Tampereen yliopisto

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INVESTIGATING LOCATION TECHNOLOGIES TO IMPROVE SAFETY AND EFFICIENCY OF CONSTRUCTION SITE OPERATIONS

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ABSTRACT

Kalle Kuparinen: Investigating location technologies to improve safety and efficiency of construction site operations
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The interest in location-aware software systems has been steadily rising over the past years and there is a need for a fully-fledged location-aware solution for construction sites. This thesis reviews the literature of different positioning technologies in order to find the advantages and disadvantages of each technology on construction site use. The review is conducted in order to answer which of the technologies and solutions are best suited for different construction site uses as well as how they can improve the safety and efficiency of the site. For indoor use, the best suited technologies for construction site is the fusion of ultra-wideband and wireless local area network-based localization and the minimum accuracy needs should be 1.32 meters. The best solution for outdoor use the fusion of inertial measurements and GPS-based localization and the minimum accuracy should be 5 meters. The suggested solutions would be feasible utilizing technology that is already in use for the most part, such as heavy machinery sensors and smartphones that the workers carry with them.

The review of the location technologies and solutions is also applied to answering how to improve the safety and navigational efficiency of the construction site through different possible implementations. Safety of the construction site could be improved by utilizing virtual boundaries and automated alarms based on position, velocity and movement direction. Snapshots of the construction site state could be stored, which include information about the location of each entity on the construction site at time of the snapshot, which could be used to review accidents and close-call situations.

Navigational efficiency could be improved by tracking the location of workers, machinery and tools on the construction site. The thesis also suggests estimating the location of a worker with different means when the positioning data is not available.

Keywords: construction site, positioning solution, location data, WLAN, UWB, GPS, IMU

The originality of this thesis has been checked using the Turnitin OriginalityCheck service.

TIIVISTELMÄ

Kalle Kuparinen: Selvitys paikkatietoteknologian hyödyntämisestä rakennustyömaan tehokkuuden ja turvallisuuden parantamiseksi
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Kiinnostus paikkatietoa käyttäviin sovelluksiin on jatkuvassa nousussa rakennusalalla. Koko rakennustyömaan kattavalle paikkatietoratkaisulle on jo olemassa sovelluksesta kiinnostunut asiakaskunta, mutta ratkaisua, joka täyttäisi kaikki asiakkaiden sovellukselle asettamat kriteerit, ei vielä ole olemassa.

Tässä diplomityössä katselmoidaan eri paikkatietoteknologioita ja arvioidaan niiden soveltuvuutta rakennustyömaaympäristöön. Kirjallisuuskatsauksessa arvioidaan kunkin teknologian soveltuvuutta rakennustyömaakäyttöön ja sitä, miten ne soveltuvat parantamaan työmaiden turvallisuutta ja tehokkuutta.

Katsauksen tuloksena sisätiloissa tehtävään paikannukseen parhaiten soveltuva teknologia on ultra-wideband -teknologian ja langattoman verkon fuusio. Sisätiloissa paikkatiedon tulisi toimia vähintään 1,32 metrin tarkkuudella. Ulkotilaympäristössä soveltuvin ratkaisu on inertia-antureiden ja GPS-pohjaisen paikkatiedon fuusio, jonka tulisi toimia vähintään 5 metrin tarkkuudella. Ehdotetut ratkaisut on mahdollista toteuttaa olemassa olevilla teknologioilla, joita on esimerkiksi raskaan kaluston sensoreissa ja työntekijöiden älypuhelimissa, jotka ovat jo osittain valmiiksi käytössä rakennustyömailla.

Tässä työssä ehdotetaan myös kirjallisuuteen perustuvia ratkaisuja rakennustyömaan turvallisuuden ja tehokkuuden parantamiseksi. Turvallisuutta voidaan parantaa käyttämällä virtuaalista paikkatietorajausta ja automaattisia hälytyksiä, jotka pohjautuvat työntekijöiden, kaluston yms. paikkatietoon, nopeuteen ja suuntimaan.

Työmaalta voidaan tallentaa tilannetietoja esimerkiksi työntekijöiden ja raskaan kaluston sijainnista tallennushetkellä. Näitä tietoja voidaan hyödyntää onnettomuus- ja vaaratilanteiden selvittämisessä ja ehkäisemisessä. Työmaan tehokkuutta voidaan myös parantaa seuraamalla työntekijöiden, kaluston ja työkalujen sijaintia. Tässä työssä ehdotetaan myös paikkatiedon arviointia tilanteissa, joissa esimerkiksi tieto työntekijän sijainnista katoaa.

Avainsanat: Rakennustyömaa, paikannus, paikkatieto, WLAN, UWB, GPS, IMU

PREFACE

This master's thesis, "Investigating location technologies to improve safety and efficiency of construction site operations" was conducted based on the suggestions and guidance of the company Topcon Technology Finland. Despite some setbacks of multiple of the agreed supervisors leaving the company's services, the company stayed supportive through the whole process to the best of their abilities.

