the increasing velocity in the first half of the movement and a decreasing velocity in the second half of the graph. The two smallest circles in Figure 29 show that the zero-point in the acceleration graph is exactly similar to the coordinates were velocity is at its maximum. The third graph in the Figure above shows the distance travelled for the sensor, which can be read of at the last point of the graph. Processing the data from acceleration to velocity and from velocity to position can be done with integration of the values. Figure 29 also shows the measurement error that appear in the sensor reading, as explained in section 6.2.4. Although, noise and bias errors certainly exist in the acceleration graph, they are not visible here. However, the result of the sensor's bias error is clearly visible in the velocity and position graphs, as is highlighted in the two largest circles of the figure. In the velocity graph is should be expected that when the sensor stops moving around, velocity becomes zero. A remaining velocity at the end of the movement, therefore, is the result of this error. Because this measurement error is not removed in (Seifert & Camacho, 2007), it appears again in the position graph, as a linear increase in distance despite the sensor is not moving. At this point, it is clear what results should be expected and how the graphs can be analyzed in order to decide if the results are as accurate as possible.

6.3.3. Step 1: set a movement-window

In order to explain how the sensor output is processed into a value representing displacement, which ultimately represents the deformation of a tower crane, the processing method is divided into four steps. Each step is explained and visualized in detail with the use of results coming from the small-scale testing stage of the first test setup. This particular dataset is chosen, as it is similar to the expected output explained in the previous section. To summarize, this test consists of a sensor movement in the x-plane along a straight wooden beam of 5,90 meter. The process of finding out the displacement of the sensor starts with extracting the actual acceleration, removing the bias error and double integration into distance.

The first step of processing the (raw) values coming out of the database, is the placement of a movement-window (Seifert & Camacho, 2007). Because, the noise in the sensor readings, as shown in the black circle of Figure 30, indicate that the sensor slightly moves, it is important to reset every value to zero. Otherwise, the error adds up quadratic after integration. The movement-window extracts the actual movement of the sensor and forms the basis for further data processing. The window is set manually, after analyzing the complete graph. The circles on the dashed line in figure 30 show the start and end coordinates for actual acceleration. This first step ends with the extraction of the sensor's actual acceleration, which can be seen in Figure 31. Similar to the expectation from previous section, the figure shows that the sensor accelerates (positive values) and decelerates (negative values). However, in this case deceleration appears between acceleration, showing that the sensor is not moved with great smoothness over the straight path of the first test.

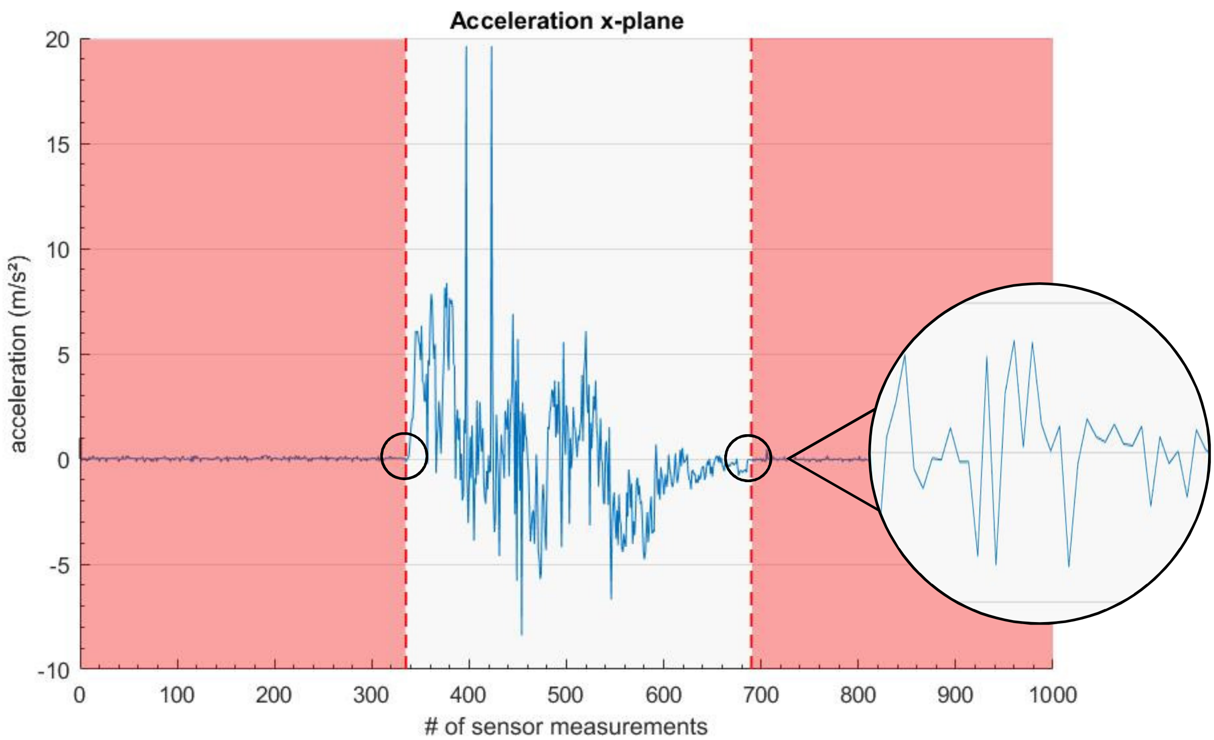

Figure 30. Selection of the movement-window to extract the actual acceleration of the sensor

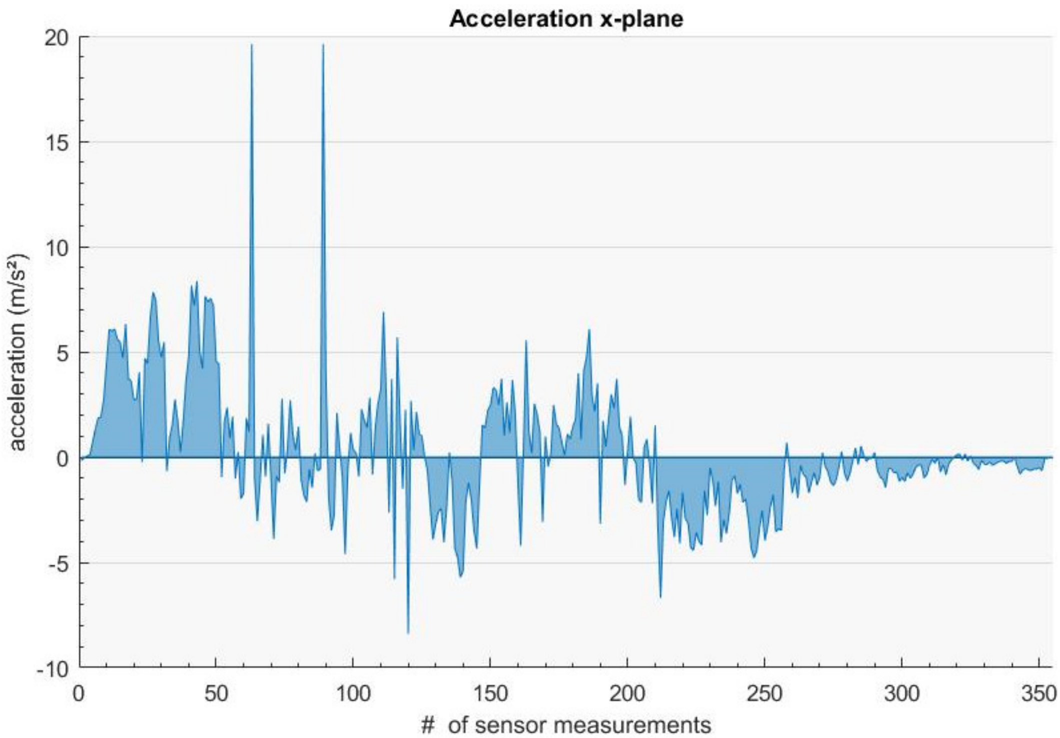

Figure 31. Acceleration graph of the sensor in linear movement along x-plane

6.3.4. Step 2: remove cumulative bias error

InvenSense (2013) state that the sensor is factory calibrated, which indicates that the largest part of the measurement errors are already reduced. Furthermore, analysis of the acceleration values outside the movement window indicate that the amount of noise is little and therefore, this type of error is accepted in the movement window. However, this is not the case for the bias error, which behaves cumulative (Woodman, 2007). Because this error is cumulative, it has a very large effect on the results of further calculations and, therefore, need to be excluded in advance. Figure 32 on the next page visualizes the sensor acceleration with (blue dash line) and without (orange surface) bias error. To make sure this error is clearly visible, only a section of the total graph is displayed. Here, it becomes clear that the error accumulates as the sensor moves. In order to take out this error, Equation 1 and 2 are established. The first equation divides difference between the average value before and after (Y) the actual acceleration outside movement-window with the total number of sensor measurements (X_i) inside movement-window. This results in the factor (Z). The second equation uses this factor to extinguish the bias error ($acc.x_{with\ error}$) by adding or subtracting the factor multiplied with the sensor measurement number, which is cumulated by one (i^{n+1}) every measurement. The result of these calculations are improved acceleration with low error contribution.

$$\frac{\langle Y_{before\ movement} \rangle - \langle Y_{after\ movement} \rangle}{\sum_{i=1}^{n} X_i} = Z \qquad (1)$$

$$acc.x_{with\ error} \pm (i^{n+1} * Z) = acc.x_{without\ error} \qquad (2)$$

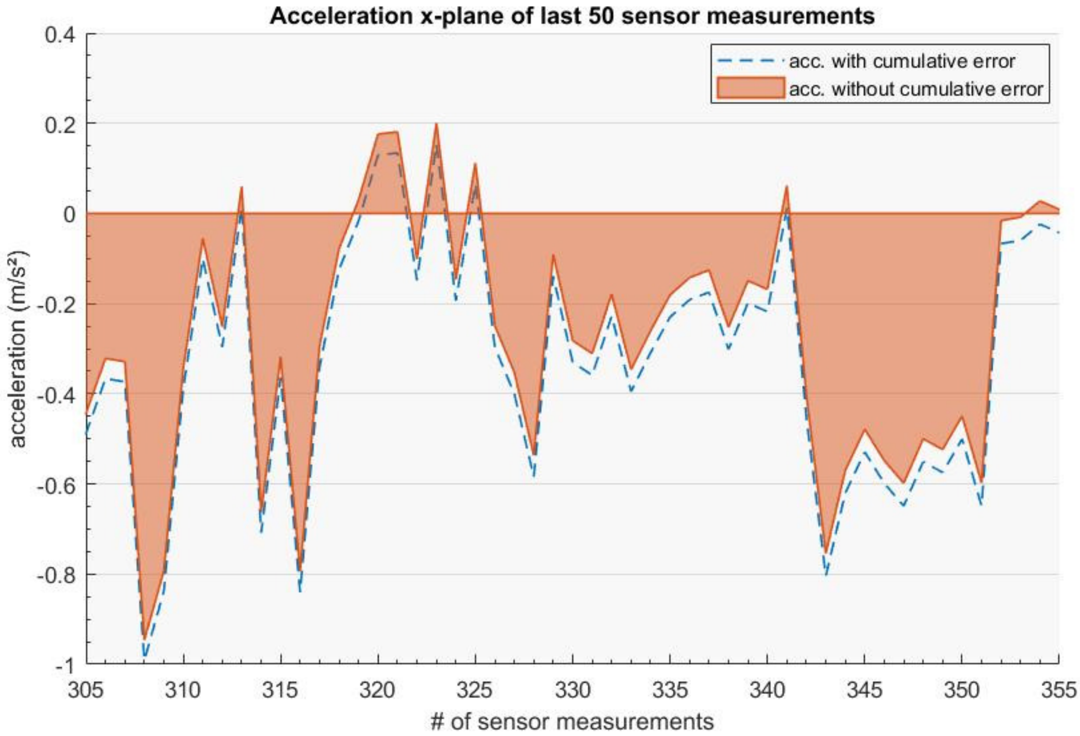

Figure 32. Acceleration with and without bias error

6.3.5. Step 3: integrate acceleration to velocity

The third step is the integration from acceleration to velocity. An important aspect here, is the use of the time between each two sensor measurements (ΔT). Whenever, the sensor starts measuring, a timestamp is added to each value and also stored in the database. In Microsoft Excel these timestamps are subtracted from each other to generate a complete column of delta times. Equation 3 obtained from Serway & Jewett (2004) shows the transformation of acceleration to velocity. This equation is very familiar, as it appears in basic physics and allows for the examination of velocity at any time. The velocity diagram shown in Figure 32 has a positive parabolic trend, such as expected in section 6.4.2. In the equation used, previously measured velocity (v_{n-1}) is summed with the multiplication of acceleration (a_n) and delta time between n and n-1.

$$\boldsymbol{v_n = v_{n-1} + a_n * \Delta T} \tag{3}$$

Although, the bias error is distinguished previously, it appears again into this step (blue dash line in Figure 33). At this stage, it remains unclear why this error appears. Nevertheless, it must be acknowledged that this error has a reasonably larger effect on the velocity of the sensor. The sensor remains at a steady velocity of 0,35 m/s instead of returning to 0,0 m/s, as it actually does. In order to take care of this error the same calculations are repeated (Equation 1 and 2) for the velocity output. Figure 33 also show the result without this error (orange surface). The following step in the process continues with the integration of velocity without cumulative error.

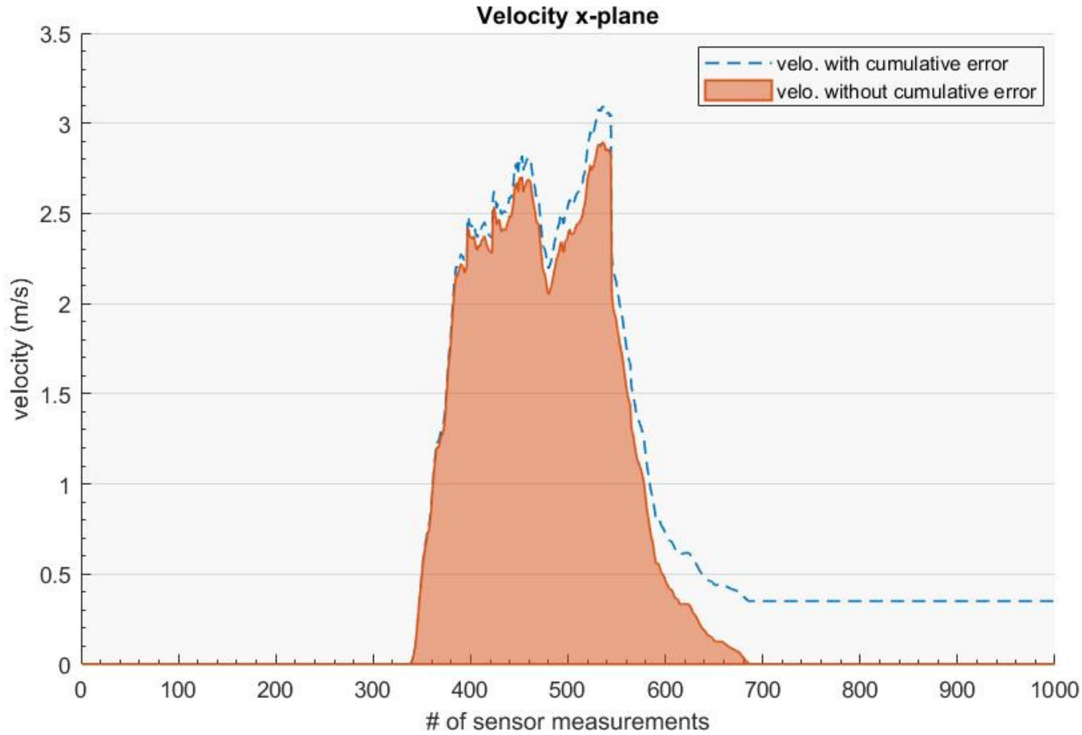

Figure 33. Velocity graph of the sensor in linear movement along x-plane

6.3.6. Step 4: integrate velocity to travelled distance

The final step in processing the data from the MPU-6050 is the integration from velocity to travelled distance. In this research, distance represents the displacement of the sensor for the small-scale tests and deformation of the tower crane's structure in the large-scale test. Equation 4 is obtained from Serway & Jewett (2004) and used to calculate travelled distance. Here, the previous travelled distance (s_{n-1}) is summed with a multiplication of previous velocity (v_{n-1}) and delta-time. This again, is summed with a multiplication of half the measured acceleration (a) and the square of delta-time. According to Serway & Jewett (2004), this equation is a kinematic one representing the motion of an object as a function of time.

$$\boldsymbol{s} = \boldsymbol{s_{n-1}} + (\boldsymbol{v_{n-1}} * \Delta\boldsymbol{T}) + (\boldsymbol{1/2} * \boldsymbol{a} * \Delta\boldsymbol{T^2}) \quad (4)$$

Figure 34 visualizes the distance over which the sensor is moved. The result of this process is the knowledge that the sensor measures a distance of approximately 6,1 meter, while the actual distance is 5,9 meter, indicating the sensor has an error of 3,3% in this test run. It shows that the sensor has the potential to meet previously set expectations. Every other result, together with detailed explanations are provided in the following section.

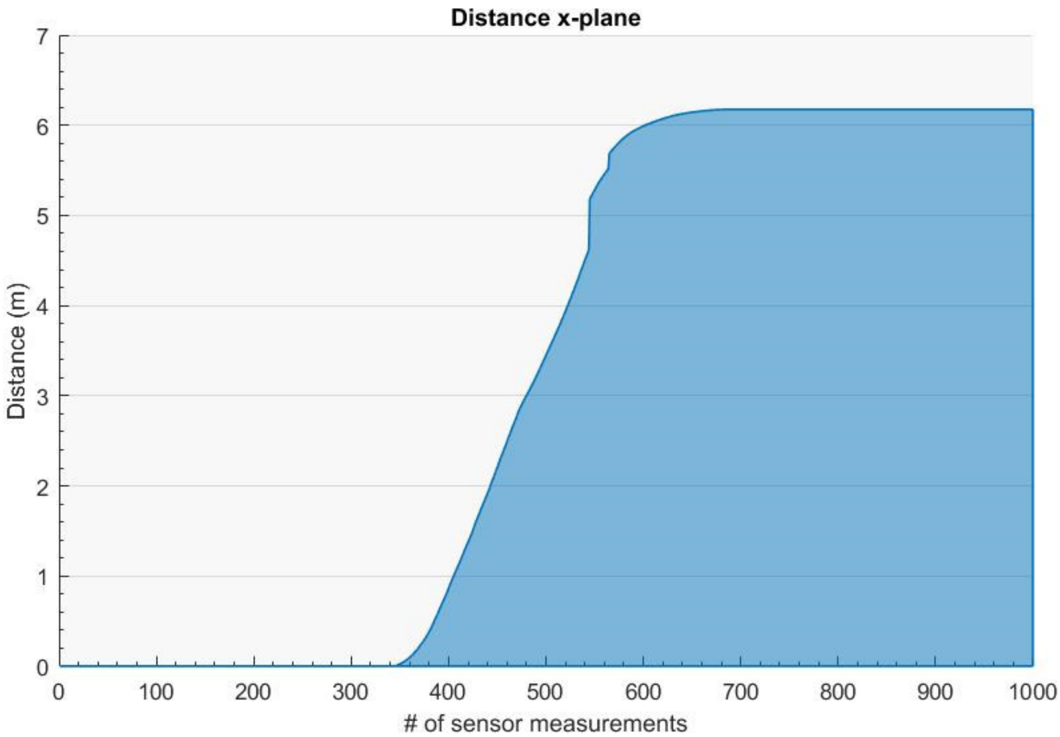

Figure 34. Distance graph of the sensor in linear movement along x-plane

6.4. Small-scale testing phase

Referring back to the development process shown at the start of this chapter, the small-scale tests represent the third and fourth step in the developmental phase of this sensor network. The prototype used during these tests consists of the RPI 3B with only one MPU-6050. Subsequently, it is ensured that the sensor is working and data could be transferred to the database, testing is started. The small-scale testing stage is divided into three different tests: a straight horizontal line distance measurement (test 1), a fixed radius rotation circumference measurement (test 2) and a fixed radius pendulum distance measurement (test 3).

6.4.1. Small-scale test setup

In test 1, the sensor is displaced over a straight horizontal line. A wooden girder of exactly 6,0 meter is used as path to move along. A platform is made in such, it can only follow the wooden girder. On top of this platform the complete prototype is fastened, with the IMU placed in a way, its x-plane (body frame) is aligned with the wooden girder (navigation frame). This conditioned characteristics allows simple extraction of useful data. Although, the MPU-6050 measures six different values, as is explained in section 6.2.4., it is tried to make use of only two DOF. This simplification is beneficial for analyzing the performance of the sensor and is seen as a starting point for exploring the most convenient transformation of data. From reviewing both DOF, it becomes clear that angular velocity is not useful and therefore, only the acceleration in the x-plane (one DOF) is representative in this first test. Logically, every other output value is influenced massively due to measurement errors, as the sensor is not moving in the y- and z-plane. Therefore, they are removed in the data transformation stage.

In this first test that is visualized in Figure 35, 36 and 37, three appropriate runs are generated. In run one and three, the sensor is moved in a forward direction. By excluding the size of the platform, both runs have a length of 5,90 meter. In the second run, the sensor is moved forward as well as backwards, generating a total length of 11,80 meter. The expected outcome of every test is a positive displacement in the forward direction and a negative outcome for the backwards motion.