A special thank you goes to the employees and my coworkers of said company, especially to Eero Kuusela, Simo Nurmi and David Rizi for sharing their valuable ideas and knowledge as well as assisting with the writing process and material collection. Additional thank you goes to Katri Särkikoski for helping with the linguistics.

This thesis would not have been possible if it weren't for my supervisors Philipp Müller and Helena Leppäkoski, who provided excellent guidance in the writing process. The materials they provided, suggestions they gave, and their careful review of the work were crucial to the success of this thesis.

Tampere 01.03.2021

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LIST OF SYMBOLS AND ABBREVIATION

CA	Coverage area model
GDPR	General data protection regulation
GGMF	Gaussian mixture model
GNSS	Global navigation satellite system
GPS	Global positioning system
IMU	Inertial measurement unit
INS	Inertial navigation system
MAC	Media access control
NFC	Near-field communication
PL	Path-loss model
RFID	Radio-frequency identification
RSS	Received signal strength
TDOA	Time difference of arrival
TOA	Time of arrival
TTF	Topcon Technology Finland
UWB	Ultra-wideband
WLAN	Wireless local area network

1. INTRODUCTION

Software development for infrastructure and construction companies has been steadily rising over the past years and there is a lot of interest for different visual management systems especially for mobile devices. From the 8 years of work experience in Topcon Technology Finland Oy, a world leader in precision measurement systems and technologies, I've noted that companies globally are interested in modern tools and software to increase the efficiency and safety of work sites. In Finland the focus has primarily been in developing tools and applications to make construction sites operate more smoothly and smartly. Key interests for software on construction site use is improving the efficiency and the safety through easy-to-use software solutions than can be used in collaboration by the management and the workers.

In this thesis the focus will be mainly on localization technologies and their uses in construction site environment. Efficiency can be improved in many ways but in this case, it shall be limited to navigational efficiency. Navigational efficiency in this case is the relation between the minimum time required and the actual time it took to reach a certain destination. The more time the software and solutions can save from navigating the construction site, the better, which does correlate to the financial bottom line favorably.

In this thesis the safety of construction sites plays a key part. When it comes to resources used, construction sites are primarily concerned about protecting their workers and secondarily protecting the equipment. With the help of software solutions, the safety can be improved with location tracking. The important safety improvements localization can bring to a worksite include collision detection, mapping out dangerous areas and aiding the investigation of any unfortunate events if data is collected of the entity whereabouts before the incident. The use of smart systems with enough receivers and transmitters makes it possible to ensure a safer construction site.

This thesis will briefly introduce the typical relevant aspects of construction site, which can be linked to the benefits of utilizing smart localization software solutions. This will lead to a research question and goals for this thesis to be defined. The thesis will continue with a literature review of localization technologies and tools, where the advantages and disadvantages will be reviewed from the perspective of construction site use. This will lead to reviewing technologies and systems that have been already proposed for construction site usage and reviewing why some of them have not been proposed. Some thought will be given to existing visual solutions, including suggestions for possible improvements and additions to be made to smart construction site software, including some suggestions that cover situations when there is loss of coverage for location data. Research will be done to point out the suitable methods for improving safety and navigational efficiency on construction sites, leading to summarizing the results of the utilization of the best suited technologies, tools and solutions. The word entity will be used to describe the targets of location tracking, such as machinery, workers, tools, facilities etc.

1.1 Construction sites

A common sight in modern construction sites in Finland are signs outside the perimeter that indicate worker safety gear and some working etiquette. This hints that safety protocols and requirements have come a long way from what they were in the past. Workers are already required to carry a lot of safety equipment and access to the construction sites is mostly controlled and a carousel-gate with a card reader is not a rare sight either. When it comes to localization technologies, they often require transmitters and receivers, which could be included in the requirements of worksite apparel that would be included in the already big list of required worksite equipment the workers have to wear at all times already.

Figure 1: Construction site of Tripla in 2018, Finland *[1]*

Construction site sizes vary based on what and where things are being built. One of the bigger modern projects in Finland has been the construction of the hybrid building complex Tripla in Pasila seen in Figure 1, which covered an area the size of 50 soccer fields [2]. The bigger and the more complicated a building site gets, the more it increases the need for the use of localization on the construction site. With multiple structures and areas all being built in their respective places, a large construction site has a clear need for navigation as it can be hard to know where everything is in a vast ever-changing environment.