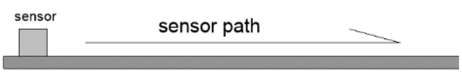

Figure 35. Schematic setup of test 1

Figure 36. Setup of test 1 – linear displacement

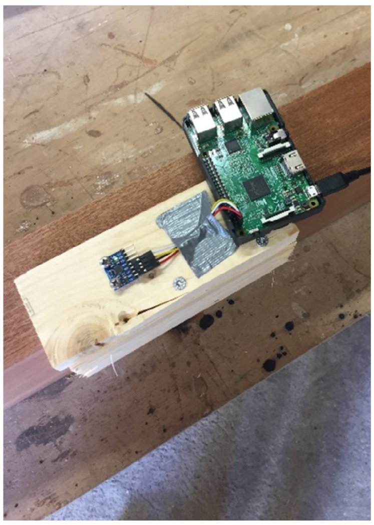

Figure 37. Sensor platform of test 1

For test 2, a structure is built that produces a circular motion with a fixed radius. The sensor is placed exactly 1,5 meter out of the pivoting center. Similar to test 1, a wooden girder is used for sensor movement. In this setup the girder provides a turning circle of 9,42 meter for one 360° rotation, as displacement path. In order to remain as horizontal as possible and discard the z-plane (body frame) out of the test, counterweights are placed at the behind the pivoting center on the wooden girder. This setup makes the prototype more complex, because it now measures the acceleration in both, the x- and y-plane. To make sure, the output is understood, ten runs are made. Five in clockwise direction and five in counter-clockwise direction. It is expected that the outcome of the test changes from positive to negative in a way. The complete setup of this test is visualized in Figure 38 and photographed in Figure 39 and 40.

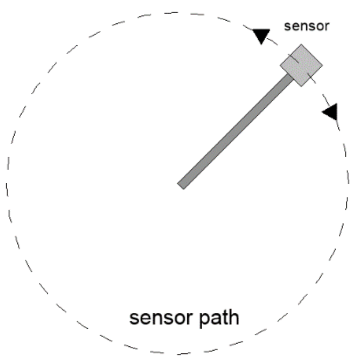

Figure 38. Schematic setup of test 2

Figure 39. Setup of test 2 – fixed radius rotation displacement

Figure 40. Sensor placement of test 2

In test 3, a structure is built that realizes a pendulum motion with a fixed radius. In this case, the sensor is placed horizontally at the end of the pendulum. The distance between the sensor and the point of pivoting is exactly 2,0 meter. Similar to test 2, this test also generates a circular motion. However, due to a different placement of the sensor, a combination of the z- and x-plane will represent the distance travelled during each run. The setup of test 3 is visualized in Figure 41, 42 and 43. the movement starts with the pendulum hanging around 45 degrees, making its larges swing 12,5% of a complete circle. Because, the movement is realized without a force other than gravity, resistance builds up and the travelled distance of each period declines. Therefore, a resistance percentage is calculated afterwards to determine the travelled distance more precise. A full test run consists of 5,25 periods over an average distance of 12,3 meters. For this particular test, five runs are made and it is expected that the output of the test is an acceleration diagram representing the shape of a wave with a decreasing amplitude.

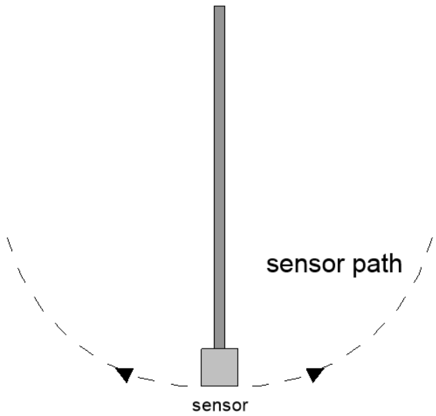

Figure 41. Schematic setup of test 3

Figure 42. Setup of test 3 – fixed pendulum

Figure 43. Sensor placement of test 3

Every setup in the small-scale testing stage is developed with the goal of understanding the MPU-6050 and its outcome. Furthermore, these tests provide a solid basis for working with and improving the prototype. However, it must be noted that there appear some weaknesses in this testing stage. Therefore, Table 6 lists the strengths and weaknesses to indicate upon the quality of the tests.

Table 6. Strengths and weaknesses of small-scale testing phase

Strengths	**Test case**
1. Displacement in a single plane	test 1
2. Displacement in x- and y-plane	test 2
3. Displacement in x- and z-plane	test 3
4. Similar motion in every run	all
5. Quick data generation	all
6. Taking into account gravitational force	test 3
Weaknesses	**Test case**
1. Manual movement, lacks a certain smoothness	all
2. Wooden girder is not 100% straight	test 1
3. Solder tips disturb horizontal placement on platform	all
4. Girder swaying in z-plane influences outcome due to gravity	test 2
5. Counterweight tils the sensor slightly out of horizontal position	test 2
6. Pendulum sways in y-plane, reducing measurement accuracy	test 3
7. Variable distance travelled decreasing the level of precision	test 3

6.4.2. Small-scale test results

The small-scale testing phase is divided into three different tests. The purpose of these tests was creating a high level of understanding about the MPU-6050. Furthermore, each test grows in complexity in order to find out the capabilities as well as the shortcomings of such sensors. This section shows and describes every test result of all three tests. Moreover, it is made clear how these tests have been contributing in the developmental curve of the sensor network. The first test, which measured the displacement of the sensor over a straight path consists of three test runs. The sensor is placed in such, the x-axis of the body-frame aligns with the local geographical frame (wooden beam). This assures that every measurements generated by the sensor over other axis could be discarded out of this specific test. Because, only the x-axis is highlighted here, complexity decreases, as it is immediately clear which of the collected data need to be processed. Table 7 shows the results the first application of the prototype after the gathered data is processed according section 6.4.

Table 7. Test results of test 1 – straight horizontal line distance

	unit	run 1	run 2	run 3
distance	m	5,90	11,80	5,90
sensor output	m	5,73	12,43	6,17
difference	*m*	*-0,27*	*0,43*	*0,17*
	%	*-4,5*	*3,6*	*2,8*

Of the three runs in this test, two measure an expected displacement of 5,90 m (only forward movement) and one expected displacement of 11,80 m (forward and backward movement). Obviously, there is a difference in the expectancies and the result of the sensor measurement. The goal of these tests, therefore is to determine if the current sensor is useful at this stage in the overall development process. The difference between the expected and measured displacement is showed in Table 7, both in meters and percentages. Interesting in cross-examining the differences, is the fact that the difference grows parallel to the change in displacement. Taking the average of run 1 and 2 gives a difference of 3,65%, which is similar to the difference of run 2.

Figure 44 visualizes the results of the first test and provides a better understanding of the emergence of the measured distance. This shows where the displacement starts and end. The distances placed in the table above comes from the y-coordinate of horizontal line before run 1 and 3 end. Comparing test run 1 and 3, it is visible that the velocity of the sensor is higher in the third run, as the start and end of the displacement are closer together. Higher velocities, therefore, possibly result in more displacement measured. The second run shows that the type of movement in an axis can be traced. The first half of this run shows an increasing displacement (forward movement), while the second half indicates that the object is moved backwards in the same direction. It is even visible that the sensor is stopped for a moment between the forward and backward displacement. The overall result of this test is the knowledge that the MPU-6050 makes it possible to determine its own displacement with a reasonable level of accuracy.

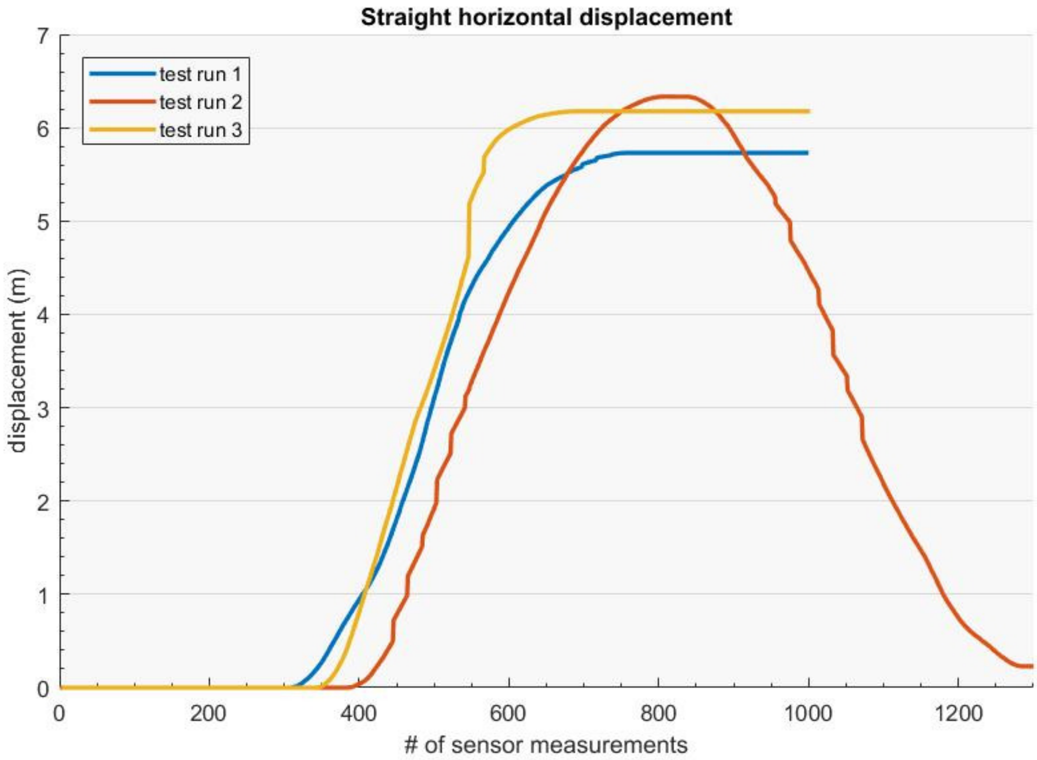

Figure 44. Results of test 1 – horizontal line displacement

The second test increases in complexity, as the rotational displacement requires the combination of two axis. In this case, the measurements of the x- and y-axis are combined. To study how the sensor handles both positive and negative measurements, several runs are made clockwise as well as counter-clockwise. Table 8 shows the results of the clockwise displacement. Here, a larger accuracy appears in comparison to the first test. Although, the first four runs result in a very precise measurement, the fifth run measures a difference over 2 meters. Logically, this is not very convenient and shows that the sensor lacks a certain robustness. Figure 45, visualizes the first five runs, similar to Table 8. A remarkable note is the difference in effect, each axis has on the output. Furthermore, there is a large difference visible in the results of the second half of the circular movement. This indicates a low consistency between each run. However, this is the case, measured displacement is similar for every run, except the fifth. The establishment of the measured displacement is finding the maximum of the graph summed with y-coordinate of the straight line at the end of each graph.

Table 8. Results of test 2 – circular displacement clockwise

	unit	run 1	run 2	run 3	run 4	run 5
distance	m	9,42	9,42	9,42	9,42	9,42
sensor output	m	9,43	9,53	9,38	9,37	11,50
difference	*m*	*0,01*	*0,11*	*-0,04*	*-0,05*	*2,08*
	%	*0,1*	*1,2*	*-0,4*	*-0,5*	*22,1*

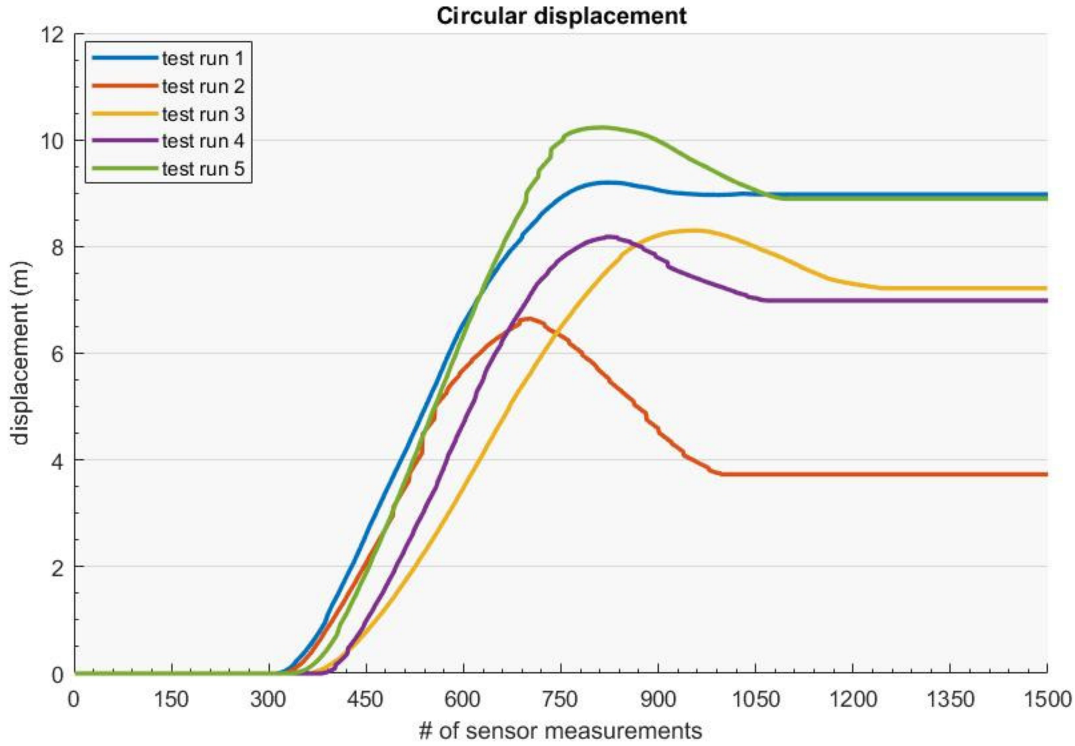

Figure 45. Results of test 2 – circular displacement clockwise2

The second test continuous with the counter-clockwise displacement, of which the results are placed in Table 9. Comparing these five runs, it can be said that the sensor measures its displacement in an accurate way. However the error in the measurement seems low, it must be noticed that some runs result in a negative difference, while others are positive. This shows that the overall accuracy of this test is between -0.21 and 0.20 meter, not taking into account the inaccurate fifth run. Figure 46 visualizes the last five runs of the second test. Interesting to see is the decreasing trend at the start of the graph, which in the clockwise displacement comes at the end. Another trend visible in the graph is the fact that all five runs are relatively consistent. The overall result of this test shows that the sensor is not completely robust and large measurement errors can appear. However, it is possible to combine multiple axes of the MPU-6050 and measure the displacement of the sensor during circular movement.

Table 9. Results of test 2 – circular displacement counter-clockwise

	unit	run 6	run 7	run 8	run 9	run 10
distance	m	9,42	9,42	9,42	9,42	9,42
sensor output	m	9,21	9,62	9,35	9,62	9,43
difference	*m*	*-0,21*	*0,20*	*-0,07*	*0,20*	*0,01*
	%	*-2,2*	*2,1*	*-0,7*	*2,1*	*0,1*

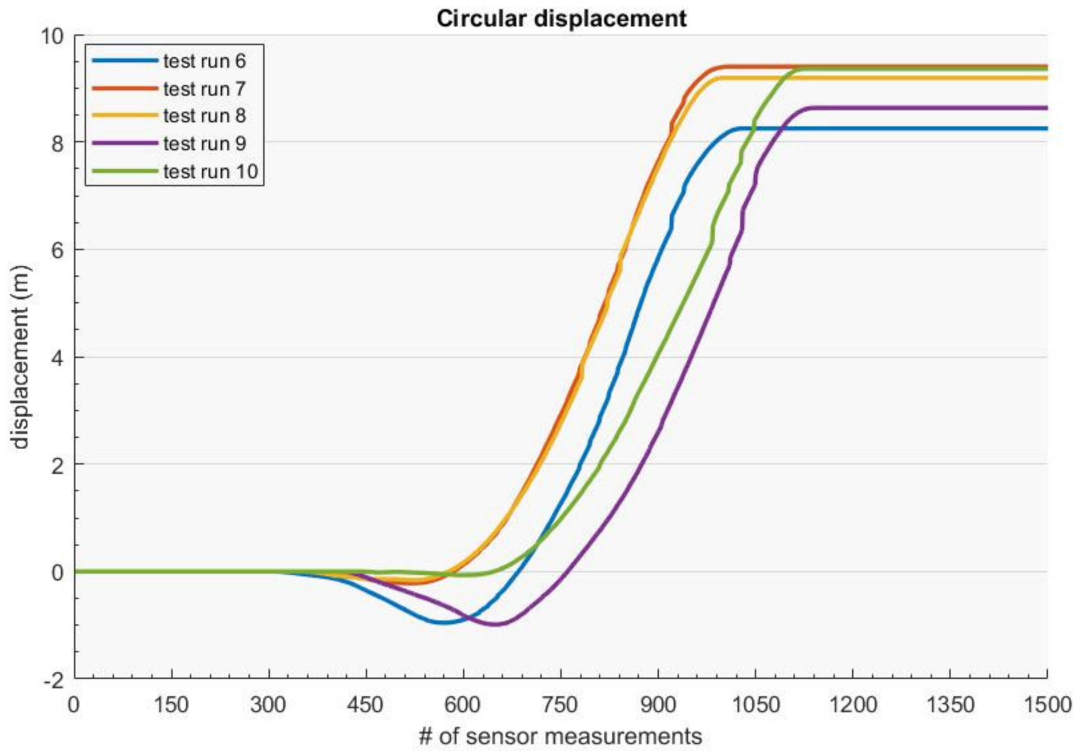

Figure 46. Results of test 2 – circular displacement counter-clockwise

The third test is the most complex of all small-scale tests. This comes due to the combination of the x- and z-axis, required for measuring the displacement of the pendulum. When the sensor is placed horizontally, the z-axis measures the earths gravitational force, which often is greater than the other forces. In the pendulum movement, the earths gravitational force transits between both, the x- and z-axis. Because, this force is significantly present during the test, it is expected that the results are less precise, than the results of previous tests without the observance of this force. Table 10 shows the results of all five runs of the third test and it is certain that their appears a lower level of precision in the measurement of the sensor. Similar to the results of the second test, one run is highly inaccurate and therefore affects the overall robustness of the MPU-6050.

Table 10. Results of test 3 – pendulum displacement

	unit	run 1	run 2	run 3	run 4	run 5
distance	m	12,30	12,30	12,30	12,30	12,30
sensor output	m	11,77	9,72	10,99	13,36	10,90
difference	*m*	*-0,53*	*-2,58*	*-1,31*	*1,06*	*-1,40*
	%	*-4,3*	*-21,0*	*-10,7*	*8,6*	*-11,4*

The complete visualization and the emergence of the measured displacement can be seen in Figure 47. In contrast to the other tests, this graph comes with a certain noise in the results. Establishing the total displacement, therefore, becomes more difficult. In order to establish this, all maxima and minima are summed. Although, most of the results come close to the actual distance, high inconsistency between the different runs is visible. This can be explained, as each run is started by a manual force that hold the pendulum in a 45 degree start position.

Another obscuring factor causing the noise in the graph is the hard to control sway in the y-axis of the sensor. The overall result of this last small-scale test is the fact that it shows that precise sensor placement is important and lower accuracy must be expected when the sensor is influenced by the earths gravitational force.

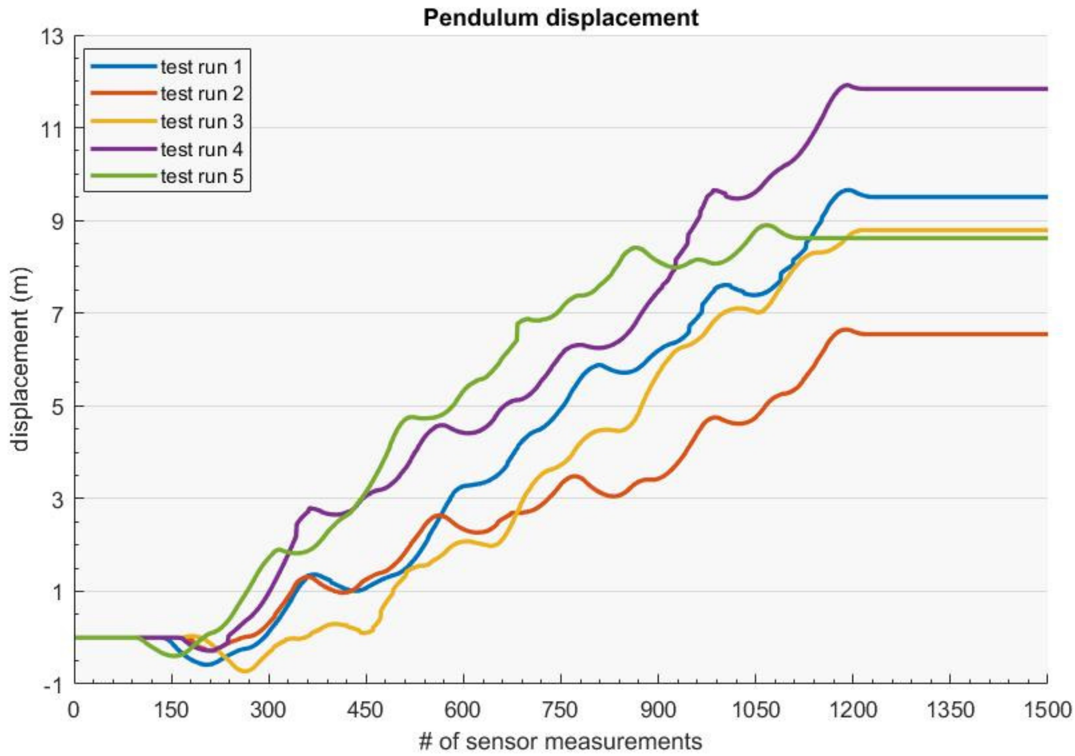

Figure 47. Results of test 3 – pendulum displacement

From a broader view, the small-scale testing stage result in a detailed understanding of the capabilities and weaknesses of the MPU-6050 in the application of measuring its displacement. Straight line and circular displacements for example are easier to measure for the sensor, while pendulum movement is more difficult to grasp. Although this is the case, it is determined that the results of the MPU-6050 are sufficient enough to scale-up the prototype. An important reason for this determination is the fact that the MPU-6050 is a low-priced sensor and multiple other types of IMUs are available that come with a higher precision and robustness (Madgwick, Harrison, & Vaiduanathan, 2011). However, the prototype created in this research is competent enough to show the usefulness of IMUs in general for a solution regarding this particular challenge, according to the results of the small-scale testing stage. The following section, therefore, explains the setup and results of the large-scale tests.