On construction sites the constantly changing environment can lead to some challenges. As the construction progresses, tools, machinery and workstations and such have the tendency to move out of the way when structures start to take shape. For example, tools and equipment can move from day to day from where they were needed yesterday to where they are needed tomorrow. Construction sites host several different types of areas that can prove challenging for localization. Big open areas that area being landscaped, underground areas and vast number of possible floors of a new construction all bring something to the table which needs to be considered when thinking about a location-aware worksite, especially from the aspect of receiving and sending signals that are used to locate entities. One important aspect of this all is that everything exists in a 3-dimensional environment and a simple 2-dimensional coordinate might have multiple different floors and underground areas beneath it.

Tools, equipment and machinery are needed on a modern construction site, but they can cause various problems through their necessity. When a tool is needed, but not found, it logically brings down the efficiency as it takes time to find where it is. As with many machines they might pose a threat to the workers if not operated carefully. Most equipment should be always supervised, which means there should be someone in the near vicinity of the location of the machine. Moving machinery is especially dangerous for workers as no amount of protection a worker can wear is enough to prevent damage from a hard collision with a heavy-duty truck for example. Localization to aid finding the tools, prevent people from leaving machine unattended and warning about hazardous moving machinery could be useful.

Construction sites host a number of dangerous areas that should be kept clear to prevent any danger to workers or equipment. A zone where landscaping is done by drilling and blasting is one example of a dangerous area that should be avoided. Technology could be used to know the location of such dangerous areas and use that information to try to prevent entities from accessing that area or preventing the start of operations in case something is within the perimeter that should not be there. If the construction site is location-aware in real time, an important piece of information would be the perimeter of a detected accident to figure out what went wrong and how it can be prevented in the future.

As mentioned before, the vastly different sizes and complexities of construction sites lead to thinking how useful navigation within the worksite could be. With location information being available of the construction site entities, it would most likely lead to big improvements in work efficiency. It would be beneficial if workers always had access to location data of where the tools are, where the equipment is and where to find other workers. Without this knowledge and when things are missing, every second spent asking around and finding what is needed is time that could be used to progress. The time it takes to find tools, equipment and people is directly correlated to the cost of having workers on the site.

1.2 Goals and limitations

The goals of this thesis are to find suitable methods and technologies that can be used in collaboration with software to increase the safety and navigational efficiency of a construction site. The goal will be divided to safety and efficiency.

This thesis aims to decide the best localization technologies for construction site use that cover the entire site, indoors and outdoors and if the solutions are accurate enough to be used for precise navigation within the construction site. Sufficient accuracy indoors would need to be able to distinguish a location in 3-dimensional space with enough accuracy to know a location on a room and floor-level accuracy, where 2-dimensional location information is enough if combined with floor-level data. Sufficient accuracy outdoors is less crucial, but the selected technologies should be able to cover large outdoor areas too. The research should answer what combination of technologies and solutions as a whole would be most feasible to be used by a software to increase the navigational efficiency of a worksite.

This thesis will also answer which technologies and solutions are best suited to create a software that works to prevent accidents on a construction site, also considering what kind of accuracy is needed to prevent possible accidents and what kind of time is needed for a worker to react to a detected danger. The selected technologies and solutions should work together so that only one software would be needed to achieve both safety and efficiency, instead of finding the best for safety and the best of efficiency, possibly dividing the solution into two parts and two separate systems.

This thesis is limited to literature review and speculative thinking based on the existing data of the localization technologies and devices without field-testing the technologies or implementing them. With the data and research from this thesis one should be able to start designing a smart construction site. Pathfinding and guided navigation will not be covered in this thesis, but it definitely should be researched more in complex changing construction site use.

2. REVIEW OF POSITIONING TECHNOLOGIES

A review of different kinds of positioning systems is found in this section as well as a look into some privacy concerns which come from utilizing location data. Each subsection will briefly introduce the technology and discuss/list its strengths and weaknesses. The strengths and weaknesses will be considered from the standpoint of utilizing them on an active, constantly changing construction site.

2.1 RFID-based Positioning

A radio-frequency identification (RFID) positioning system is typically based on a set of RFID transponders also called RFID tags and a locator node which reads the information from these tags using wireless radio waves which transmit the identity [3]. One way of constructing a positioning system using RFID would be to place a lot of RFID tags around a construction site, each of them identifying a location in the site such as a certain room on a certain floor. The cost of placing RFID tags would not be very high even with great amounts of them placed as they are very cheap with a price under 20 cents per passive tag [4]. If each actual location of RFID tag would be stored and a reader in its vicinity would detect it, it could be used to deduce the location of the reader.

Passive RFID tags, which do not require any source of power and only act as a “mirror” for the sent signal from the RFID sensor, pose an issue for smartphones. Most smartphones come equipped with near field communication (NFC) which is able to function similarly to RFID, but the issue here is that the effective range of NFC is not very high (4 – 10cm) [5] as it is meant for short-range communication [4]. Active RFID tags have their own transmitter and power source which gives them a lot more range up to 100m [7], but they are then subject to the battery eventually running out. The battery life for different advertised active readers seems to be around 1-5 years depending on the power, range and manufacturer, but they come with exponential cost (approximately 30€) [4] compared to passive tags.

A summary of different types of RFID positioning shows that the mean error of RFID positioning with passive RFID tags can be low and the positioning extremely accurate for navigational use. The mean error has proven to be below half a meter in many different types of implementations and research [5]. Even though the cost of tags is low and the accuracy can be high, many of the mentioned research uses over 10 sensors per square meter, which would mean that a simple small construction site for a block of flats with 10 stories, each being 200 m2 would already host around 20 000 RFID tags. It is very likely that the RFID tags could be spaced out a lot more sparsely as sub-meter level accuracy is not needed indoors.

In construction sites placing RFID tags and setting up their location during construction would be completely feasible for indoor use as usually the floor plan is already done when the structures start rising from the ground. Each room could host a few tags, just enough for the reader to detect what is near. When the walls start going up, it should be easier for a RFID reader to read only the tags within the same room accurately placing a construction worker inside a specific room of the building for example. It is unlikely that the construction workers would carry proper RFID readers with antennas for this to work properly with passive tags.

In outdoor setting on construction sites RFID tags might have some uses but covering the entire, constantly changing landscape with tags would not work. Machinery could host RFID tags that serve to detect if workers are near them, for example a construction workers phone could identify them as the operator of a forklift. In a use case of machinery, the range could be short enough for passive tags to work with NFC when the operator is for example sitting in the machine chair with a passive tag embedded within the chair.

2.2 WLAN-based Positioning

In construction it would be completely feasible to install a wireless local area network (WLAN) on the construction site. Tracking the positions of workers on the construction site would require a set of access points scattered to cover the entire site. The location then could be tracked from the connection between the user devices and the access points. Positioning using WLAN-based systems can work by deriving the user device location from the received signal strength (RSS) from the access points [6]. The received signal strength and media access control (MAC) addresses of the access points are already present in the transmitted data, requiring no changes to the access points software, which explains why this positioning method is commonly used with WLAN [7-9].

It is also possible to utilize WLAN using location fingerprinting methods, which tend to be less complex than locations modeled from signal propagation, especially indoors [10]. Fingerprints in this case mean location report, reception reports and location observations. Methods that utilize these technologies compare the received signal strength from the access points against a database of information (called a radio map) containing fingerprints.

Research on WLAN positioning has showed that it is capable of only moderate accuracy indoors. It was noted that the line of sight between the user device and the access point had a significant effect on the signal strength, which was a reduction of around 10dB [11], which would be common in complex environments such as construction sites. One research suggest that the mean error for WLAN indoor localization was under 5 meters on mobile android devices with and without utilizing the compass on the device [11], while another research by Davidson and Piché suggests an indoor accuracy to be about 10 meters [12]. These accuracy levels suggest that the accuracy is enough to for example find a person from a general area, but perhaps not accurate enough to pinpoint what room or floor they are in and fulfill all the requirements of a location based positioning system alone.

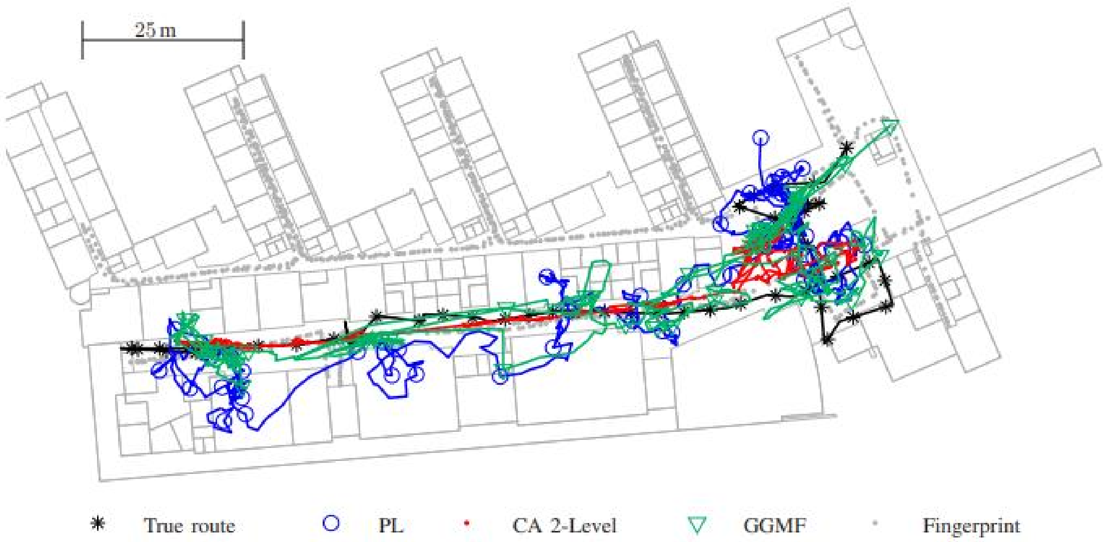

Figure 2: WLAN-based location indoors at University *[10]*

As seen from Figure 2, the technology is feasible to be used indoors, as a university building is a decent comparison against any new construction/building being developed. In this figure there is a comparison between the actual path taken to path loss model (PL) that is based on signal power loss, coverage area models (CA) which is based on elliptical probability distribution and gaussian mixture (GGMF) which is based on a convex combination of Gaussian density functions. Each of the methods prove to be enough in providing location data that is useful on a construction site if there is interest in where someone was at a given time or where to find someone else. [10]