6.5. Large-scale testing phase

As is visualized in the process for prototype development, the large-scale testing phase is the next step. Before the prototype is useful for this testing phase, it is extended from one to three sensors. Every single sensor is installed on a RPI 3B or RPI 0W, as can be seen in Figure 48. The RPI 3B is used as main controller because it is more powerful as the two other controllers. The RPI 3B runs the database and establishes a Wi-Fi network. Subsequently, the RPI 0Ws, both log onto this network and publish their data via the MQTT protocol into the database. Publishing data to the RPI 3B at the same time, the sensor is measuring, slows down the sensor heavily (from > 100 readings per second to < 10 readings per second). This is solved by pushing the sensor measurements in a text file directly on the RPI 0Ws and publish them in a separate process from that file into the database. This ensured a steady measurement of approximately 120 readings per second for each sensor. Hence, it becomes clear that extending the prototype has required additional effort in order to make it function properly. Every part of the codes used in the prototype development is chronologically structured in Appendix III.

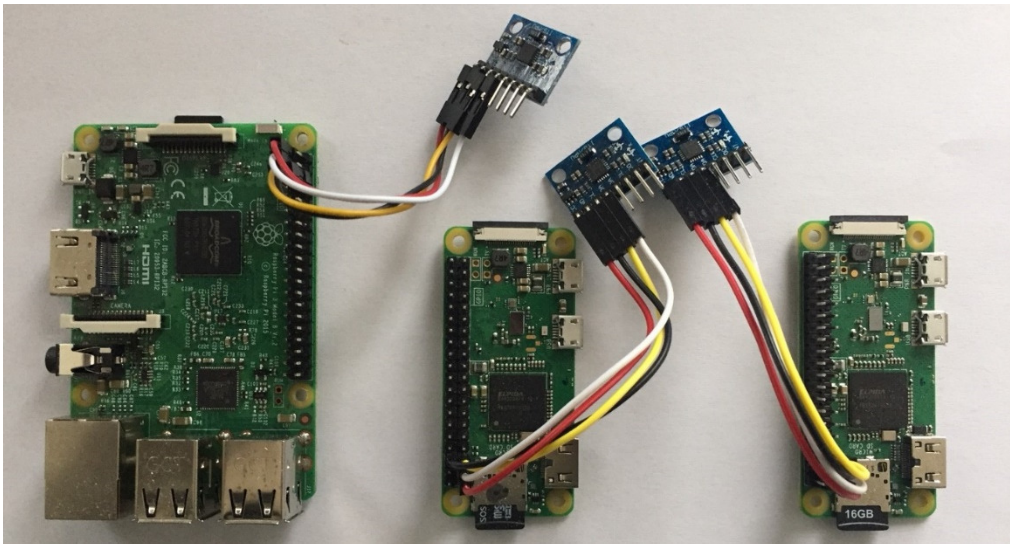

Figure 48. Extended prototype from one to three sensors

6.5.1. Large-scale test setup

When it became clear that the prototype could successfully be developed, agreements had to be made with a company that was willing to cooperate for this test. Dura Vermeer released a tower crane for the large-scale test together with two assistants that fixed the sensors and operated the crane safely. The crane, shown in Figure 49 is a top-slewing tower crane with a hoisting height of 20,1 meters and a jib of 55 meters. The dimensions of the tower are 1,98 meter square and the jib has a width of 1,84 meter and a height of 1,96 meter. The object that was lifted during the test is a large office unit, normally placed on construction sites for supervisors. The object has a weight of 2,8 tons. Due to the available space in the working space of the crane, the object is lifted at 36,7 meters from the tower of the crane.

Figure 49. Top-slewing tower crane used for the large-scale tests

In order to measure the deformation of the tower as well as the jib, sensors are placed at the positions indicated in Figure 49. As can be seen, two of the three circles are red. Unfortunately, only one out of three sensors actually started measuring. Despite the effort of making the prototype as robust as possible, the system failed to setup a sufficient connection between the RPIs. After analyzing the log of the RPI 3B it became clear that it was tried continuously to setup a connection, indicating the prototype works. However, the system stopped trying when the crane moves during each test run. Conclusively, this indicates that the Wi-Fi signal is disturbed during test runs. Two possible explanations for this failure were found. First, the presence of a highly powerful electric engine that produces an electromagnetic field, possibly obscuring the signal of the prototype. Second, the crane is controlled with a radiographic system, of which, some are operational on the same frequency as Wi-Fi does (2,4 gHz). It must be noted that those explanations are obvious, however, not proven. The green circle in figure 49 indicates the position of the working sensor during the actual test runs. Fortunately, this position is expected to displace most as result from the deformation of the crane's tower. This expectancy is previously calculated in section 6.6.2. and has a maximum of 230 mm.

Figure 50. Assistant placing the sensors on the jib

Figure 51. Sensor placed on top of the crane's jib

Actual placement of each sensor was a difficult activity because one assistant had to climb along the jib to mount the sensors on top of the jib. In preparation for this test, it is decided to protect the sensors in wooden boxes as these are stronger than plastic ones and do not have much influence on the signal strength (Figure 50 and 51). In total five runs are realized in this phase. Each run exists of equal and reasonable simple movements. First, the object is lifted from the ground and after some time, the object is placed on the ground. This movement allows the crane to deform as constant as possible. In order to measure this motion the x- and z-plane are expected to be useful for this test, similar to the third test of the small-scale testing phase. The y-plane is not used here, as the crane remains in a fixed position during each run. The greatest strength of this test is the actual implementation on a tower crane that enables a strong indication of the prototype's usefulness. Weaknesses of this setup are: malfunctioning sensors, rough weather conditions and the crowded environment around the crane that made it impossible to record the test sufficiently. Despite, these weaknesses, this test is useful in determining the deformation of the crane's tower and therefore, it remains possible to find out the potential of the prototype.

6.5.2. Large-scale test results

This section describes the last step of the prototype development process in this research, which continues upon the results found in the small-scale testing phase. During that phase, it is decided that the results justify the action to grow the prototype and start testing on a tower crane. The purpose of the large-scale test is to support this early findings and discover if it is actually possible to measure deformation in the structure of a tower crane. The ultimate goal of solving this challenge was the analysis of object displacement that results from crane deformation. From the explanation given in section 6.3.2., it becomes clear that this is not possible, as not all sensors worked during the test runs. Therefore, the focus shifted to measuring the deformation in the crane's tower only. From the rules of thumb used to calculate the largest deformation expected it becomes clear that at the position of the sensor, 24,6 meter above ground and close to the tower, the deformation is maximal 0,23 meter. Although, the calculation method used is discussed and setup with structural engineers, it can be expected that the sensor output is less close to this reference than the often beneath 10% error margin from the small-scale tests. During this testing phase, only the x-plane had to be analyzed because the z-plane remained similar over time. This is logical because the tower of the crane is not deforming downwards, which was expected to be the case for the sensors placed on the jib further away from the tower. The data processing method developed in the small-scale testing phase also generated the largest precision in the large-scale test output. In conclusion, this indicates that the results of the test are the most optimal possible for the sensors used. Table 11 shows the numerical results of the tower crane test, of which all results for every step in the data processing method are placed in Appendix IV.

Table 11. Results of tower crane test

	unit	run 1	run 2	run 3	run 4	run 5
max. deform.	m	0,23	0,23	0,23	0,23	0,23
sensor output	m	0,54	0,15	0,13	0,07	0,32
difference	*m*	*0,31*	*-0,08*	*-0,1*	*-0,15*	*0,09*
	%	*57,4*	*-34,8*	*-43,5*	*-65,2*	*39,1*

The crane used during this test is reasonably small in contrast to many other tower cranes. The assistants, which normally are tower crane mechanics, mention that the deformation of the crane's tower easily grows to 0,5-0,75 meters when reaching a hoisting height of around 100 meters. This information combined with the maximum deformation of the crane used during the test indicate the measure of coordination problems that can occur in the established CLP. Therefore, it can be said that keeping track of the deformation is vital for precise and realistic CLPs. From Table 11 it becomes clear that the sensor is able to measure a certain deformation in the right order of magnitude. Nevertheless, the accuracy of the sensor measurement is relatively low. Run 1 and 4 are least precise, certainly compared to each other. Run 2 and 3 are both reasonably close to what is realistic. The challenge already notified that multiple (un)predictable variables contribute to the deformation. Because, the weather conditions during the test were rough (strong wind) and the manual control of the crane, which resulted in slight differences each run are expected to be the largest contributors of the in between differences of the runs.

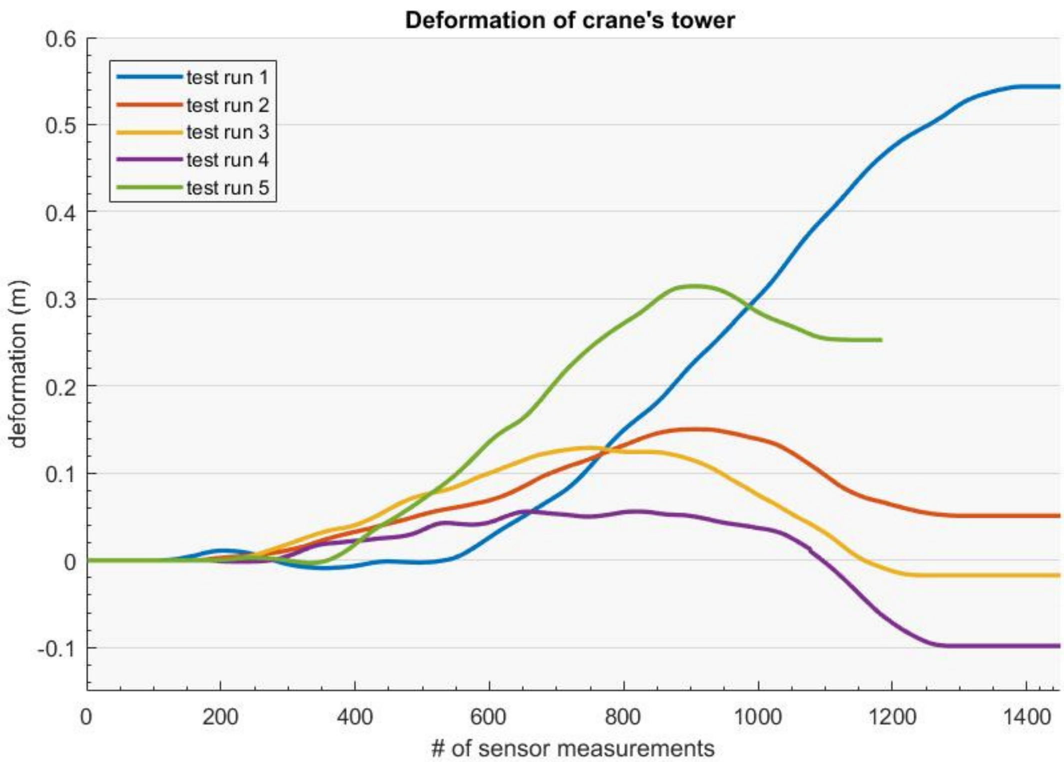

Figure 52. Results of large-scale tower crane test

Figure 52 provides more detail in the actual deformation movement that is measured. The practiced movement of the test consisted of lifting an object, which causes the tower to deform and placing the object back on the ground, which causes the crane to deform back in its neutral position. Apart from test run 1, every run shows that this movement is actually measured. This strongly indicates that the prototype works as is ought to. The reason for the difference in movement of the first run remains unclear, however, it is expected that the object was not perfectly beneath the hoisting hook. This causes a little sway of the object, resulting in a larger deformation of the crane's structure. When the object is placed on the ground for the other test runs, it automatically is straight beneath the hoisting hook. This finding shows the importance of first proceeding the movement of a test run before the actual test starts. Another finding that appears in the graph is that test run 2, 3 and 4 result in a decreasing maximal deformation output. Presumably, this is caused by the event of not releasing all tension from the hoisting cable, which prevents the structure of the crane from deforming back in a neutral position. This is clearly visible in run 2 and 3, were the forward movement is larger than the backwards movement. In run 4, this probably causes the low deformation measurement of 0,07 meters. Furthermore, run 4 indicates a larger backwards movement of 0,17 meters, which is very close to the deformation in run 2 and 3. Equally important, run 4 indicates a movement back to a neutral position, causing the larger outcome of run 5. The relation between the runs indicate the difference in movements made by the operator. However, it must be noted that he did not fail to support the test, but small differences certainly affect the outcome of the sensitive sensors used for this prototype.

6.6. Usefulness of the prototype

The prototype developed during this research is proposed to solve the challenge of coordination problems for the CLP, caused by the (un)predictable variables that result in deformation of a tower crane's structure. Measuring this is only one of the multiple variations that need to be captured to adjust the pre-constructional CLP to the real situation. Considering a fully functioning system, the process can be visualized in the manner shown in Figure 53. This Figure tries to place the developed prototype in perspective of the numerous other systems that are necessary to generate safe and more accurate CLPs than could be made in the pre-constructional phase. Two other systems that certainly need attention are the ones that capture the deviations of the building under construction and the dynamics on site. The Figure also shows that the CLP coordination problems include more than structural deformation of cranes themselves.

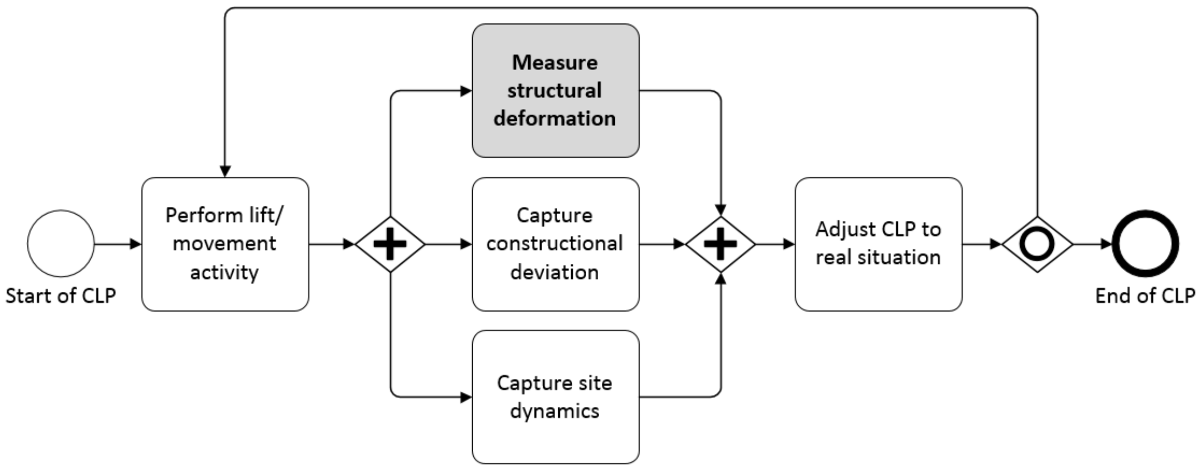

Figure 53. Placement of sensor system in fully functioning process

In regards to this purpose of solving the challenge, it can be said that the sensors used in the prototype system are committed to measure displacement of their own body with reasonable accuracy. Furthermore, the IMU sensors of the prototype were able to measure the deformation movement of the crane's tower during the large-scale test phase. Therefore, it is clear that the prototype contribute to the overall solution of CLP coordination problems. However, it has also been found that the IMU MPU-6050 sensor has difficulties with combining several measurement planes. Especially, when the z-plane should be taken into account. Because the IMUs are measuring the earths gravitational force with their z-plane, the outcome becomes less precise, as this forces is larger than the forces appearing in actual movement of the sensor. Because, this research developed a working prototype, it is clear that without reservation the overall usefulness of the prototype depends on the accuracy of the IMU sensors.

The statement above provides a starting point for further development and it seems appropriate to continue improving the prototype, as is visualized in Figure 54. First, the prototype system should overcome potential Wi-Fi connectivity problems due to interfering systems. A potential solution for this is, changing the frequency from the standard 2,4 gHz to 5 gHz, which is currently less used, especially in the remote control systems tower cranes can be operated with. In addition, improving the prototype certainly requires more accurate sensors. One example is the Next Generation IMU (Figure 55). This is an IMU sensor and microcontroller combined that already is equipped with an algorithm that provides accurate measurements and is able to transfer the values via Wi-Fi, similar as the prototype of this research is doing (X-IO Technologies, n.d.). Naturally, this high-performance IMU comes with a certain price-level that can only be bridged after the potential of its application is proven. Therefore, the use of such equipment logically follows after the prototype developed here. Pursuing this further during this graduation research is not possible due to the limited time-scope. However, it is important to provide a clear future direction for the prototype.

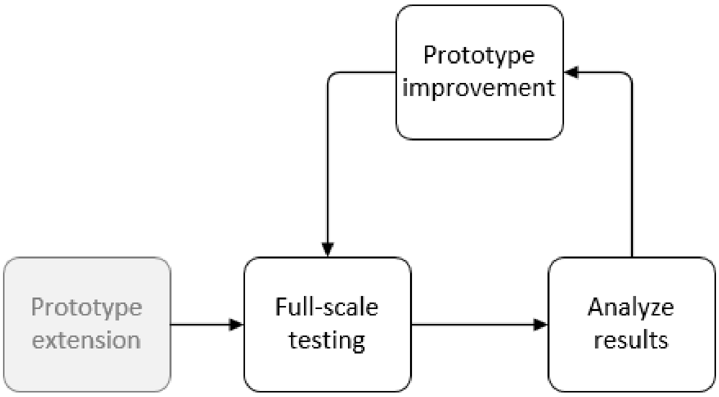

Figure 54. Prototype development process continued

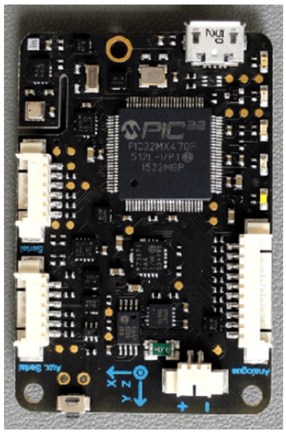

Figure 55. High performance IMU sensor (X-IO Technologies)

7. Discussion

Although, there are six different type of tower cranes, their operations are processed similarly. Therefore, the exploration presented for automation fit tower cranes in general. Although, it is Indicated that automation of tower cranes is possible, it must be acknowledged that genuine application remains highly difficult. Many crane fabricators do not focus on developments regarding new technologies that serve crane operations, which clarifies a certain lack of innovation in the industry. However, technologies that do exist, certainly contribute to the optimization of tower crane processes and mark the start for actual automation purposes, as explored during this research. This discussion is structured according to the order of sub-questions handled during this research and critically reviews their answers.

How is the tower crane operating process currently organized in the construction industry?

The current tower crane operating process in the construction industry is organized according to identical process phases as the construction process itself. As it is understood that the construction process is conservative, the tower crane process is classified similarly. Although, there is an overarching directive that supposes the use of an evaluation phase for tower crane operations, practice shows that this is not used very often. This makes it more difficult to improve the tower crane operating process. Beneficial to such a comprehensive process is the level of safety that could be reached, as many risks are mitigated. This mainly comes due to the great amount of checks and plans that need confirmation. The automation of tower cranes is expected to improve this process from different courses. One example is the establishment of a digital platform that, among many other aspects, secures the requirements of every stakeholder to ensure completely transparent relationships.

Transparency is found to be very important, especially for the owner of a tower crane, however, this is not often the case in the current process. Also in the current process, the configuration of the crane exceeds capacity. This is the result of the ratio between rental prices and worker loans. In most cases, it is more logical to rent a larger crane that relieves work pressure and generates savings regarding man-hours, instead of selecting the most efficient crane possible. This shows that the use of tower cranes is highly influencing the construction approach of a project and therefore, an improved data-driven tower crane operating process potentially comes with many advantages. Nevertheless, the traditional nature of the industry makes it very difficult to change such large processes at once, which is the case for automation of tower cranes.

Which data from the pre-construction phase serves the automated tower crane operation process?

Pre-constructional data that is created in a digital approach can be related best to the use of BIM. Therefore, the use of BIM is key to automated tower crane operations. This field is rapidly expanding, as most construction companies increase their adoption in BIM related technologies. Two of the most important features are the high level of interoperability and continuously updated information that assists stakeholders in their project approach. Nevertheless, it becomes clear that the industry is immensely lacking behind compared to developments made in the field of science. Because, this finding came forward in both literature and the interviews, it is susceptive that the exploration to automation of tower cranes currently could be successfully implemented by the industry. It is supposed that there should be less need for personal experience and an increase in the use of data to support strategies and improve processes. Furthermore, every stakeholder defines their own approaches, while a standard one will benefit automation purposes, otherwise, it is certain that a large number of conflicts remain to appear in the operational phase of tower cranes.

It also becomes clear that a large amount of detailed information is needed in order to serve an automated tower crane. It should be possible to establish and analyze the complete construction process, showing all crane maneuvers already in the pre-constructional phase. This is expected to help in the determination of efficient lift paths and detection of possible collisions between the crane and other objects. Although, examples exists of such high level BIM use, developments remain necessary in the following categories: 4D planning, clash detection and the use of path planning algorithms in BIM models. The use of such algorithms allow for the creation of CLPs that ultimately replace the manually created crane planning. However, before using CLPs becomes possible, construction machines and supplementary equipment, such as excavators and scaffolding should be included in BIM. A finding that is very important to accompany these developments is the minimum LOD quality of 300 for the BIM models, as this is seen as the first level that provide sufficient detail of object information. A consequence of this intensification in the pre-constructional phase, is the tremendously increasing workload during this stage. This can be seen either as an advantage or a disadvantage. Advantageous is the fact that work done early in the project often will decrease the number of mistakes and inefficiencies during the executional stage. A major disadvantage for many stakeholders is the notion that whenever the project is discontinued, lots of effort is lost. In general, it is expected that much effort is already is needed to enable realization of all these necessary developments in practice. Moreover, this is very important otherwise the automation of tower cranes remains highly difficult.

Which data is needed to realize the application of automated tower cranes, complementary to pre-constructional data?

The crane operator is one of the starting points to find out what data is needed. From the interviews, it becomes clear that the operator is able to sense the behavior of the crane during its operations and oversees a large part of the construction site and prevents it for hazardous situations. This results in the generation of countermeasures in order to remain in control over the load. An automated crane without operator, certainly should be equipped with these functionalities. This statement provides a clear indication that various sensing systems should collaborate to take over these characteristics. Although, many technologies (RTLS) are available, analysis shows that most of them are not very accurate in environments similar to construction sites. Mainly, this comes due to their average measurement errors, which are too high for application on tower cranes. Nonetheless, this particular field of research is highly popular and it can be expected that some of the available RTLS systems become more attractive in the near future. Furthermore, research efforts are made to combine RTLS systems to increase their accuracy.

As described in section 2.4.2. there is a wide range of RTLS systems available. Some of these technologies did prove their functionality in applications that track resources through the entire supply chain of provide data for other project management purposes. Those are seen as very important to the overall process of utilizing automated tower cranes. Compared to the other described RTLS systems, UWB has the highest potential in assisting safety and productivity management of construction sites. Nevertheless, combination with other RTLS systems remain important to increase its usefulness. Without reservation, it is clear that multiple systems should be fitted on the crane, as well as on other equipment, workers and objects to create a self-sufficient functioning tower crane. This big-data approach should ensure acquisition of real-time information, process analysis and evaluation to capture inefficiencies and constantly adapts the overall system to the real-time situation. Many of the findings coming from literature are supported by the example project. However, one big difference is the fact that they want to model external forces, such as wind and rain. This is supposed as an almost impossible activity, as those externalities are highly inconsistent in the crane's workspace. Therefore, it is expected that measuring these forces will generate more success in the overall application of the example project. The knowledge obtained during this research is not limited to a certain type of tower crane. However, it must be noted that each type of tower crane, as explained in section 2.1.1. comes with differences in respect to their use and deployment. Therefore, it is recommended to adapt the strategy of automating a tower crane to the type that will be used.

How can the idea of automated tower cranes be explored and what challenges remain before utilization reaches viability?

From the first three research questions it is tried to determine what elements belong in the exploration for automation of tower cranes. The exploration established states that a completely digital process should be designed that can be transparently managed and is accessible for every stakeholder. This makes the exploration highly challenging to implement, especially for companies working in the executional phase. Presumably, these stakeholders should renew and modernize their entire approach. Therefore, the exploration already shows that education of personnel is very important and it is expected that stakeholders start to see the benefits of this more efficient process. Furthermore, this development becomes harder to neglect, as more effort is undertaken to implement applications that need this overarching digital process.

Although, the exploration states what could be useful in the automation of tower cranes, it is also understood that multiple strategies potentially lead to a working system. It is tried to provide a certain depth with the help of exemplifying the possibilities of different sensors and technologies that support the pre-constructional CLPs to overcome the difficulties that appear in reality. One shortcoming of the exploration is that it assumes a reasonably positive standpoint from technological possibilities. However, it must be noted that practitioners remain with many questions and opt for a step in-between, namely, the use of a hybrid system that uses automation for a large part of the CLP and a crane operator for the more detailed actions. At least until, the exploration becomes technologically feasible. On the one hand, this indicates that the exploration possibly is one step to far for implementation in the near future. On the other hand it shows what is possible in the long-term, evidenced by literature and experts from practice. Furthermore, it is likely that automated cranes are more useful when high level of prefabrication is being used. Therefore, the Asian context of the example project makes sense as starting point. In Europe, more traditional building methods are being used, which require the crane to lift smaller components, making it more difficult to successfully deploy the exploration. Interesting is the fact that various challenges are identified. Therefore, this is a clear basis for future research as it shows which directions certainly should be investigated, before automated tower cranes become reality.

In pursuance of the remaining challenges, how to measure structural deformation of tower cranes with the use of sensors during lift activities?

The method for measuring deformation as explained in this report, fits the approach indicated by during the exploration. In contribution to the reliability of the method is the fact that an explanation of the problem is underpinned very precise in other research efforts and understood by the interviewed experts. This means that a proper solution for the challenge can be useful for an increase in efficiency in regards to automation. The method itself takes a process-oriented approach to solve an issue that occurs in the structural frame of the tower crane. However, it may be expected that defining a calculation method is another possible angle to deal with the deformations that occur during crane operations, as this enables further analysis in the pre-constructional phase. Although, this seems an option, it is chosen to value the results indicating that this is nearly impossible. To continue, expected deformation is tried to be calculated in a highly abstract manner. One shortcoming here, is the lack of detail in the outcomes. However, with the existing knowledge about the characteristics of steel structures, it is supposed that this provides the best reference values possible.

The process of prototype development and testing the sensor follows a clear path with a growth in complexity. On the one hand, this enables a clear understanding of the method resolving the problem of constant crane deformation. On the other hand, the repetition of test runs is seen as too little for making precise conclusions about the prototypes robustness and accuracy. This statement appeared after analyzing the results of the small-scale testing phase. Here, it is visible that some outcomes are exceeding the more common inaccuracies. Therefore, future research need more test runs, which was difficult to do here, as the graduation research is bounded by certain requirements. One other improvement to the increase in reliability of the developed method, is the use of more expensive and precise sensors, as examples are revised in this report that show, higher accuracy is possible. However, these examples use very complex mathematical algorithms that also benefit this level of precision. Nevertheless, it must be recognized that complexity is not always helpful in the overall usefulness of a system. The prototype developed here, should be seen as a proof of concept, which tries to provide reliable measurements in a convenient manner. During this research it is assumed that a coordination system, explained in the exploration already exists. However, as explained, it is expected to only become possible in a long-term perspective. Consequently, this study provides an example of what sensors and data gathering techniques can do in the executional phase of construction projects.

Is the method for measuring structural deformation of tower cranes leading to a solution for the selected challenge?

Despite the fact that not all measurements are completely precise, the method developed illustrates that it has the potential to be useful in solving the challenge and therefore contributes to the overall automated process. However, current calculation method is only possible afterwards, as a ratio is determined according the average value before and after the actual movement. This statement indicates that real-time measurements, currently are not possible with the setup of this prototype. Nonetheless, this should be studied as well when using improved IMU sensors, as it is supposed that these can overcome this issue. The principles make it possible for the developed system to collaborate with the other systems indicated previously in the exploration to automation of tower cranes. Although, the prototype is currently a stand-alone system, it captures its measurements in a database structure. This structure is supposed to be core to the overall system installed on a tower crane. Furthermore, the sensors are measuring structural deformation, but expectedly contribute to capturing the object displacement due to these deformations. This helps in increasing the level of precision of the CLPs generated in the pre-constructional phase. Although, testing this expectancy was not possible during the large-scale test.

8. Conclusion

During this research, it is investigated what could be involved in bringing the construction process to the next stage and cope with the increasing complexity of projects. This is shown in both, a process- as well as a technological-oriented proposition. The automation of tower cranes is very well suited for this case, because this piece of equipment can be seen as the cornerstone in the executional phase of large construction projects. Because, automation and digitalization are two far-reaching concepts for improving the construction approach, multiple domains are reviewed and analyzed in this thesis, of which current practice, BIM and sensor technology are the most prominent. Ultimately, this resulted in an exploration that combines every aspect important to automate tower cranes and provides a solution for the increase in precision of the CLPs determined in the pre-constructional phase. The following sections depict the statements that conclude the complete research attempt in regards to its scientific and societal relevance. The chapter ends with recommendations for future research.

8.1. Scientific relevance

After discussing the answers to the sub-questions of this research, conclusions can be made upon the main research question, which is as follows: *How can tower cranes operating on large construction sites be automated in order to improve the object assembly process with the use of sensor data?*

In order to automate tower cranes, much effort remains necessary in developments regarding the use of BIM. It is needed to extend the possibilities for analysis and planning of the construction process already during the pre-constructional phase. Furthermore, it must become possible to adapt the planned situation to the dynamics and deviations on site. Although, this research illustrates different approaches and technologies, it must be concluded that automation of tower cranes, currently, is not possible. In general, the complete construction process should be digitized, starting with a central management system as a platform that contains all project information and is accessible to every stakeholder. BIM is seen as a suitable approach to realize this, however, the level of adoption in the industry slows important developments down. One of the implications of this research, therefore, is the assumption that CLPs can be generated already in the BIM process. Nonetheless, this remains only possible in scientific research. The use of sensors starts to find its course into practice. In particular, this is highly important for application on tower cranes, as it enables comparison and adaptation between the planned and realistic situation. This allows for data-driven decisions in the experience oriented industry. Nonetheless, it must be recognized that the location based sensor technologies analyzed, are not precise enough to perform sufficient on automated tower cranes. A strategy of combining multiple sensor technologies, therefore, is expected to increase the potential of the overall concept. The data conceived during this research, for solving the selected challenge, shows an application that improves the object assembly process with the use of data. Therefore, it can be concluded that the use of sensor technologies is contributing to the automation of tower cranes in general, although, much effort remains in the development of precise measurement systems.

8.2. Societal relevance

The relevance of this research for the AEC industry bridges the factual misfit between technological advancements and their implementation in construction processes. It is evident that complexity increases and manual solutions are labor intensive. While this is recognized, it must be concluded that already existing technologies, serving automation of tower cranes, are not being used. Despite the fact that those will reduce the manual labor and provide a starting point for the exploration. In order to result in a process that enables working with automated tower cranes, standardization, communication and data sharing are key concepts that need improvement. Besides, standardization of processes, standardization in the form of prefabrication is concluded to serve automation as well on construction sites. This clearly indicates the broad challenge, the industry is facing regarding the improvement of current construction practices.

This research is one example that shows the contribution of sensor technology for data acquisition, as it enables progress tracking, analysis and measuring differences between the planned and as-built situation. Evidently, this is indispensable as personal experience currently leads the overtone in decision making processes. However, it must also be concluded that the level of maturity of technological advancement in the scientific field is far ahead in comparison to the level used in the industry. Nevertheless, the example project uses similar approaches as found in literature, meaning it is possible to transit whenever the willingness to do so exists. On the short term in the automation of tower cranes, most success is proposed in a system where automation takes over the large and relatively easy maneuvers, while the crane operator accomplishes the more detailed operations. As a matter of a fact, the operator remains available to take over control in the appearance of potential accidents. At least until it becomes possible that a combination of multiple sensor technologies in collaboration with earlier perceived data enable better control of tower cranes than human operators do.

8.3. Recommendations for future research

As indicated in the conclusions of the previous two sections it becomes clear that potential clearly exists in the automation of tower cranes. Nonetheless, much research and technological development is necessary to develop actual applications. The list of challenges generated during this research opens up a mass of future research directions in different domains within the AEC industry. Furthermore, it remains unclear how construction workers communicate with the crane and vice versa. Certainly, in the beginning of implementation it could be expected that the crane interactively collaborates with humans. Also, the generation of CLPs in BIM is highly important, as they are expected to come with great benefits in comparison to the ones manually created. Finally, it is surprising were the developments of precise RTLS systems will lead to and hopefully, they will be wider applicable in the automation of construction equipment. Overall, full automation of tower cranes will become possible in the future. However, in the mean-time, human involvement should not be set aside.

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Appendices

Appendix I - Matrix of project phases and involved staff

activities R = responsible E = executional A = advising C = Controlling	**Involved companies/staff**											
	Project team	Str. Eng. (design)	Str. Eng. (lead)	Str. Eng. (partial)	Coordinating engineer	Crane (dis)assembly staff	Controlling expert	Crane operator	Crane supervisor	Crane guidance expert	Point man	Maintenance staff
Initiative												
Judgement design (tower crane)	R/E	-	A/C	A/C	A/C	-	-	-	-	-	-	-
Determining design principles	R/E	-	A/C	A/C	A/C	-	-	-	-	-	-	-
Contract												
Determining contract principles	R/E/C	A	-	-	C	A	-	-	-	-	-	-
Design												
Determining principles (strength, stiffness and stability)	-	R/E	-	-	-	-	-	-	-	-	-	-
Defining crane plan	R/E/C	A	-	-	C	A	-	-	-	-	-	-
Initiative design	C	R/E	-	-	-	-	-	-	-	-	-	-
Structural calculations	-	R/E	-	-	C	-	-	-	-	-	-	-
Judgement construction location	R/E	A	-	-	-	-	-	-	-	-	-	-
Definitive design	C	R/E	-	-	-	-	-	-	-	-	-	-
Releasing drawings and calculations	R	E	-	-	C	-	-	-	-	-	-	-
Assembly												
Creation plan for assembly	R	A	-	-	-	R/E	-	-	-	-	-	-

in relation to design												
Creation of assembly plan	C	-	-	-	-	E	-	-	-	-	-	-
Supervision of assembly process	C	-	-	-	-	R/E	-	-	-	-	-	-
Pre-handover crane	-	C/E	-	-	-	R	-	-	-	-	-	-
Handover crane	C	A	-	-	A	R/E	-	-	-	-	-	-
Operation												
Operation in accordance with lifting plan	C	A	A	A	A	-	-	-	-	-	-	-
Assembling anchoring	E	A	A	A	A	R/E	-	-	-	-	-	-
Turnover after changing configuration after handover	C	A	-	-	A	R/E	-	-	-	-	-	-
Lifting in accordance with lifting plan	C	-	-	-	-	-	-	R/E	R/E	C	E	A

Disassembly												
Determining principles disassembly crane	R/E	A	A	A	A	A	-	-	-	-	-	-
Creation plan for disassembly	C	-	-	-	A	E	-	-	-	-	-	-
Determine plan for disassembly	R/E	-	-	-	-	-	-	-	-	-	-	-
Supervision of disassembly process	C	-	-	-	-	R/E	-	-	-	-	-	-
Dismantling anchoring	R	-	-	-	A	E	-	-	-	-	-	-
Evaluation												
Organization of evaluation meeting	R/E	A	A	A	A	A	A	A	A	A	A	A

Appendix II – Expert interviews

A. Tower crane process and developments in the industry (J.P. van Eesteren)

Company:	J.P. van Eesteren	Name:	Eric Nicolaas
Time:	09:00-10:00	Function:	Tender manager
Place:	Hanzeweg 16, Gouda	Experience:	> 25 years
Date:	17-08-2017	Education:	-
Duration:	Approx. 60 minutes	By:	J.M. Pouw
		Function:	Graduate Intern at Witteveen + Bos (TU/E)

1. Could you introduce yourself?

The interviewee is working already 28 years at J.P. van Eesteren and until 15 years ago worked on construction sites in the preparation and coordination of executional phase of projects. Now he is working at the office in the tender phase as a tender manager. Key activities in his work are creating plans to realize projects of possible clients and convince them to give the project to J.P. van Eesteren.

2. Is J.P. van Eesteren using the Tower Crane Directive of 'Bouwend Nederland'?

The interviewee himself is not familiar with the Tower Crane Directive. Although he recognizes its existence and states that the structural engineer working at J.P. van Eesteren do work according to the directive. Furthermore, one of the engineers visited the interview and said he currently is part of a workgroup that is creating an additional section for the Directive, specific for (mobile) crane foundations.

3. Which people are usually involved in the different phases of the tower crane process?

In the tender phase, a tender manager starts with the idea to use a specific type of crane. With this idea, the interviewee goes to the people working at the material service of J.P. van Eesteren that are responsible of the cranes. Another important person is the structural engineer that makes the appropriate calculations needed for tender plan. People working in the executional phase of the project take over the idea of the interviewee and start adding more detail to the plan. Sometimes, it is decided to take another approach in crane specification, but this is not very often the case. Those people again meets with the people working at the material service and the structural engineers involved. When this is finished, the plan is made definitive. Whenever cranes can be used that are owned by J.P. van Eesteren, the process continues within the company. Whenever the stock of cranes is already deployed, the crane is rented by 'van der Spek'.

4. *What are the latest technologies in use to support the overall tower crane process on construction sites of J.P. van Eesteren? (e.g. LiDAT wireless sensor system, Crane planner software)*

Litronic, is the standard controlling system applied on tower cranes. This system makes it easier for the crane operator to control the crane. The interviewee states that this is not part of his expertise and therefore is not familiar with technologies that can be used on tower cranes. The interviewee notices that there is a system in use that enables multiple cranes operating in each other's reach that prevents for collisions between cranes.

5. *Can you explain the process of the initiative phase for using tower cranes? Which people are involved and what information should be taken care of during this phase?*

In the tender phase of a project it is decided if the use of a (tower) crane is necessary. Whenever this is the case, a crane analysis is made by looking at the weights that need to be lifted, prices of cranes, working heights and necessary range. With this information a crane type is selected and priced by the material service department of J.P. van Eesteren. After this, first calculations are made to check the plan.

6. *Can you explain the process of the contracting phase for using tower cranes? Which people are involved and what information should be taken care of during this phase?*

J.P. van Eesteren is required to rent the crane from its own material service department. This department makes an offer for J.P. van Eesteren, which usually is transformed in the actual price. Only when the cranes are out of stock of J.P. van Eesteren is partnering with other contractors to realize a project, it is allowed to rent a crane from the market.

7. *Can you explain the process of the design phase for using tower cranes? Which people are involved and what information should be taken care of during this phase?*

However, the start of the crane design is made with rules of thumb and experience at the very beginning of the process. This conceptual design is handed over to the structural engineers that make the necessary calculations. Structural calculations are made by J.P. van Eesteren' s own structural engineers, that also do work on crane related projects not being built by J.P. van Eesteren. It is also possible that the renting/leasing company of the crane is concerned in the structural calculations and design of the crane.

8. *Can you explain the process of the (dis)assembling phase for using tower cranes? Which people are involved and what information should be taken care of during this phase?*

J.P. van Eesteren does have their own people that (dis)assemble cranes. However, it is common to do this work in cooperation with van der Spek. A mobile crane is hired to (dis)assemble the crane. Because of the number of trucks that deliver parts for the crane and the tightness of schedules, it is normal that cranes are (dis)assembled at night. During the life-cycle of the crane a good relation with its importer/owner is vital, as these companies advise and help in all aspects about the use of tower cranes. One rule of thumb is that around 3-4 months after the rough constructional works, the crane is disassembled from the construction site.

9. *Can you explain the process of the operation phase for using tower cranes? Which people are involved and what information should be taken care of during this phase?*

The interviewee states that it is tried to setup the crane as soon as possible on the construction project. This is considered in the scheduling and construction site lay-out plan of the project. The crane operator is very busy each day to provide the crane to every contractor and sub-contractor on the construction site. More and more it is logic to use the crane at night. Sometimes, the crane schedule is not met at a particular day. When this happens it occurs that the crane staff is working overtime to solve the issue. Furthermore, during some projects it is necessary to hoist stocks of materials around the construction sites at night, and perform hoisting activities for (sub)contractors during the day. In the operational phase it is decided when and what material are hoisted on the construction site. This is performed manually and maybe it is a good idea to create a system, such as Ellips to make this easier. Ellips is a system that registers logistical movements. J.P. van Eesteren thinks it is very important to make use of an experienced point man that secures and guides loads carefully.

10. *Can you explain the process of the evaluation phase for using tower cranes? Which people are involved and what information should be taken care of during this phase?*

Within J.P. van Eesteren projects are evaluated after realization. Important in the evaluation phase are the costs and safety. The interviewee states during this question that safety is of major importance within the company. A sub-question of the interviewer about statements made in scientific literature about the cranes being the most dangerous equipment on construction sites is answered by the interviewer with the explanation that tools are more dangerous and cranes in general are very safe.

11. *What is your opinion of how to improve the current tower crane process?*

The interviewee says, this is difficult to say. Camera systems should be applied more often. And states that the human factor is very important in hoisting activities. Especially, in the construction industry where there is large differentiation in materials. Automating tower cranes will come with many issues. For example, when does the crane know a lifting activity is finished and what is the role of the point man. Another, interesting point of the interviewee is the effectiveness of automating the crane. Time losses mainly come from the construction method, waiting times of (sub) contractors that are in need of a crane.

12. *Do you think BIM can play a role in this and how should it support the process?*

According to the interviewee, BIM certainly is useful in the automation process. BIM becomes better and better and it is easy to extract elements from the model that can be lifted by crane. The interviewee agrees with the statement that BIM really has the future in the construction industry.

13. *What are the consequences if the operational process is automated on site?*

Safety and the loss of time created by other influences than the crane operator.

B. Tower crane process and developments in the industry (van der Spek)

Company:	van der Spek	Name:	Leon Heijdra
Time:	09:00 – 10:00	Function:	Technical Manager
Place:	Vianen	Experience:	> 25 years
Date:	22-08-2017	Education:	-
Duration:	Approx. 60 minutes	By:	J.M. Pouw
		Function:	Graduate Intern at Witteveen + Bos (TU/E)

1. Could you introduce yourself (e.g. education and career path)?

The interviewee is already working 27 years at van der Spek at the department of tower cranes. Furthermore, he is giving advice and support to the companies that commissions a crane, supports and guides the commercial and technical departments of van der Spek. When a crane is commissioned by a contractor and they are in need of information of required documents, the interviewee collects this information and provides this to the contractor. Direct contact with the Liebherr factory is also an important aspect of the interviewee's job.

2. Is van der Spek using the Tower Crane Directive from Bouwend Nederland?

Van der Spek is using the Tower Crane Directive, in fact, the interviewee participated in the making of the specific directive. It is tried to follow the directive when necessary. However, part of the directive is hard to follow for the supplier of the tower crane because the largest role in the directive is for the contractor and user of the crane. The directive strives to reach a certain level of safety. This does not mean that whenever certain guidelines are not followed precisely, the process becomes unsafe. The interviewee notices that some contractors that use tower cranes are at the lower bound of the overall safety margin, while others are at the upper bound. In general tower cranes are very safe. However, when an accident occurs, it is the result of an accumulation of errors and mistakes. Because contractors are aware of this, it becomes tempting for them to sometimes take more risk.

3. Which people are usually involved in the different phases of the tower crane process?

- Commercial staff members that handle the request of the contractor.
- Advisors/representatives that help in formulating the specifications of the crane.
- Planners that plan the (dis)assembly, delivery and return of the crane. Furthermore, planners make the budget of the overall service of van der Spek.
- Structural engineers that make the structural calculations required for the use of the crane.
- A team (3 – 5 persons) that (dis) assembles the tower crane.
- Crane operator and point man

4. *What are the latest technologies and sensors in use to support the overall tower crane process on construction sites of van der Spek? (e.g. LiDAT wireless sensor system, Crane planner software, Cycoptronic, Sycratronic)*

The only sensors van der Spek as a company has placed on the tower cranes equipped with Litronic are to locate the position of the loads when lifted by the crane. However, these sensors are not providing a complete picture of where the load actually is and how it is orientated. This means that when the crane is assembled, the sensors are setup according to the dimensions of the crane. First the minimum and maximum position of the hook is set and then the start and end position of the jib are set. Within this spectrum, the sensors know where the load is according to the directions given by the crane operator. The interviewee states that the use of these sensors are highly basal. The name of the sensors are: height sensor, flight sensor, angular displacement sensor, load sensor, load-moment sensor and anemometer. Sometimes mobile tower cranes are equipped with sensors that capture the position of the cranes. Tower cranes that are bought after 2013 by van der Spek are equipped with the LiDAT system. However, the interviewee states that the use of this system and is basic and not often used to its full potential. This system mainly is useful for maintenance and less for the construction process of contractors.