Even though WLAN-based positioning has been deemed working and field tested in locations such as the different floors and locations in the Tampere University of Technology (Hervanta Campus) with hundreds of access points and plentiful fingerprint data [10], it leads to questioning whether setting up such a network to a construction site is worth it. It is only natural that construction sites are ever-changing so a constant need of moving or adding access points would be necessary during the construction. Modeling location with RSS and the use of fingerprint-methods can prove to be problematic when the access point coverages change and when the physical environment changes so that the fingerprint location data is no longer valid. For example, if new walls are added between access points and a fingerprint location, that fingerprint becomes invalid. If one could say that a WLAN with plentiful access points would be present in every construction site, a strong argument could be made in favor of using WLAN-based positioning, but usually such network is only found in completed projects. There is always the option to integrate building such networks into early construction phases which would enable utilizing them early, but feasibility of this should be researched.

One issue with WLAN-based positioning an access points in construction sites is the open areas, such as landscaping areas, roads and such. Placing access points for the network might be troublesome if they need to be outside and cover large empty areas. A question is also raised on how to track moving entities on the construction site using WLAN. These moving entities could be for example cranes, bulldozers, trucks and other machinery that operates on these sites normally.

2.3 Ultra-wideband

Ultra-wideband (UWB) by definition is a short-range radio frequency technology that utilizes frequencies that are at least 500MHz or 20% over the center frequency [16]. UWB uses short nanosecond pulses that are transmitted over an “ultra-wide” range of frequencies. The technology is based on wireless communication between transmitters and receivers.

Location using UWB is determined similarly to how it is done in WLAN-based positioning. Distance between the transmitter and receiver can be calculated from the time it takes for the signal to be transmitted. The distance between the transmitter and the receiver can be calculated in three main algorithms: angle of arrival, time of arrival and time difference of arrival.

The most complex of the three, the angle of arrival algorithm requires large dimensions of antenna arrays and is prone to error accumulation. The requirements and complexity are enough to not consider this method to be used on construction sites.

Time of arrival (TOA) is simple, but it requires the receivers and senders to have their clocks synchronized. Unsynchronized clocks can lead to high loss of accuracy. If workers on a construction site would be tracked through their mobile devices, it would be bold to assume that synchronization between the devices and the transmitters would be in sync. Mobile devices would not be feasible to be used with this method as they most likely won't be synchronized, unless a two-way method is used where the distance estimation would be modeled from the time it takes to send a signal and receive a response. The two-way method will be subject to more inaccuracy as the signal travels double the distance compared to one-way TOA, but it pays off when the need for synchronization is eliminated. Synchronous TOA could work better if the positioning system would use synchronized receivers in worker badges for example. [13]