5. *Can you explain the process of the initiative phase for using tower cranes? Which people are involved and what information should be taken care of during this phase?*

The process for van der Spek starts with the request from a contractor for a tower crane. This request is handled by a commercial staff member of van der Spek. Often a contractor just says he wants a specific type of crane. The people of van der Spek always try to get more information so they can think alongside the contractor. At this stage, van der Spek needs to know what the crane should lift, were it is placed on the construction site. Sometimes, van der Spek advises in positioning the crane for efficient use. When the type of crane is specified, a rental rate is determined.

6. *Can you explain the process of the contracting phase for using tower cranes? Which people are involved and what information should be taken care of during this phase?*

The rental price of a crane is determined partly on the number of hours a crane is used per day, the crane capacity, working height and its commission. This information determines which crane components are necessary for the project. This means that the plans of the contractors are bespoken with van der Spek. However, sometimes a contractor is not really honest about the number of hours the crane is used. The contract with van der Spek is for the crane itself and the additional activities necessary for making and keeping the crane operational.

7. *Can you explain the process of the design phase for using tower cranes? Which people are involved and what information should be taken care of during this phase?*

After the visit at the construction site, the planner makes a budget for the overall tower crane project van der Spek is arranging. Furthermore, structural calculations are made and whenever a crane design is not specified in the books, the crane fabricator is asked to check if the design can be applied in this particular project.

8. *Can you explain the process of the (dis)assembling phase for using tower cranes? Which people are involved and what information should be taken care of during this phase?*

Before a crane is assembled, van der Spek is visiting the construction site. Here it is checked were the mobile crane is positioned for crane assembly. The strategy of crane part supply is checked, as this sometimes give additional problems. This is done by the planner and the companies representative. At a certain point in time, the crane must be delivered to the construction site. Before the crane is delivered, a check is done by the planner if all arrangements are finished and the site conditions are similar as is discussed in the design phase of the crane. Van der Spek has its own (dis)assembling staff, depending of the crane, a team exists of 3 – 5 people. Transport and the mobile crane are rented by van der Spek. The process of disassembling is the same as assembling, however, in backwards order. A note from the interviewee is approaching the municipality in the process whenever the project is realized in inner-city areas. During these projects it is often necessary to arrange road blocks, redirections, safety of passengers in the area.

9. *Can you explain the process of the operation phase for using tower cranes? Which people are involved and what information should be taken care of during this phase?*

Van der Spek is not involved in the operational phase of the crane, part from service and maintenance. However, when the user of the crane comes across an element that is too heavy for the crane, van der Spek advices and consults (sometimes with the help of the fabricator) if the limits may be stretched for this situation. The interviewee state that when this occurs, additional requirements are made that lowers the involved risks.

10. *Can you explain the process of the evaluation phase for using tower cranes? Which people are involved and what information should be taken care of during this phase?*

Van der Spek is not evaluating the data that is collected. The interviewee says van der Spek is being traditional in this. In the evaluation of a construction project it is highly exceptional if van der Spek is participating in the evaluation process of the contractor. The interviewee thinks, it could be helpful for them to improve their own processes.

11. *What is your opinion of how to improve the current tower crane process?*

In the approach contractors currently plan their project, many improvements are necessary. Especially the preparation phase of a project is not detailed enough. This comes with consequences for the type of crane that is chosen. Making simulations and the use of BIM are helpful in increasing efficiency of crane use. Liebherr, is developing planning software that works with 3D simulations. However, the number of parameters that can be changed is yet to little to generate real improvement. This software is still in its development phase.

12. What are the consequences if the operational process is automated on site?

According to the interviewee, the use of tower cranes can be automated in such, it helps the crane operator in his daily activities. For precise steering, a human is still highly important in controlling the crane. Furthermore, the point man guides the crane operator in the last few millimeters for attaching and releasing loads. For lifting and moving loads around, the crane should be able to operate automatically. The interviewee agrees that it is possible to operate a crane automatically. However, most of the time, a crane is waiting on holding elements in place. This means that the speed of the process will not improve that much. in the communications between operator and point man, many mistakes occur. It is expected that this can be improved when making use of a certain level of automation. A very important insight in automating the tower crane process is the fact that tower cranes bend and move when lifting loads. This means that whenever the hoisting table is giving a certain weight at a specified distance, the crane bends over when lifting that load. The specified distance is in reality a little larger. Sensor systems should be able to calculate this deformation.

13. Additional information about automating tower cranes

- When a crane operator is working at a height of 100 meter. It is impossible to see what is happening on the ground floor.
- The technologies developed by Liebherr are not quite the ones asked for on the market by the European contractors and crane operators. Therefore, those technologies find it difficult to set foot on the ground. It must be noted that this is the personal opinion of the interviewee.
- An Israeli company that made missile guiding systems in the past, nowadays tries to rewrite this technology and make it useful for tower cranes. With this system it is possible to laser point a certain location, that can be found by the crane automatically.
- Liebherr is a serious in their development of additional technologies that can be applied in cranes and the crane process. From the question of the interviewer about Liebherr being the world's market leader as tower crane fabricator is answered as follows: In some parts of the world, Liebherr is not being able to access the market. In Europe, Liebherr is in the opinion of the interviewee the market leader that is seen as the Mercedes of the tower cranes.
- The interviewee agrees that tower cranes are not the most dangerous equipment on construction sites. Though, mobile crane accidents appear more often, as they tend to fall over more easily.
- Vertical transport comes with certain risks. In inner-city projects this risk often is too large. Additional measures are taken, for example crash decks over streets directly besides the construction site. Sometimes, it is decided to use the crane only at nights to reduce these risks. This even can be required by the municipality before the building permit is granted.
- Cranes are designed upon a long-term life expectancy, in such, they can handle acute exceedance of weight limits by more than 20%. However, cranes are less able to handle long term exceedances of weight as they will affect the lifespan of the crane.
- The rental prices of cranes in general are not increased very much in the past 15 years. The interviewee gives an example of his own rule of thumb: a 250 meter/ton crane with a mast of 40 meters and a jib of 40 meters costed 2500 gilders/week. Nowadays, the same crane costs 1200 euro per week. However, when this crane is bought, the selling prices is twice as high. With this statement, the pressure on prices that appear in the industry is shown.
- When the process of displacing loads is automated, it is important to primarily focus on sensing precisely where the load is and how it is hanging beneath the hook.

C. Tower crane process and developments in the industry (Dura Vermeer)

Company:	Dura Vermeer	Name:	Mr. Van der Bijl/Mr. Romijn
Time:	13:00-14:00	Function:	Head/specialist of vertical transport
Place:	Haaften	Experience:	+ 10 / +20 years
Date:	28-09-2017	Education:	-
Duration:	Approx. 60 minutes	By:	J.M. Pouw
		Function:	Graduate Intern at Witteveen + Bos (TU/E)

1. *Could you introduce yourself (e.g. education and career path)?*

Interviewee 1 (Mr. van der Bijl): since 10 years Interviewee 1 is the head of the vertical transport department at the material service of Dura Vermeer. This department exists of 19 cranes, 10 person lifts, 9 crane operators and a (dis)assembly team.

Interviewee 2 (Jan Romijn): is a material specialist regarding vertical transport. Interviewee 2 has worked 5 years as an operator of tower cranes and for 16 years, is in the function of specialist.

2. *Is Dura Vermeer using the Tower Crane Directive of Bouwend Nederland?*

Interviewee 1 is one of the authors of the Tower Crane Directive. It is stated that Dura Vermeer is using the Directive. However, it is a directive and therefore is seen as a helpful tool in checking the designed process and setup of the crane. Company standards and guidelines are ranked above the directive, which is more of supportive duty. The interviewee also knows recently interviewed experts, as they all played a role in the creation of the directive.

3. *What are the latest technologies in use to support the overall tower crane process on construction sites of Dura Vermeer? (e.g. LiDAT wireless sensor system, Crane planner software)*

Litronic is not the standard technology in a tower crane. This all depends on the type of tower crane, the height of the investment the client is willing to pay to the manufacturer and the purpose of using the crane. At Dura Vermeer, the more heavy cranes are equipped with Litronic, while the smaller cranes do not. Dura Vermeer is using a technology regarding boundaries on construction sites. Interviewee 2 mentions that one of their cranes at a project in Utrecht cannot rotate above the train tracks. Prior to the operational phase of the crane, the computer is pre-programmed to these boundaries. In Dutch this technology is called: (Arbeids Bereik Begrenzing).

LiDAT is the latest technology of Liebherr. The interviewees are not that familiar with this system, but are informed about its existence via the importer. Interviewee 1 has understood that this system monitors and acquires data about the cranes operations. Dura Vermeer is not yet using this technology and mentions that this could be of major importance in future perspective.

4. *Can you explain the process previous to the operational stage of the tower crane? What information should be taken care of?*

The interviewees agree that the most efficient crane configuration is not always determined. This mainly comes from the fact that many variables must be taken into account: the speed of the crane, its capacity, the number of lifts, the rental price of the crane and the duration of each lifting activity. Interviewee 1 mentions a discussion with a colleague, were it is bespoken what type of crane is useful in a particular situation. A smaller and faster crane in this case needed three lifts for a particular set of formwork, while an over dimensioned crane just needed one. The savings of (dis)assembly of the formwork rapidly is leading against the rental price of the crane. This example indicates that the configuration of the process is leading the decision of choosing a crane configuration. Especially, in Europe were the hourly loans are much higher and therefore efficient implementation is outweighed by this.

5. *Can you explain the process of the operation phase for using tower cranes? What information should be taken care of during this phase?*

Lifting plans are not made at all in the pre-construction phase. The crane is commissioned to the people who manage the construction site. So, if they make lifting plans, it must be on short-notice and often it is estimated how many cycles can be made. Going on in the process it becomes clear how efficient the crane is and what can be done in order to improve this, if even possible. This enables the daily planning of free crane time, which can then be used by for example the sub-contractors.

6. *Can you explain the process after the operation phase? Is there for example an evaluation about usage of the tower crane?*

Useful evaluation happens very little, except on the subject of costs. In order to evaluate, data must be collected about the process. This also means that companies, such as Dura Vermeer should invest in methods that can capture this information from the start of the project, to be helpful in the evaluation. The opinion of interviewee 1 is that evaluation is very important and should be done more often and to a larger extend than expenses and profits.

7. *From literature it is concluded that there often is not that much swing in hoisted loads, as the weights are heavy and the hook block often has two cables points? Is this really the case for tower cranes?*

Interviewee 2 explains that swing really is present in the deployment of tower cranes. Therefore, the rule exists that at certain weather conditions regarding the force of wind, all activities should be stopped. The amount of swing is dependent of the crane operator, as this person should feel the load and constantly reacts of its movements. As a rule, it must be tried to maintain a vertical position above the load at all times. Whenever the jib stops rotating, the load swings further. A crane operator must take this behavior into account at the same time as, the weather conditions, and type of load. This all results in different behavior of different cranes.

8. *Is a crane operator just focusing on its own activities, or is there anything else asked from this person?*

Coordinating loads is just one of the activities of a tower crane, as this person constantly monitors the safe operations on the construction site. Furthermore, this person must sense everything that happens beneath and around the crane. Interviewee 2 mentions one example he himself has experienced during his period as crane operator. Here a crane suddenly appeared in an area at the construction site, which can be categorized as a blind spot. The interviewee did not see this and a hazardous situation appeared.

9. *What is your opinion of how to improve the current tower crane process? Is BIM part of this improvement?*

Improvement of the current process, according interviewee 1, starts with more experience in the field of practice for the people who design and prepare all plans. Establishing relations between the different involved specialties within a company is the basis for this. Furthermore, for many materials that are delivered to the construction site it remains unclear how they can be safely hoisted and with which hoisting equipment. This all is determined by the crane operator and point man. So, the efficiency comes from the experience of those people. Therefore, the directive states that a good education for those people is important for the process and construction site safety.

10. *What do you think about the concept of automating the tower crane? And is this possible according to you? How should you do this?*

When thinking about automating a tower crane, it must be considered that the hook of the crane can freely rotate. Whenever, the machine is not capable of detecting loads that rotate, dangerous situations happen. Interviewee 1 describes an example of hoisting low weight wooden baffles with a large surface, that reacted as kites on the wind. As a machine, this is really difficult to sense and react upon. Therefore, interviewee 1 states that whenever automated tower crane ideas are created, several conditions should be stated previously. To continue, with the example, these kinds of behavior of loads, do not only appear when wind forces are too large. It can be the case that the behavior of wind changes around the building under construction, which results in unacceptable conditions. However, these conditions are difficult to measure, as they are not similar in the entire c-space of the crane and therefore, the level of safety can be easily undermined in using automated tower cranes. This is also exemplified in the explanation of interviewee 2 regarding this subject. Both interviewees are clear in their statement that the human factor is difficult to replace in tower crane operations. In a further discussion about automating tower cranes, it comes to the attention that many problems need a solution before a crane can be automated.

In the discussion of the automated cranes at the seaport of Rotterdam, The interviewees both mention important facets of why this is possible. First, all containers have similar sizes, which is beneficial in automation purposes. Second, the cranes hoist with four hoisting points that stabilize the load and prevent unpredicted movements. Third, the containers are attached to a hoisting frame, which automatically attaches to the load. On tower cranes, this is totally different.

Several aspects should be taken into account when automating the tower crane. The BIM model should be used to determine locations regarding tower crane, building, objects etcetera.

11. *What are the consequences if the operational process is automated on site?*

If this is the case, the BIM model needs to be perfect to serve the crane. Furthermore, tolerances are currently taken into account, how is this captured and solved in the automated process remains the question. Also, last minute changes of plans are not possible anymore, while these are not rare in the traditional process. One possible solution for this arises from the thoughts of interviewee 1 as he describes that all these changes must be processed in the BIM model.

The dynamics of the crane itself need to be taken into account. Displacement for example is always present as the crane always moves. This displacement occurs in the tower and jib of a crane and reduced the accuracy of the crane. Therefore, countermeasures are necessary, also for other variables related to the process. These behavioral variables, however, are different for each crane and are difficult and almost impossible to standardize.

Placing the crane operator in the site office or onto the ground is not seen as beneficial to the interviewees. This comes down to the fact that when an operator is sitting above in the crane, this person senses what the machine is doing and can react upon this. Looking at computer screens or standing beneath the crane with a remote control, lacks this sense of feeling and slows down the reaction upon movements. According to interviewee 1, human sensitivity is part of the tower crane. According to interviewee 2, whenever a crane operator is sitting in the site office, the distance between this person and the crane only increases. In this case, the operator is not feeling anything and must capture all information from screens. This is possible in bulk handling terminals, but not desired on construction sites.

12. *Are you able to tell how the structural calculations are made?*

Standard configurations of a tower crane are designed and calculated within Dura Vermeer. All other types are consulted with the fabricator and importer of the cranes. Interviewee 1 mentions an example of a crane configuration placed inside the shaft of an elevator. Here a maximal displacement of 20 centimeters was allowed. Dura Vermeer requested a possible configuration from Liebherr, which also made the calculations. Interviewee 2 mentions a similar example he faced during his time at a former employer were a crane has bended against the concrete floor of the building under construction. On-site engineering then was possible as replacing the crane is the last option because this delays the process by an enormous amount of time. Steel anchors were placed and filled with wooden beams to change the bending curve of the crane.

13. Can the displacement of the crane be calculated and how can you approach this?

The displacement can be calculated, but this is not done by Dura Vermeer themselves. Whenever, this is necessary, external structural engineers from the fabricator or importer are consulted.

14. *The focus of my research lies on taking into account displacement of the mast and jib. Can you explain what kind of structural calculation are made for the crane?*

    There is a large difference in the norms used for constructional calculations and mechanical engineering calculations. Interviewee 1 proposes an example were a crane configuration is calculated according to the two different types of norm. according to the mechanical engineering calculations, 60 tons of ballast were needed to guarantee the crane is not falling. Next, calculations are made according to the constructional norms and the same configuration needs 120 tons of ballast. Furthermore, the different types of forces that apply on the crane are also different in the two calculation methods.

15. *Is there someone within the company I can approach for a similar interview? Or is it possible to eventually use a tower crane for sensor placement?*

    Yes, both interviewees are interested and are willing to help if necessary.

16. *Additional discussion/information*

    At least two people are needed to operate a tower crane, the crane operator and point man. Both are in function to stop the hoisting activities when hazardous situations appear.

    Interviewee 1 agrees with the notion that BIM is reasonably adopted in the pre- and post-construction phases, while it remains very difficult to implement this process in the construction phase itself. As a reason, the interviewee mentions that many aged people are working in the construction sector that miss the much need knowledge to completely understand and ability to work with BIM. Thereby, the people who can, miss the knowledge from the field of practice. This difference is becoming larger and is seen as a real challenge. Furthermore, the information provided in the pre-construction project is far from 100% complete and correct. This is also seen as a barrier for improved BIM implementation.

D. BIM in practice and industry developments (Witteveen+Bos)

Company:	Witteveen+Bos	Name:	Jan van Staverden
Time:	13:30-14:30	Function:	BIM expert
Place:	Deventer	Experience:	> 25 years
Date:	18-09-2017	Education:	Civil Engineering
Duration:	60 minutes	By:	J.M. Pouw
		Function:	Graduate Intern at Witteveen + Bos (TU/E)

1. *Could you introduce yourself (e.g. education and career path)?*

The interviewee started at WB in 1981 as a technical drawer of construction drawings for civil projects. During his career, he followed another education to structural engineer. The interviewee says, he is the first one within WB that started working with 3D modelling on old-fashioned work stations. During his time at WB, many different projects of construction and civil nature were part of his daily work. The interviewee was involved in very large project, such as the North-South line in Amsterdam and currently the development of the new ring road of Antwerp.

2. *Could you mention important activities in your daily schedule?*

Coordinating the BIM process and making 4D and 5D models belong to his current activities. During the interview, the interviewee shows many different products he made in the last couple of months. Furthermore, the analysis of all these models with the project team and detection of clashes as well as the generation of expert models and analyses are more examples of the interviewees daily schedule.

3. *What problems do often appear when using BIM in projects?*

The disadvantage is the existence of stakeholders that do not share the interests in BIM and remain working in 2D. When there is one company, out of ten that is lacking the use of BIM, the whole process collapses in the sense of any advantages. Furthermore, many companies perceive BIM as expensive, as the initial costs are higher. However, the interviewee stated that this is not true. As the cost reduction is realized in the second half of a project. Finally, the interviewee shows a picture of a time planning created for the development of a large infrastructural project in Groningen. This planning was laid down on the floor and people were crawling over it to see what is mend. According to the interviewee, there should not be thought of disadvantages. BIM 4D is generally more understandable than the printed for meter long Gantt charts. Projects also become more complex and must be engineered in shorter times. This makes the manual 2D process impossible.

4. *Is LOD an often used concept in the use of BIM? From which level is it useful to perform QTOs?*

LOD is a world-wide recognized concept that is very useful to indicate the level of detail/quality of the objects in BIM models.

5. *How is a BIM 4D model created? Which information is necessary at this point?*

A team of modelers create the 3D BIM model, which is made to a pre-specified level. After this, the planning is created according to the codes in the BIM model (as is seen by the interviewer in an example of the interviewee). In Autodesk Navisworks, the modelled elements can be linked to the tasks of the planning. Naviswork then automatically generates the 4D simulation. When this link is created and the software recognizes the relation, time paths can be adjusted. Here the process can be very quickly analyzed and made more efficient. 4D BIM models are according to the interviewee, real discussion models. In the past, the same process was used, however, a scrapbook was drawn. Indicating, the 4D method is far more efficient and clearer.

6. *How is a BIM 5D model created? Which information is necessary at this point?*

5D BIM models are a bit different. The 3D BIM model generates data. However, in this model, much data is not necessary. Here a filter is applied to find the right data useful for the 5D BIM. The export of quantities are put in a table in Microsoft Excel. These tables can be coupled to cost prices from cost engineers. Here it is important to take into account the right level stated in the contract. If this is done properly, cost schedules can be derived. Currently, WB is starting to use the software 'Cleopatra'. According to the interviewee, this enable automatic cost scheduling from the BIM model with more convenience. Furthermore, WB is using the service of BIMXtra. This is a platform that connects every project stakeholder and has many complementary functionalities. In short, System Engineering, BIM, databases, document output, revision management, all updated in real-time. BIMXtra also has the functionality to check and modify the object parameters in the model.

7. *How are QTOs made correctly and is this really of an higher quality as manual calculations?*

The interviewee states that a good 4D or 5D BIM model only suits, if the data is inserted correctly. According to him, this often is problematic. BIM protocols and Information Delivery Specification are written, but when the deadline approaches, mistakes ae made and data is being contaminated. Consistency in modeling and coding is of major importance during the BIM process.

8. *Is it able to perform a complete BIM QTO or is it a combination of BIM and manual calculations?*

This is not discussed during the interview. However, the interviewee is currently involved in the creation of right QTO and cost scheduling. Here the interviewer notices that much data is included manually. Here, it can be concluded that according to the level of BIM adopted by WB and their knowledge, a combination of BIM and manual calculations remain the current practice.

9. *What is your idea, of how to generate hoisting activities from BIM? (is it able to make object parameters for this?)*

According to the interviewee, this is possible to regulate. Within BIMXtra it is possible to generate a possible workflow, similar as a 4D planning. The difficulty arises, when the project is erected in a traditional method. The applicability suits steel frame and prefab construction methods. Whenever one object consist of two hoisting movements. It still is possible to model this occurrence, with the help of hinder. The interviewee remains with his statement to use the principles of 4D planning. One example is pouring concrete. By adding the hinder times, this can be modelled as well (combining hoisting movements with pouring times).

10. Additional information of the interviewee

- The interviewee is explaining in detail what WB is doing with the BIM process, indicating their leading position in the market. Furthermore, he is explaining the different types of projects that is worked on and shows the different 4D planning's. Finally, future direction of BIM functionalities within WB are described.
- BIMXtra is the new approach used in projects of WB, instead of Autodesk products, such as Navisworks. Here, more functionalities come together and the level of collaboration with the project stakeholders increases.
- The interviewee mentions among others two examples of specialties regarding BIM. First, he explains that laser scans were compared to the Revit model to check whether rebar can placed correctly in the available space, by determining the distance between the deep wall (special type of wall used in underground projects) and the concrete surface layer. The outcome of this analysis was a visualization of location were the workers must cut away bits of the deep wall for correct rebar placement. A second example was the design of a metro station in Delft. The interviewee stated that it was required that machinists can look 300 meter ahead to check for red/green signage. With sight lines the trajectory was analyzed and adjusted to this requirement.
- The interviewee has made geotechnical structures with information in the BIM model. This makes the model also applicable for geo-engineers.
- The disadvantage of manual activities, is the lack of transparency. This makes it difficult to capture changes. Gradually, the system is changed to a lay-out were everyone can view the progress in projects.
- The interviewee has provided a detailed presentation about BIM, he is giving to the civil engineering study on the school of applied science on a yearly basis.
- BIMXtra and Relatics agreed upon a collaboration. This indicates its usability in the whole construction industry and captures complete process management.

Appendix III – Python codes

This appendix shows each aggregate Python code used for the prototype system that measures crane deformation.

A. Controlling the MPU-6050 sensors

```
import smbus                                    #import package

class mpu6050:                                  #define class
  GRAVITIY_MS2 = 9.80665                        #define variables
  address = None
  bus = smbus.SMBus(1)

  ACCEL_SCALE_MODIFIER_2G = 16384.0             #sensitivity scale
factors
  ACCEL_SCALE_MODIFIER_4G = 8192.0
  ACCEL_SCALE_MODIFIER_8G = 4096.0
  ACCEL_SCALE_MODIFIER_16G = 2048.0
  GYRO_SCALE_MODIFIER_250DEG = 131.0
  GYRO_SCALE_MODIFIER_500DEG = 65.5
  GYRO_SCALE_MODIFIER_1000DEG = 32.8
  GYRO_SCALE_MODIFIER_2000DEG = 16.4

  ACCEL_RANGE_2G = 0x00                         #sensor range registers
  ACCEL_RANGE_4G = 0x08
  ACCEL_RANGE_8G = 0x10
  ACCEL_RANGE_16G = 0x18
  GYRO_RANGE_250DEG = 0x00
  GYRO_RANGE_500DEG = 0x08
  GYRO_RANGE_1000DEG = 0x10
  GYRO_RANGE_2000DEG = 0x18

  PWR_MGMT_1 = 0x6B                             #other necessary
registers
  PWR_MGMT_2 = 0x6C
  ACCEL_XOUT0 = 0x3B
  ACCEL_YOUT0 = 0x3D
  ACCEL_ZOUT0 = 0x3F
  TEMP_OUT0 = 0x41
  GYRO_XOUT0 = 0x43
  GYRO_YOUT0 = 0x45
  GYRO_ZOUT0 = 0x47
  ACCEL_CONFIG = 0x1C
  GYRO_CONFIG = 0x1B

def __init__(self, address):                    #startup the sensor
  self.address = address
  self.bus.write_byte_data(self.address, self.PWR_MGMT_1, 0x00)

def read_i2c_word(self, register):              #read the i2c registers
  high = self.bus.read_byte_data(self.address, register)
  low = self.bus.read_byte_data(self.address, register + 1)

  value = (high << 8) + low
```

```
  if (value >= 0x8000):
    return -((65535 - value) + 1)
  else:
    return value

def get_temp(self):                          #read/convert temperature
  raw_temp = self.read_i2c_word(self.TEMP_OUT0)
  actual_temp = (raw_temp / 340.0) + 36.53
  return actual_temp

def set_accel_range(self, accel_range):      #initiate accel range
  self.bus.write_byte_data(self.address, self.ACCEL_CONFIG, 0x00)
  self.bus.write_byte_data(self.address, self.ACCEL_CONFIG,
  accel_range)

def read_accel_range(self, raw = False):     #read acceleration range
  raw_data = self.bus.read_byte_data(self.address,
self.ACCEL_CONFIG)
  if raw is True:
    return raw_data
  elif raw is False:
    if raw_data == self.ACCEL_RANGE_2G:
      return 2
    elif raw_data == self.ACCEL_RANGE_4G:
      return 4
    elif raw_data == self.ACCEL_RANGE_8G:
      return 8
    elif raw_data == self.ACCEL_RANGE_16G:
      return 16
    else:
      return -1

def get_accel_data(self, g = False):         #dictionary with
  x = self.read_i2c_word(self.ACCEL_XOUT0)    measurement results
  y = self.read_i2c_word(self.ACCEL_YOUT0)
  z = self.read_i2c_word(self.ACCEL_ZOUT0)

  accel_scale_modifier = None
  accel_range = self.read_accel_range(True)

  if accel_range == self.ACCEL_RANGE_2G:     #set acceleration range
    accel_scale_modifier = self.ACCEL_SCALE_MODIFIER_2G
  elif accel_range == self.ACCEL_RANGE_4G:
    accel_scale_modifier = self.ACCEL_SCALE_MODIFIER_4G
  elif accel_range == self.ACCEL_RANGE_8G:
    accel_scale_modifier = self.ACCEL_SCALE_MODIFIER_8G
  elif accel_range == self.ACCEL_RANGE_16G:
    accel_scale_modifier = self.ACCEL_SCALE_MODIFIER_16G
  else:
    print("Unkown range - accel_scale_modifier set to
    self.ACCEL_SCALE_MODIFIER_2G")
    accel_scale_modifier = self.ACCEL_SCALE_MODIFIER_2G

  x = x / accel_scale_modifier               #divide measurement
through
  y = y / accel_scale_modifier                scale factor
```

```
  z = z / accel_scale_modifier

 if g is True:                              #multiply   value   with
gravity
    return {'x': x, 'y': y, 'z': z}          variable to obtain m/s2
as
  elif g is False:                           unit
    x = x * self.GRAVITIY_MS2
    y = y * self.GRAVITIY_MS2
    z = z * self.GRAVITIY_MS2
    return {'x': x, 'y': y, 'z': z}

def set_gyro_range(self, gyro_range):       #initiate gyro range
  self.bus.write_byte_data(self.address, self.GYRO_CONFIG, 0x00)
  self.bus.write_byte_data(self.address, self.GYRO_CONFIG,
gyro_range)

def read_gyro_range(self, raw = False):     #read gyro range
  raw_data = self.bus.read_byte_data(self.address, self.GYRO_CONFIG)

  if raw is True:
    return raw_data
  elif raw is False:                        #set gyro range
    if raw_data == self.GYRO_RANGE_250DEG:
      return 250
    elif raw_data == self.GYRO_RANGE_500DEG:
      return 500
    elif raw_data == self.GYRO_RANGE_1000DEG:
      return 1000
    elif raw_data == self.GYRO_RANGE_2000DEG:
      return 2000
    else:
      return -1

def get_gyro_data(self):                    #dictionary with
  x = self.read_i2c_word(self.GYRO_XOUT0)    measurement results
  y = self.read_i2c_word(self.GYRO_YOUT0)
  z = self.read_i2c_word(self.GYRO_ZOUT0)

  gyro_scale_modifier = None
  gyro_range = self.read_gyro_range(True)

  if gyro_range == self.GYRO_RANGE_250DEG:
    gyro_scale_modifier = self.GYRO_SCALE_MODIFIER_250DEG
  elif gyro_range == self.GYRO_RANGE_500DEG:
    gyro_scale_modifier = self.GYRO_SCALE_MODIFIER_500DEG
  elif gyro_range == self.GYRO_RANGE_1000DEG:
    gyro_scale_modifier = self.GYRO_SCALE_MODIFIER_1000DEG
  elif gyro_range == self.GYRO_RANGE_2000DEG:
    gyro_scale_modifier = self.GYRO_SCALE_MODIFIER_2000DEG
  else:
    print("Unkown range - gyro_scale_modifier set to
    self.GYRO_SCALE_MODIFIER_250DEG")
    gyro_scale_modifier = self.GYRO_SCALE_MODIFIER_250DEG
```

```
  x = x / gyro_scale_modifier                  #divide measurement
through
  y = y / gyro_scale_modifier                   scale factor
  z = z / gyro_scale_modifier
  return {'x': x, 'y': y, 'z': z}

def get_all_data(self):                        #combine and return all
  temp = self.get_temp()                        measurement values
  accel = self.get_accel_data()
  gyro = self.get_gyro_data()

  return [accel, gyro, temp]

  if __name__ == "__main__":                   #print  data  in  specific
form
    mpu = mpu6050(0x68)
    print(mpu.get_temp())
    accel_data = mpu.get_accel_data()
    print(accel_data['x'])
    print(accel_data['y'])
    print(accel_data['z'])
    gyro_data = mpu.get_gyro_data()
    print(gyro_data['x'])
    print(gyro_data['y'])
    print(gyro_data['z'])
```

B. Set up the MQTT client

```
import paho.mqtt.client as mqtt                #import package

MQTT_BROKER = "127.0.0.1"                      #define variables
MQTT_PORT = 1883
MQTT_KEEPALIVE_INTERVAL = 45
MQTT_TOPIC = "testTopic"
MQTT_MSG = "Hello MQTT"

class mqpub:                                   #define MQTT client
object
  def __init__(self, broker="127.0.0.1", mqttport=1883,
  mqtt_keepalive_interval=50):
    self._MQTT_BROKER = broker
    self._MQTT_PORT = mqttport
    self._MQTT_KEEPALIVE_INTERVAL = mqtt_keepalive_interval
    self._mqttc = mqtt.Client()
    self._mqttc.on_publish = self._on_publish
    self._mqttc.on_connect = self._on_connect
    self.connect()

def _on_connect(self, mosq, obj, rc):          #connect event
  print("Connected to MQTT Broker")

def _on_publish(self, client, userdata, mid):      #publish event
  print("Message Published...")

def connect(self):                             #connect with broker
method
```

```
  self._mqttc.connect(self._MQTT_BROKER,
  self._MQTT_PORT, self._MQTT_KEEPALIVE_INTERVAL)

def publish(self, MQTT_TOPIC, MQTT_MSG):     #publish message method

  self._mqttc.publish(MQTT_TOPIC,MQTT_MSG)

def disconnect(self):                        #disconnect method
  self._mqttc.disconnect()
```

C. Controlling the Raspberry Pi's

```
from mpu6050 import mpu6050                  #import packages
from datetime import datetime
import time
import paho.mqtt.publish as mqpub
import paho.mqtt.client as mq
import os
import threading
import setproctitle

global thread                                #define variable
thread = None

def getserial():                             #extract serial number
  cpuserial = "0000000000000000"
  try:
    f = open('/proc/cpuinfo','r')
    for line in f:
    if line[0:6]=='Serial':
      cpuserial = line[18:26]
    f.close()
  except:
    cpuserial = "ERROR000"
  return cpuserial

class threadSensor(threading.Thread):        #start thread event
  def __init__(self, serial):
    threading.Thread.__init__(self)
    self._exitFlag = threading.Event()
    self._serial_number = serial

def run(self):                               #create text file
  mpu = mpu6050(0x68)
  f = open('buffer.txt','w+')
  while not self._exitFlag.is_set():
    try:
      accel_data = mpu.get_accel_data()
      gyro_data = mpu.get_gyro_data()
      timestamp=str(datetime.now())

    except Exception as err:                 #in case error occurs
      print(err)

  f = open('buffer.txt','r')                 #write values in text
file
```

```
  for line in f:
    arr=line.split(',')
    mqpub.single("RPI_acc_gyro","{},{},{},{},{},{},{},{}"
    .format(self._serial_number, arr[1], arr[2],arr[3], arr[4],
arr[5],
    arr[6], arr[7]), hostname="192.168.66.1")
  f.close()
def stop(self):                            #stop thread event
  self._exitFlag.set()

def on_disconnect(client, userdata, rc):   #disconnect from client
  print("Disconnect reason: ", str(rc))
  client.connected_flag=False
  client.disconnected_flag=True

def on_subscribe(client, userdata, mid, qos):   #subscribe from
client
  print("Subscribed: "+str(mid)+" "+str(qos))

def on_message(client, userdata, msg):     #mqtt messages to control
  global thread                             RPIs/sensors
  if msg.topic == "RPI_Start":             #start measuring all
sensors
    if thread == None:
    thread = threadSensor(getserial())
    thread.start()
  elif msg.topic == "RPI_Stop":            #stop measuring all
sensors
    if thread != None:
    thread.stop()
    time.sleep(1)
    thread = None
  elif msg.topic == "RPI_Poweroff":        #power off all sensors
    if thread != None:
    thread.stop()
    if getserial() == "52935b70":
    time.sleep(10)

if __name__ == "__main__":                 #control program
  setproctitle.setproctitle("Crane Sensor")
  mqclt = mq.Client()
  mqclt.on_subscribe = on_subscribe
  mqclt.on_message = on_message
  try:
    mqclt.connect("192.168.66.1", 1883, 50) #connect to RPI 3B
    mqclt.subscribe("RPI_Start", qos=2)     #subscribe to topic
    mqclt.subscribe("RPI_Stop", qos=2)
    mqclt.subscribe("RPI_Poweroff", qos=2)
    mqclt.loop_forever()                    #continue for ever

except Exception as err:                   #in case error occurs
  print(err)

mqclt.disconnect()                         #MQTT disconnect
```

D. Transfer sensor values to database

```
import time, datetime                          #import packages
import paho.mqtt.client as mq
import mysql.connector
import setproctitle

Sensors = {"52935b70": "Sensor-rpi",           #define variables
  "505af225": "Sensor-zero1",  "a2d71a58": "Sensor-zero2"}
sql=mysql.connector.connect(user="******”, password=”*******”,
database=”Crane_Displacement”)
cursor=sql.cursor()

def on_disconnect(client, userdata, rc):       #disconnect mqtt event

  print(“Disconnect reason: “, str(rc))
  client.connected_flag=False
  client.disconnected_flag=True

def on_subscribe(client, userdata, mid, qos):     #subscribe mqtt
event
  print("Subscribed: "+str(mid)+" "+str(qos))

def on_message(client, userdata, msg):         #message mqtt event
  arr = str(msg.payload, encoding=”UTF-8”).split(“,”)
  data= {‘serial_numb’ : Sensors[arr[0]], ‘acc_x’ : arr[1], ‘acc_y’
:
    arr[2], ‘acc_z’ : arr[3], ‘gyro_x’ : arr[4],‘gyro_y’ : arr[5],
    ‘gyro_z’ : arr[6], ‘timestamp’ : arr[7],}
  print(“{},{},{},{},{},{},{},{}”.format(Sensors[arr[0]], arr[1],
    arr[2], arr[3], arr[4], arr[5], arr[6], arr[7]))

cursor.execute(“INSERT INTO `accel_gyro`      #import to database
  (`serial_numb`, `acc_x`, acc_y`, `acc_z`, `gyro_x`,
  `gyro_y`,`gyro_z`, `timestamp`) VALUES(%(serial_numb)s, %(acc_x)s,
  %(acc_y)s, %(acc_z)s, %(gyro_x)s,%(gyro_y)s, %(gyro_z)s,
  %(timestamp)s)”, data)
sql.commit()

if __name__ == "__main__":                     #control program
  print("Started Central")
  setproctitle.setproctitle("Crane Central")    #change process
title
  mqclt = mq.Client() # create MQTT object
  mqclt.on_subscribe = on_subscribe    #set on_subscribe event
  mqclt.on_message = on_message # set On_message event

  try:
    mqclt.connect("192.168.66.1", 1883, 50) #connect to MQTT
    service
    mqclt.subscribe("RPI_acc_gyro", qos=2)  #subscribe to topic
    RPI_acc_gyro
    mqclt.loop_forever()                    #continue forever
```

```
except Exception as err:                     #in case error occurs
  print(err)

mqclt.disconnect()                           #MQTT disconnect
cursor.close()                               #close database index
sql.close()                                  #close database session
```

E. Export database table to Microsoft Excel

```
import time, datetime                        #import packages
import mysql.connector
import os

if __name__ == "__main__":                   #database connection
      sql=mysql.connector.connect(user="******",
password="**********",      database="Crane_Displacement")
      cursor=sql.cursor()
      cursor.execute("SELECT serial_numb, timestamp, acc_x, acc_y,
      acc_z, gyro_x, gyro_y, gyro_z from accel_gyro")
      f=open('export.csv', 'w+')             #open .csv file

for (serial_numb, timestamp, acc_x, acc_y, acc_z,      #export format
gyro_x, gyro_y, gyro_z) in cursor:
      tsmin=timestamp.strftime("%M")         #timestamp separation
      tssec=timestamp.strftime("%S")
      tsmsec=timestamp.strftime("%f")
      acc_x_str=str(acc_x).replace('.',',') #replace dot with comma
to
      acc_y_str=str(acc_y).replace('.',',')  make excel understand
the
      acc_z_str=str(acc_z).replace('.',',')  values are actual
numbers
      gyro_x_str=str(gyro_x).replace('.',',')
      gyro_y_str=str(gyro_y).replace('.',',')
      gyro_z_str=str(gyro_z).replace('.',',')
      print("{};{};{};{};{};{};{};{};{};{}   #establish order format
      ".format(serial_numb, tsmin,tssec, tsmsec, acc_x_str,
acc_y_str,      acc_z_str, gyro_x_str,     gyro_y_str, gyro_z_str),
file=f)

cursor.close()                               #close database index
sql.close()                                  #close database session
```

Appendix IV – Large-scale test results

This appendix shows the results of all five test runs generated during the large-scale testing phase and is structured according the data processing steps explained in section 6.4 of the report. In subsequent order: the actual acceleration measurement, setting the movement window, integration to velocity and integration to distance (in this case deformation) is placed here. As already is explained in the report, only one out of three sensors actually worked during the test. Fortunately, this sensor was located at the top of the tower (Figure 1), where deformation is expected to be predominant.

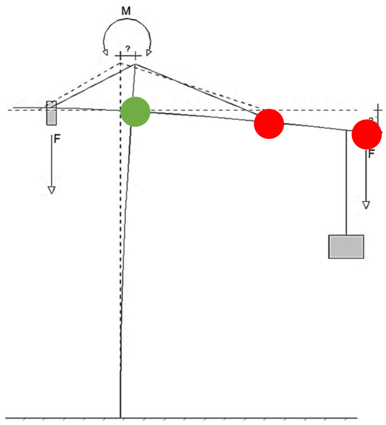
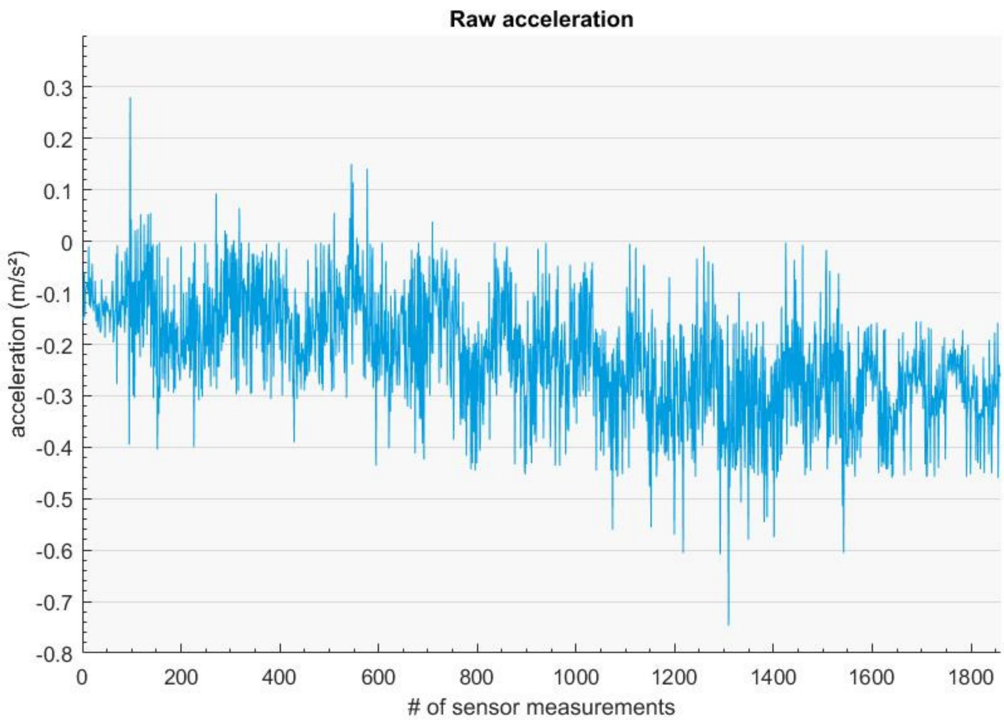
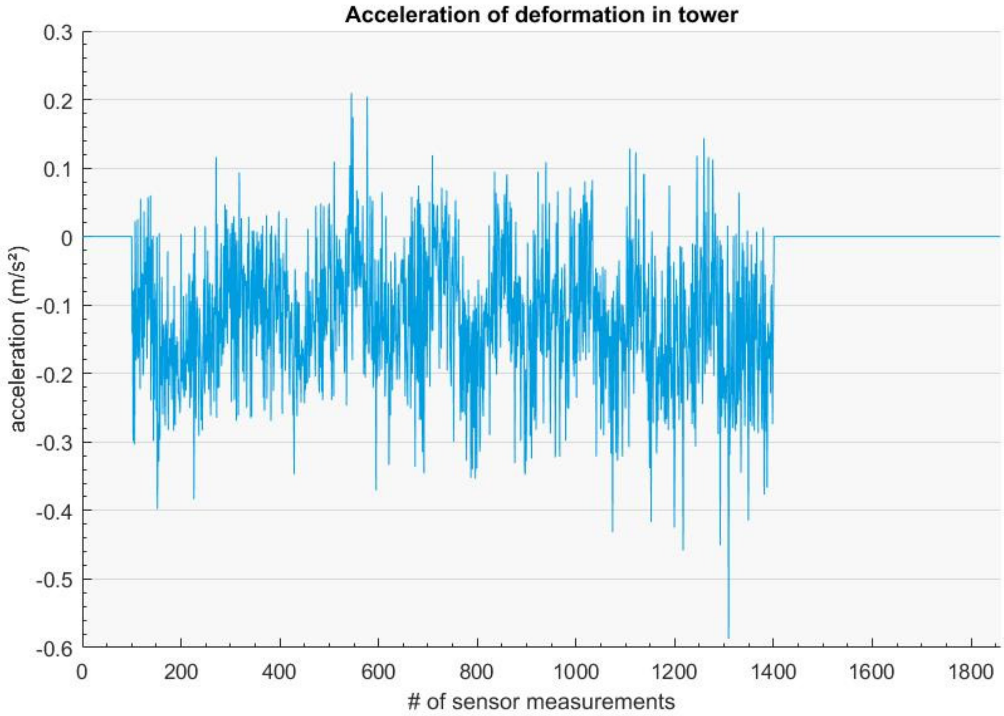
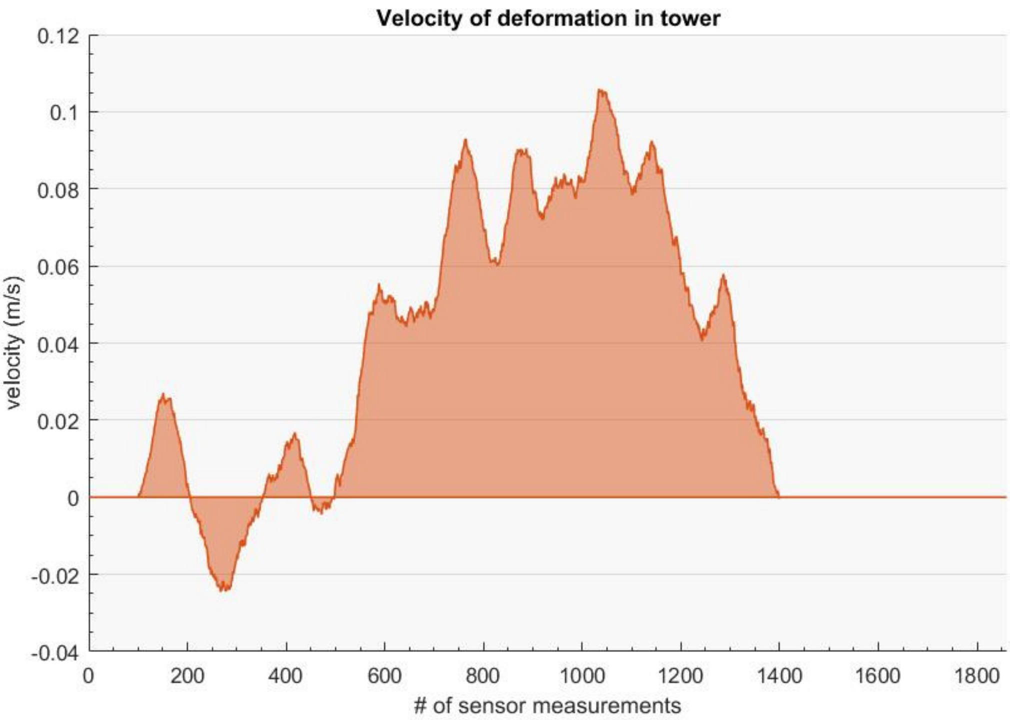