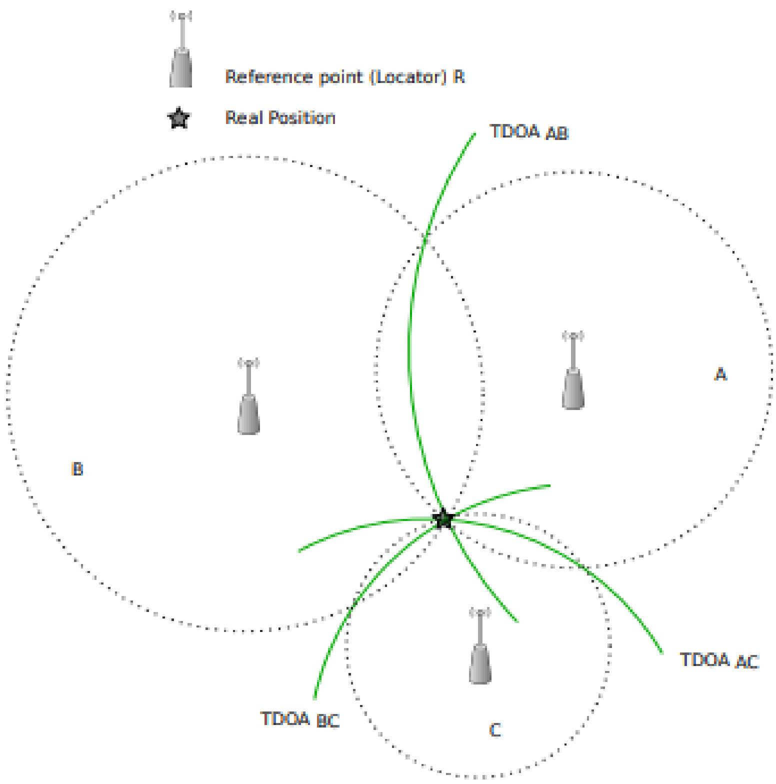

***Figure 3: TDOA-based algorithms** [14]*

Time difference of arrival (TDOA) estimates the position of the receiver from the signal time difference between the receiver and multiple transmitters [4]. This method is especially useful when clock synchronization is not guaranteed which makes this method viable to be used on a construction site. UWB transmitters could be scattered around the worksite and at least 4 reference nodes would be needed to track the location in 3 dimensions [14].

There are multiple positive things to be said of UWB. It uses very little power which means it can be used license-free, as it does not get classified as radio equipment nor does it interfere with most existing radio systems. In addition to this UWB uses less battery compared to other positioning techniques which allows for better battery life for the devices used. The used frequencies are capable of penetrating different kinds of light construction materials , which is beneficial for use in construction sites with high probability of lacking line-of-sight. It is important to know that steel and concrete can significantly slow down the signal and thicker concrete walls can even block it completely, which will affect the accuracy of the calculations negatively [15, 16]. UWB can be very accurate, which would make it very appealing choice for construction site use [14]. As the technology works with multiple types of receivers, location data can be gathered from vehicles and other moving entities on a construction site.

The negatives for UWB include that it can be very expensive when compared to other technologies [14]. As the range between the receivers and transmitters in UWB positioning can’t be too high and some sources claim that the maximum indoor range would be 100m using low rate UWB [17], it would lead to having a lot of transmitters on bigger construction sites. A 10-hectare (1 square kilometer) construction site would already contain more than 100 transmitters if it was to cover the whole area so that it would have in minimum 4 points within 100m range of the receiver at any given time.

2.4 Inertia measurements

Measuring the direction and amount of movement can be used to detect which way and how fast something is moving. This can be especially useful on a construction site for safety purposes. For example, the direction and amount of movement of a truck on the construction site when its location is known can be used to calculate if it is heading towards a possible collision.

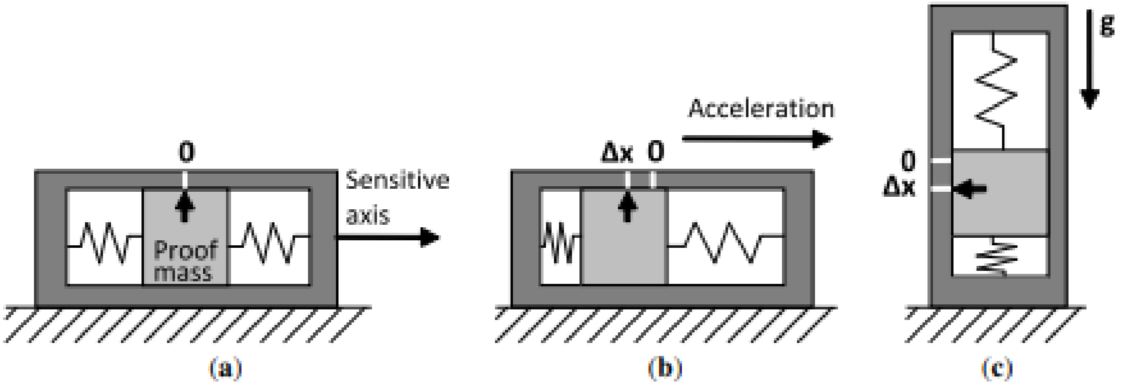

Figure 4: A mass-and-spring accelerometer under different conditions a) at rest or in unform motion b) accelerating c) at rest *[18]*

Inertial measurements can be done through measuring acceleration in different directions. A simple description for an accelerometer would be a mass connected to springs that registers acceleration in the direction of its orientation. With a set of three accelerometers in the each of the 3D axis a direction and an amount could be calculated. [18] It is not necessary for the accelerometers to be aligned with the axes and the direction can still be calculated if the angles are known. The described tri-axis accelerometers are very popular in the low-cost segment of components.

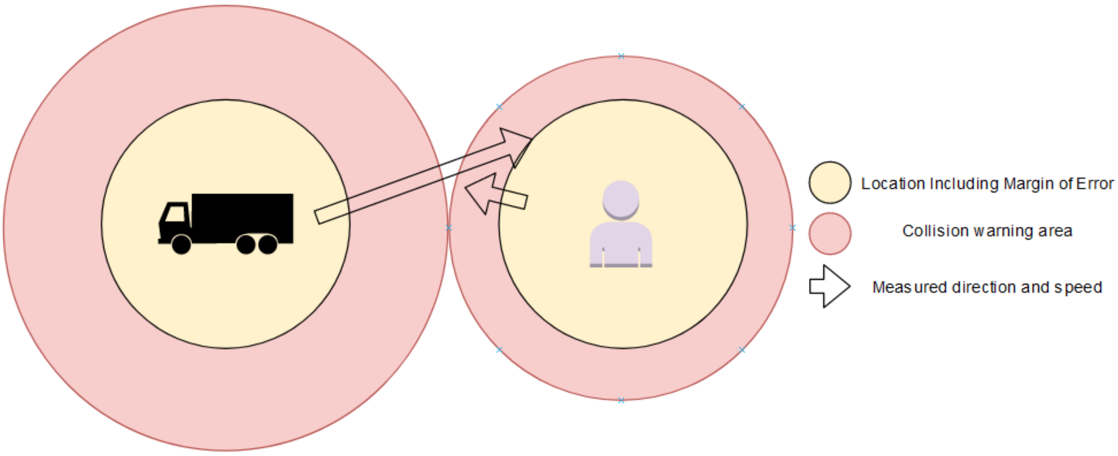

Figure 5: Accelerometer collision detection system

On construction sites accelerometers would be beneficial additions to all moving entities. Collected data from the movement direction and current position can be used to predict possible collisions. The required inertial measurement devices could be mounted relatively easily on most moving work equipment and most mobile devices come with built-in inertia measuring hardware.

For example, a software could be built to track the movements of a truck and when a probable collision is detected between the truck and something else, it could be used to trigger an automated alarm. When each moving entity on the worksite has their location known in the system, an area could be calculated around it if we have information on the accuracy of that location as seen in Figure 5. In addition to this area, another area would be added based on the accelerometer reading as a collision warning area that would grow bigger based on the speed. If two of these areas would clash at any point between entity, it would result in an alarm of some sorts. A successfully implemented system like this would be an incredible asset for worksite safety.

More inertia measurements can be collected by utilizing rotational inertial rate sensors, which are also called angular rate sensors or gyroscopes [18]. Gyroscopes are used for measuring angular orientation. Gyroscopes alone are not particularly useful to be used on a construction site on their own, but they have the potential to be used together with accelerometers and other technologies to aide more accurate positioning and navigation.

Alone inertia measuring is not enough for construction site use. Navigation and positioning with inertia would require a starting point from which the position would be then calculated based on rotations and movements registered by the hardware. Proper inertia navigation system (INS) requires accurate sensors and that results in these systems being expensive and usually heavy and power-hungry, making an INS not commendable for construction site use. [18]

2.5 Geofencing

Geofencing refers to using location technology and location data to create geographic boundaries that a software can use to detect events such as entities entering, exiting or colliding in the specific area [19]. The circular areas that were shown in Figure 5 can be classified as geofencing as it portrays a virtual perimeter in a real construction site environment.

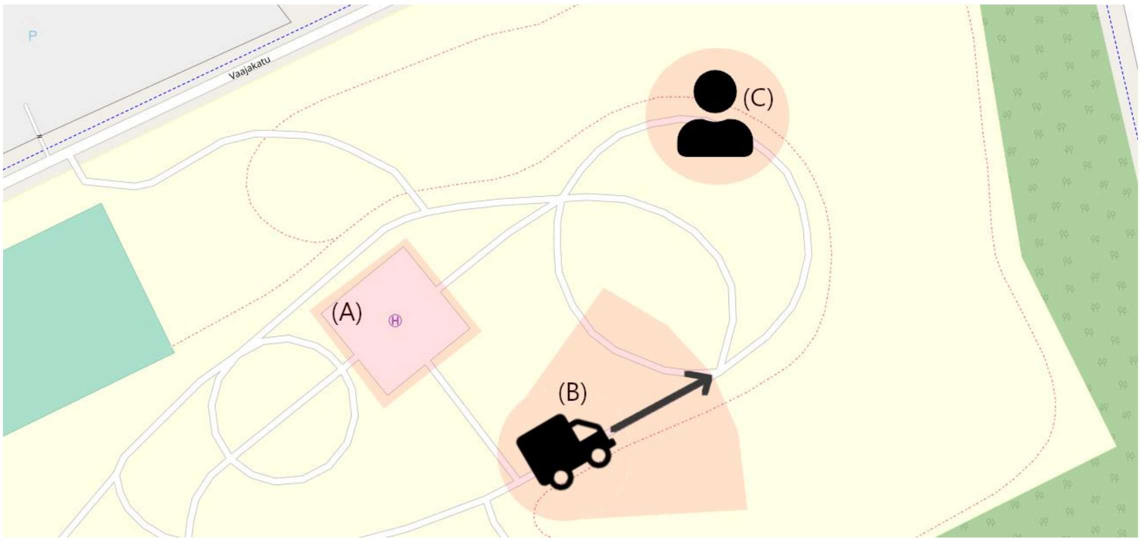

Figure 6: Geofencing examples

There are multiple use-cases for geofencing around construction sites. The first of the cases is utilizing geographic boundaries to detect possible collisions between moving entities, such as a truck and a worker. Another use-case for geofencing would be to mark certain areas as dangerous zones, which any entity should not access. Geofencing could also be used to fence in entities in an area of an accident. For example, if an accident is detected by some machinery, a software could register all the entities within a certain margin of that area for future investigation. In Figure 6 the red areas represent the geofenced areas.