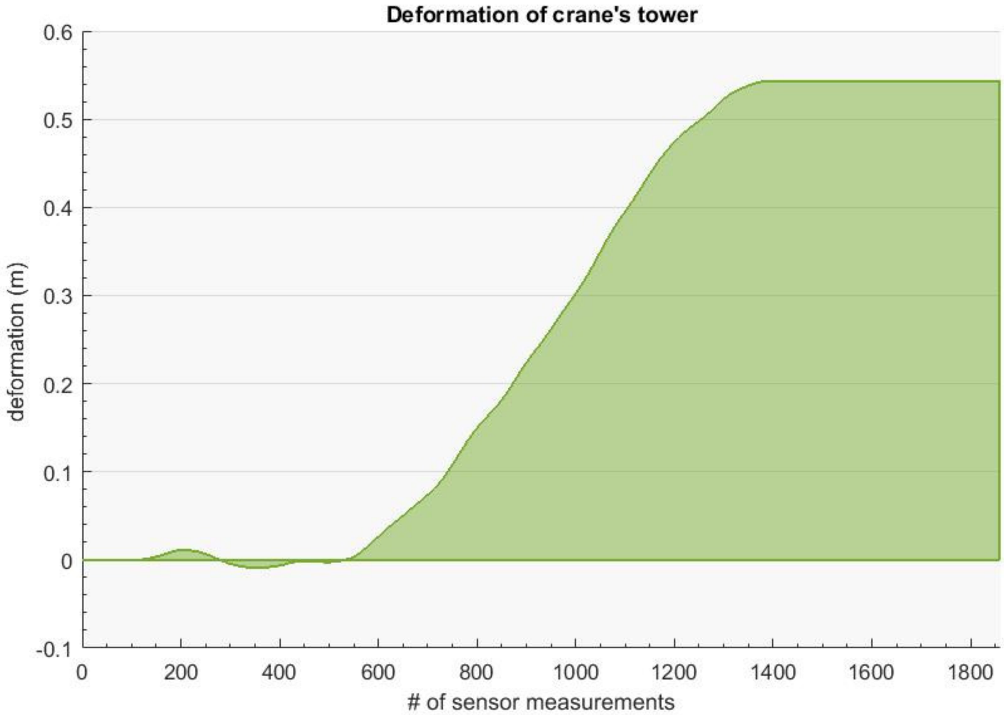
Figure 1. Sensor placement

A. Large-scale test run 1

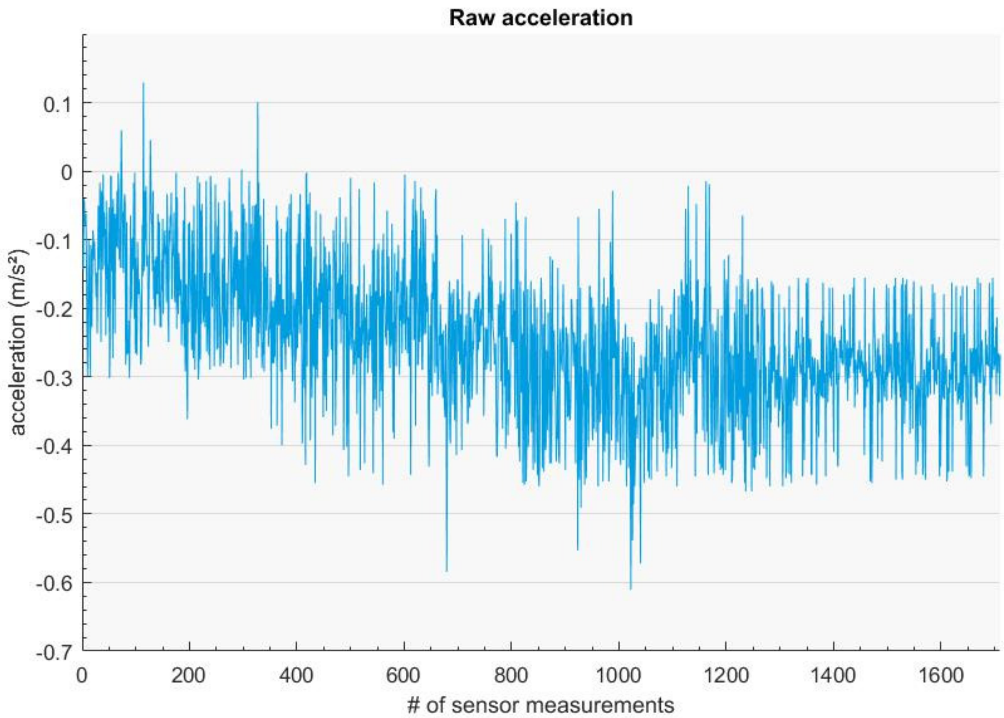


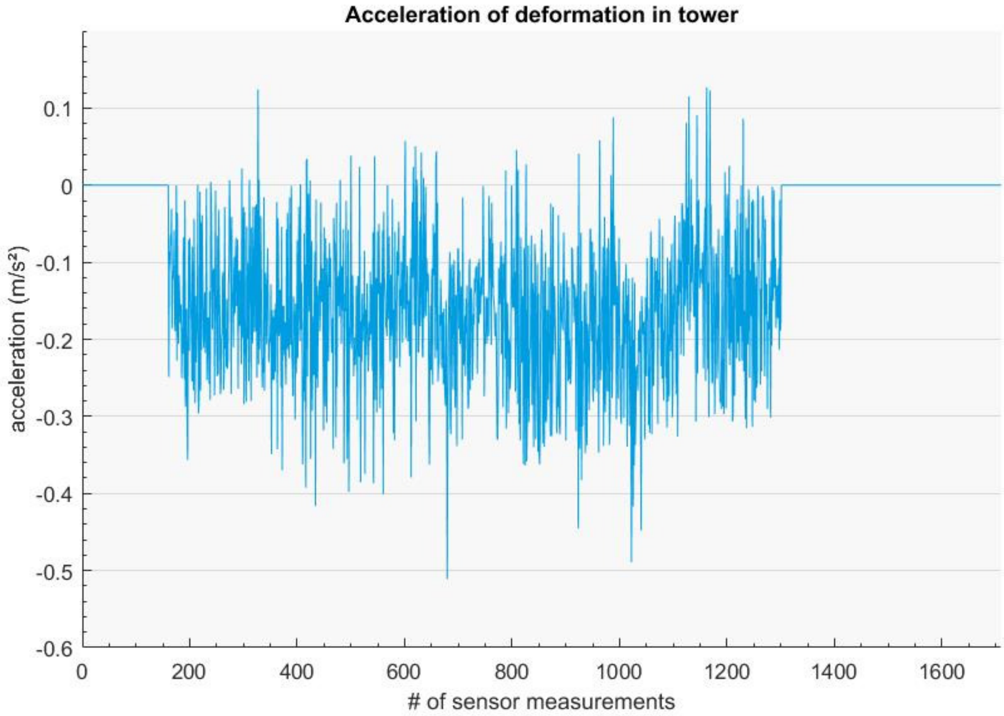

Acceleration of deformation in tower
acceleration (m/s²)
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
0
200
400
600
800
1000
1200
1400
1600
1800
# of sensor measurements

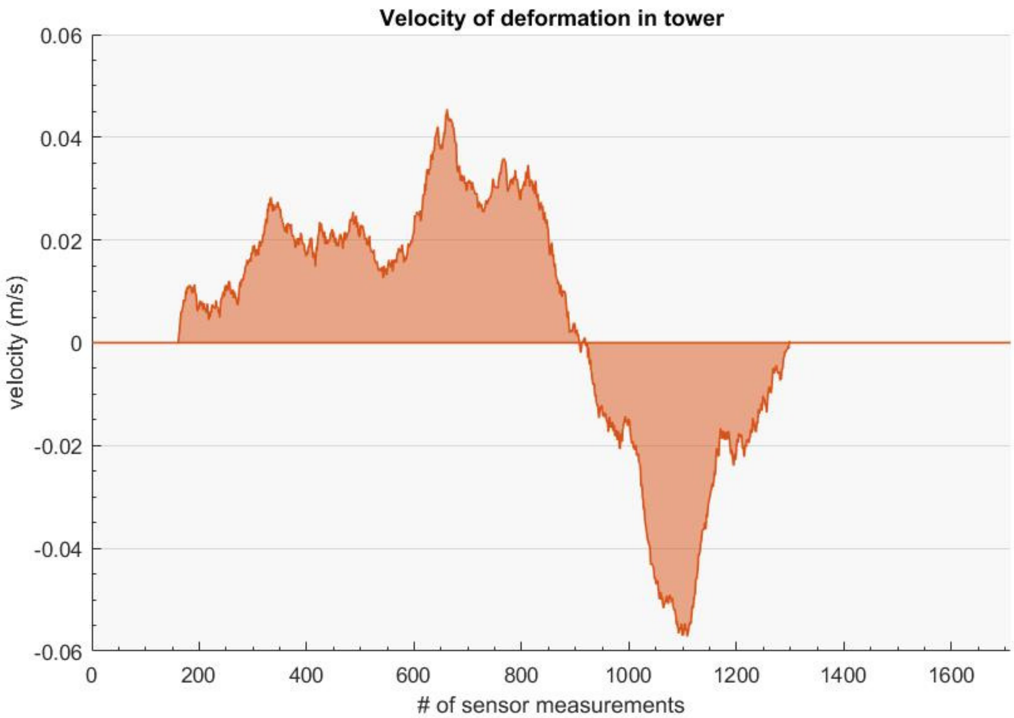

Velocity of deformation in tower
velocity (m/s)
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
0
200
400
600
800
1000
1200
1400
1600
1800
# of sensor measurements

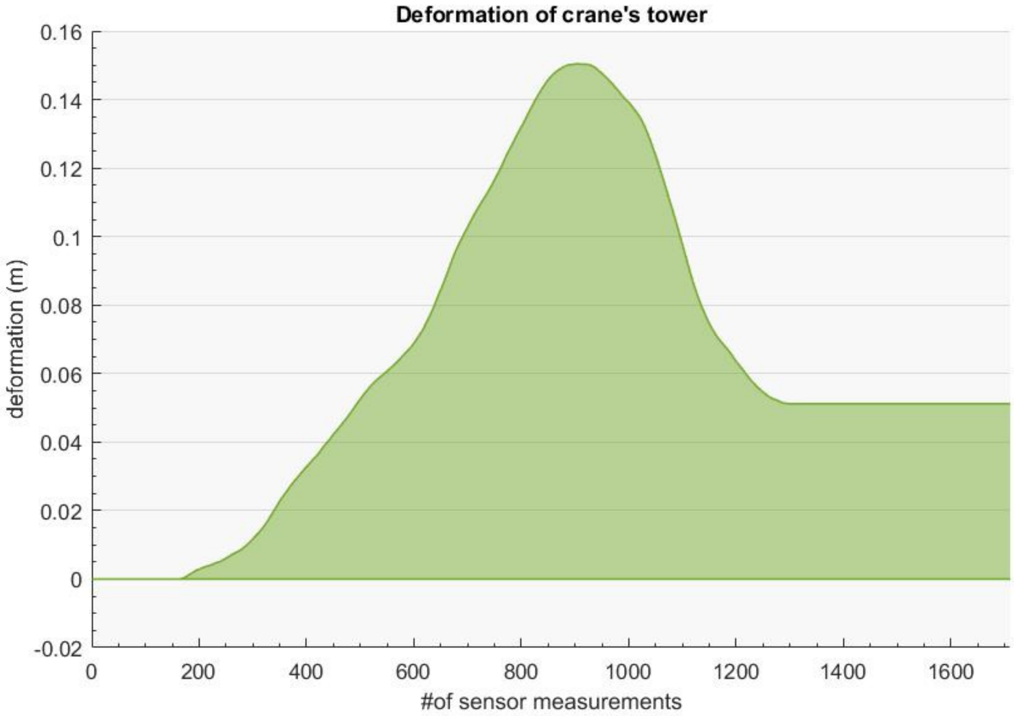


B. Large-scale test run 2

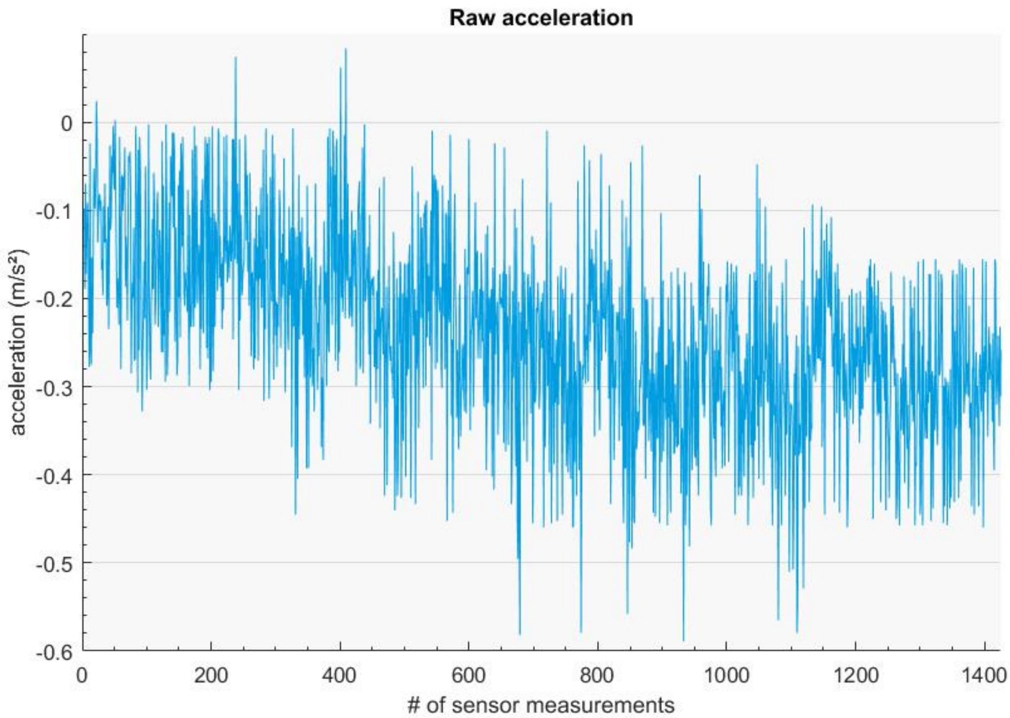


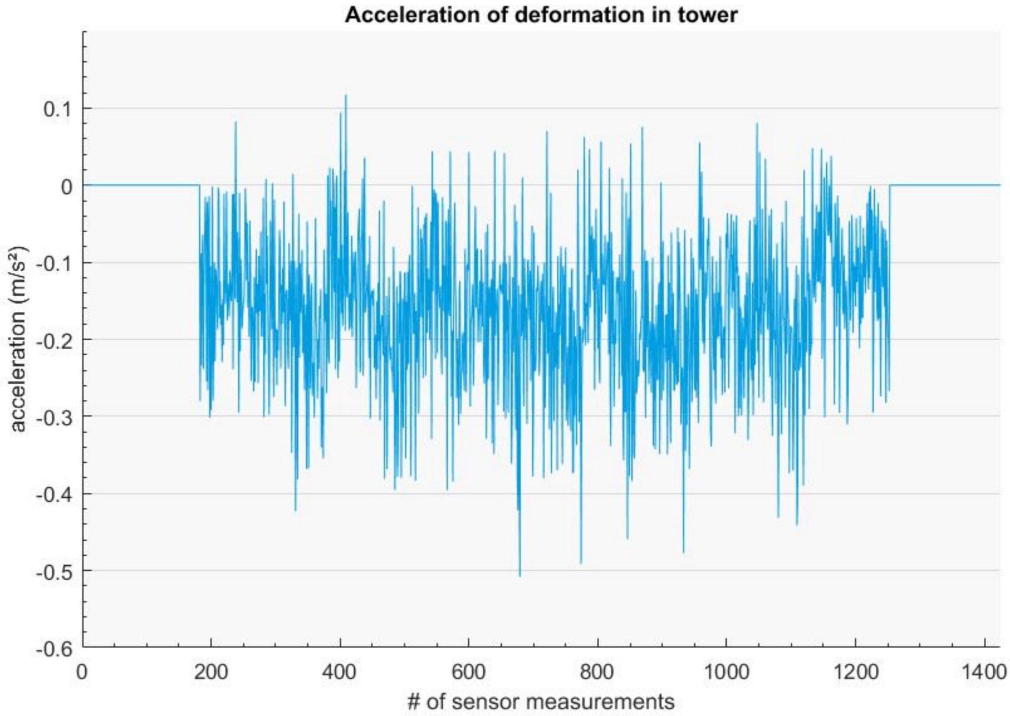

Acceleration of deformation in tower
acceleration (m/s²)
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
0
200
400
600
800
1000
1200
1400
1600
# of sensor measurements

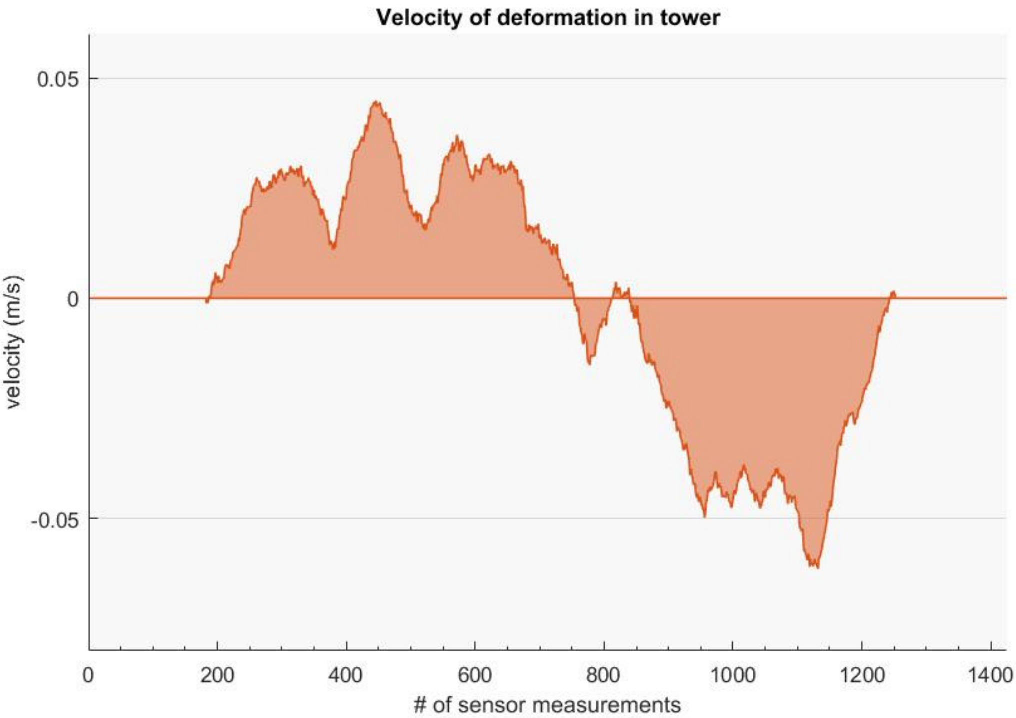

Velocity of deformation in tower
velocity (m/s)
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
0
200
400
600
800
1000
1200
1400
1600
# of sensor measurements

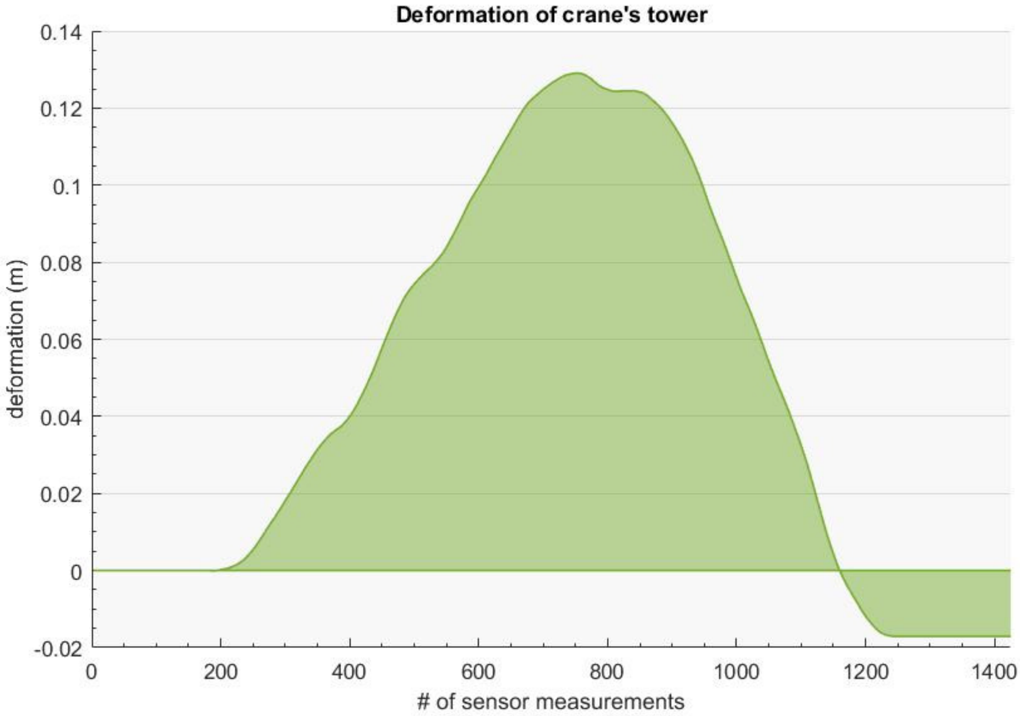


C. Large-scale test run 3

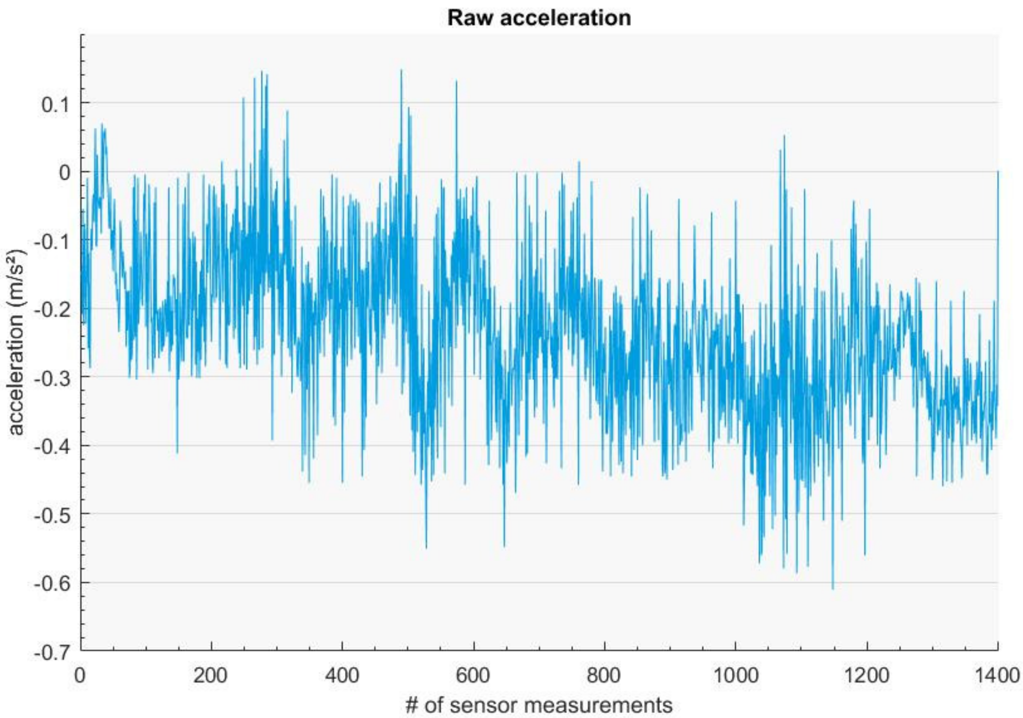


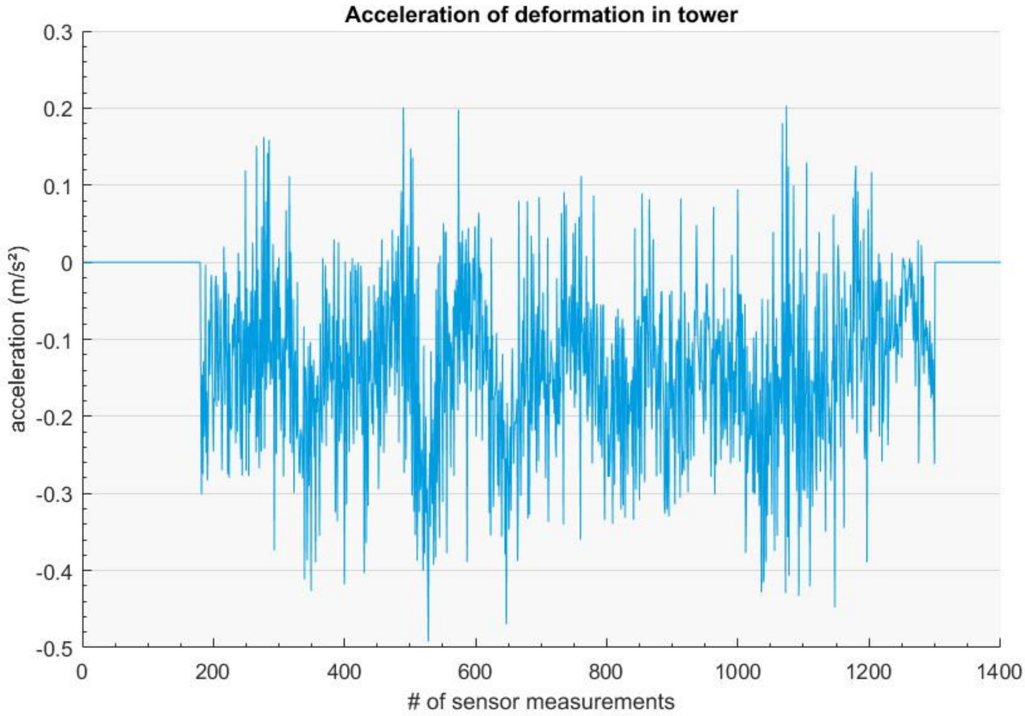

Acceleration of deformation in tower
acceleration (m/s²)
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
0
200
400
600
800
1000
1200
1400
# of sensor measurements

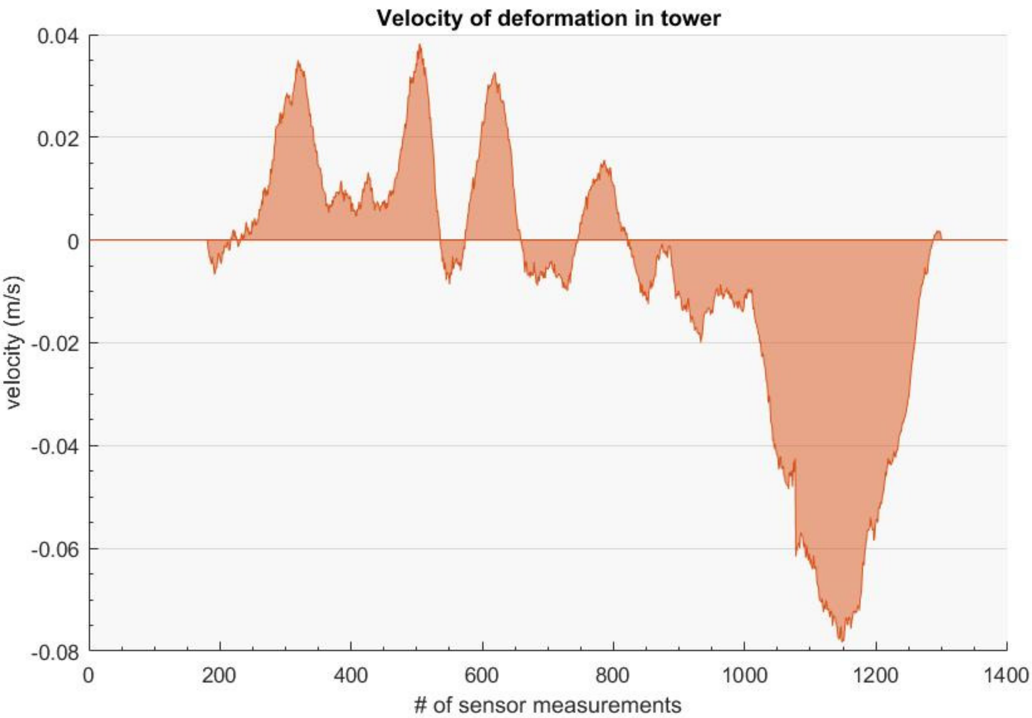

Velocity of deformation in tower
velocity (m/s)
0.05
0
-0.05
0
200
400
600
800
1000
1200
1400
# of sensor measurements

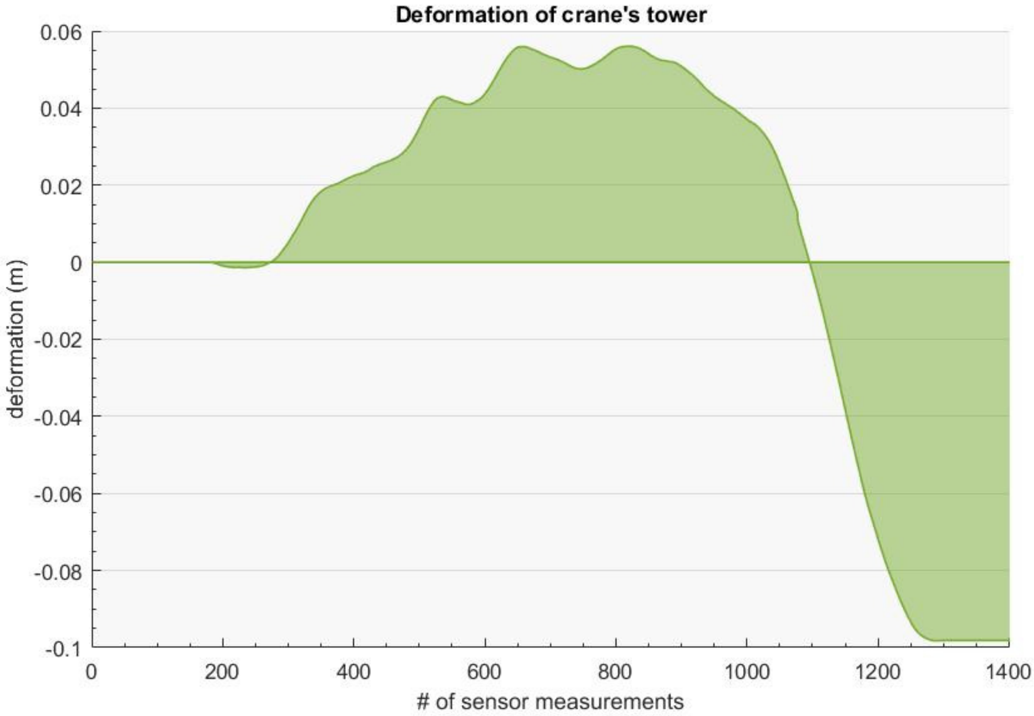


D. Large-scale test run 4

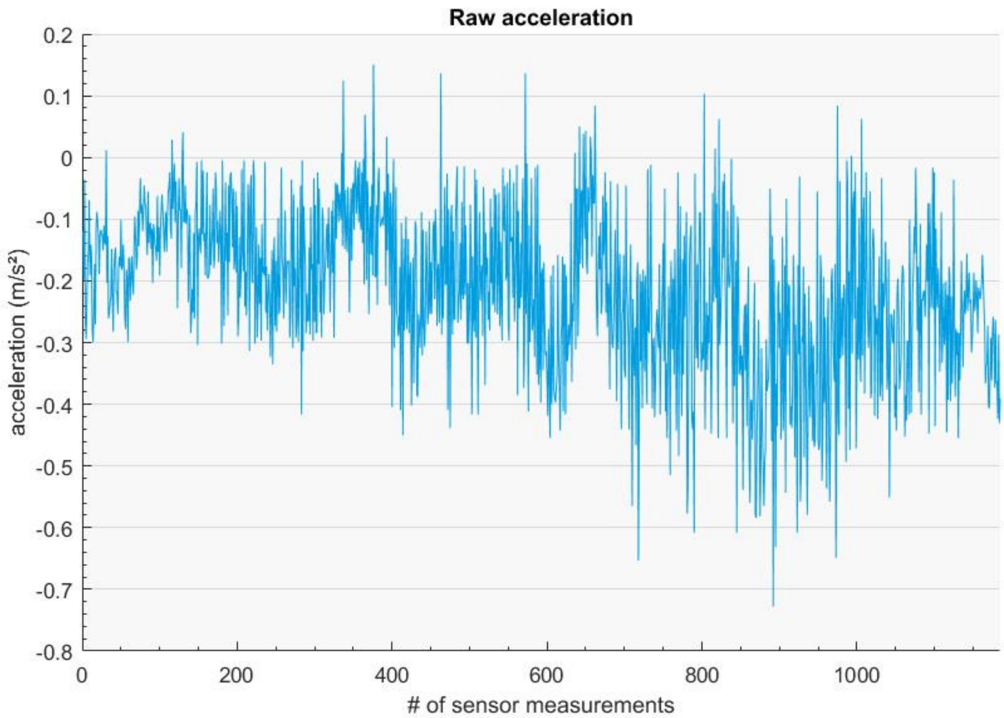


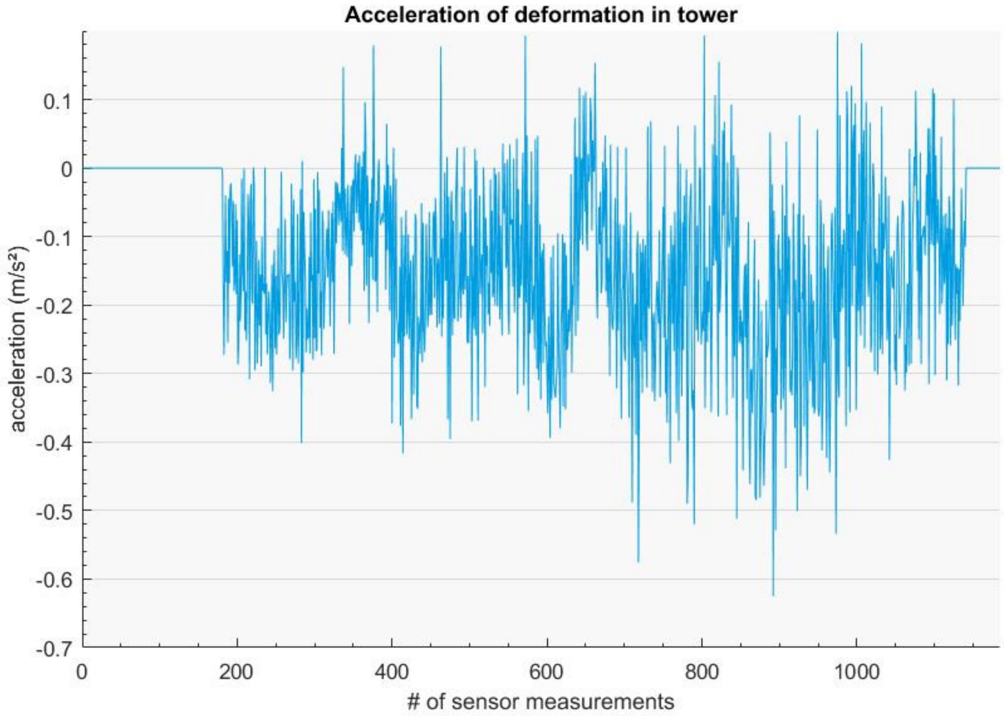

Acceleration of deformation in tower
acceleration (m/s²)
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
0
200
400
600
800
1000
1200
1400
# of sensor measurements

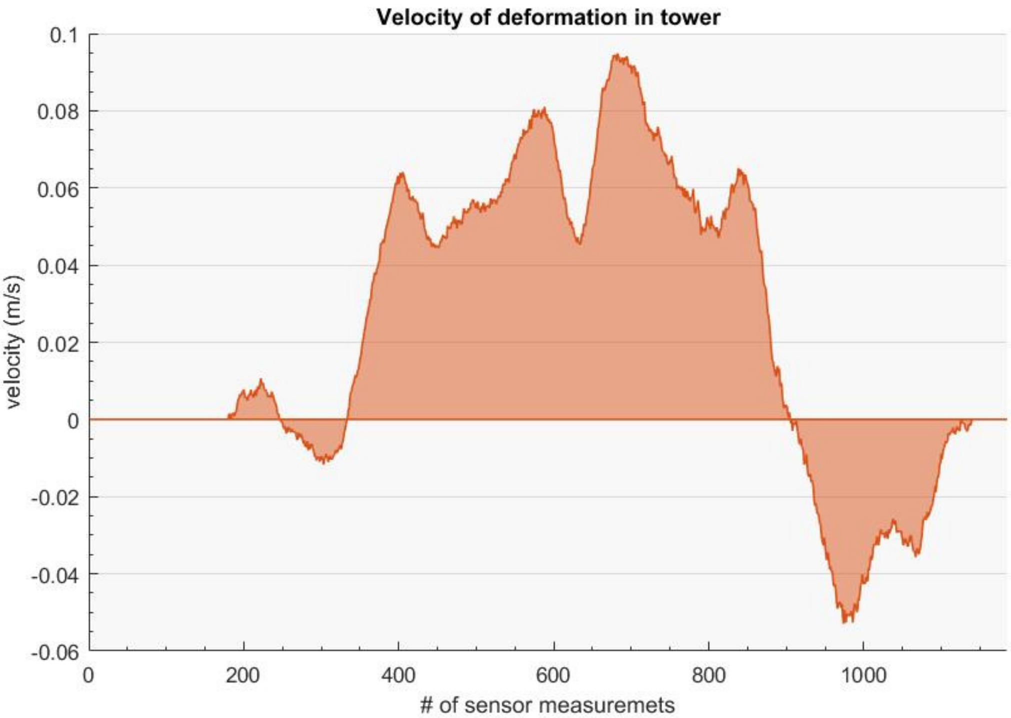

Velocity of deformation in tower
velocity (m/s)
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
0
200
400
600
800
1000
1200
1400
# of sensor measurements

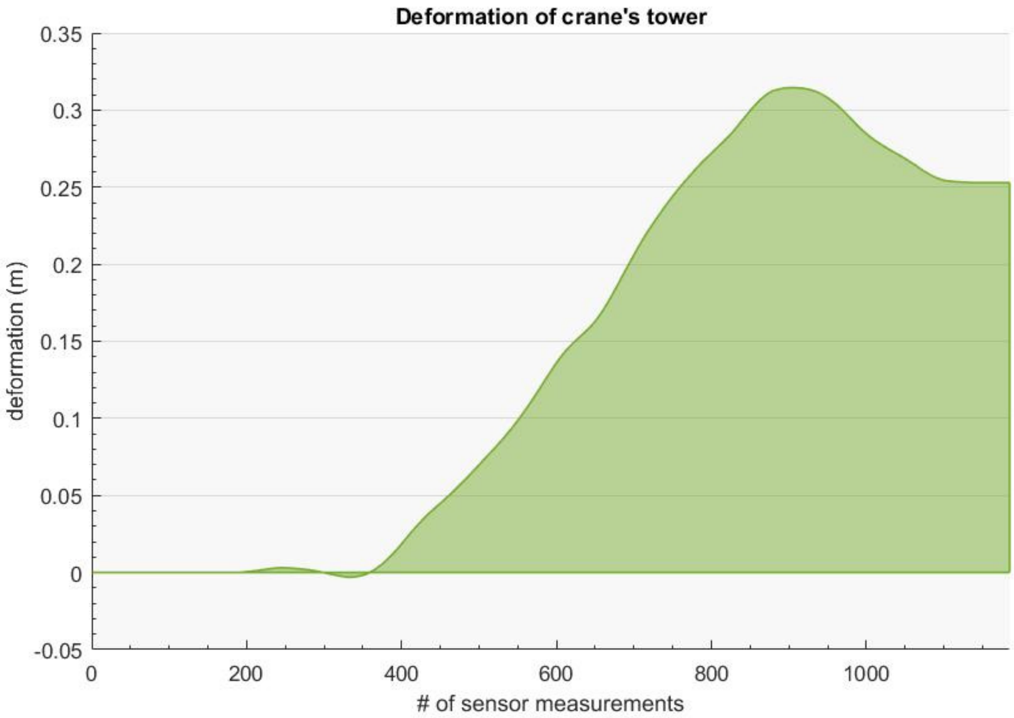


E. Large-scale test run 5




Acceleration of deformation in tower
acceleration (m/s²)
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
0
200
400
600
800
1000
# of sensor measurements


Velocity of deformation in tower
velocity (m/s)
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
0
200
400
600
800
1000
# of sensor measuremets


Deformation of crane's tower
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.05
deformation (m)
0
200
400
600
800
1000
# of sensor measurements