Situation A in Figure 6 could represent an area where some dangerous excavation is in progress. The geofenced area would mark the dangerous area which could be monitored in cases where a worker unaware of the danger would be walking towards the direction and cross the geofence. A software could detect this and immediately alert the worker on their mobile device for example. Inward-facing areas such as situation A are useful for keeping people out from an area, but there might also be a use for outward-facing boundary which is designed to keep entities within itself [20]. One example of this could be heavy machinery which could have logic to automatically shut down or alert someone if a supervising worker leaves its vicinity, if it should not run unattended.

The size and shape of the area varies between different moving entities. A truck, as seen in situation B, which is capable of moving at high speeds should have a more cone-shaped geofence as the most dangerous area is directly in front of the truck also factoring in the possibility that the truck can turn, but usually never move directly sideways or backwards. In situation C the entity is a worker which is capable of moving in any direction easily, but not with excessive speed. The shape of the geofence around a worker is therefore more circular compared to vehicles.

Constructions sites do not exist in a 2-dimensional environment, so the third dimension must be considered while utilizing geofencing. Sometimes a dangerous area that needs to be geofenced could be located on a specific floor in a building for example. This implies that the software monitoring the fences would need to be accurate enough to register altitude on sufficient level for any successful detections to occur. Overall geofencing is extremely useful for construction site usage especially from the safety aspect. All construction sites should aim to be accident free and smart location-based solutions can help achieve that goal.

2.6 Collaborative positioning

Collaborative positioning refers to the entities in a location aware system communicating and collaborating by sharing data. By sharing relevant information about positioning, it allows possibilities for more accurate calculations, more coverage and better reliability. Especially in construction site use where there usually is lots of complex terrain and plenty of obstructing elements, collaborative positioning can prove to be useful when connection from the receiver is not always guaranteed to a transmitter. Having the vast amount of moving entities that communicate with each other to form a better, more robust location network is definitely appealing.

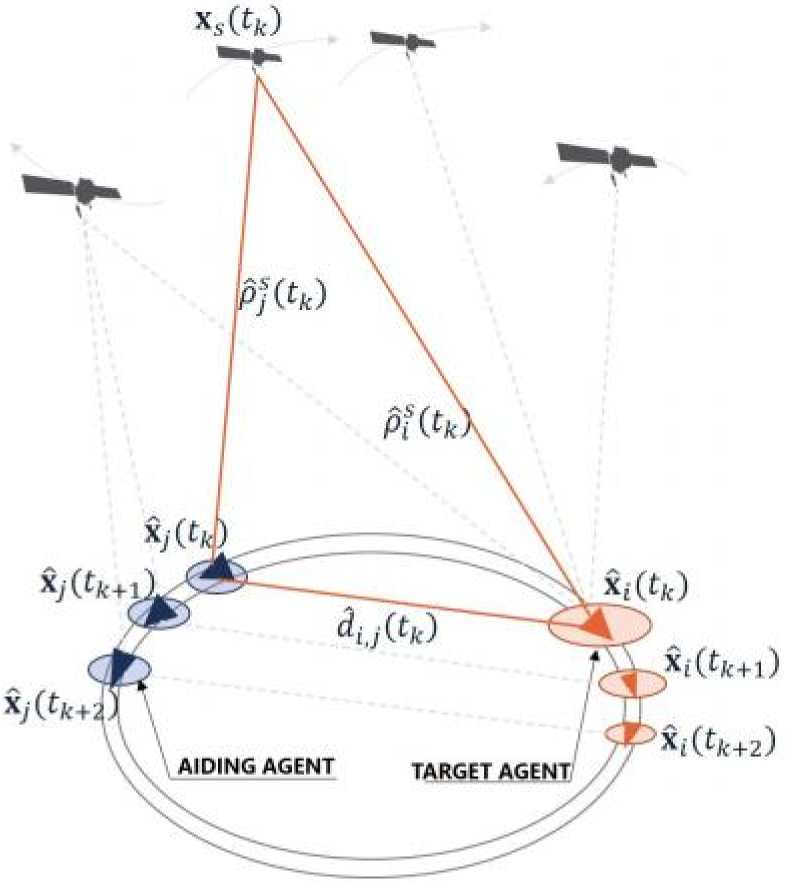

Figure 7: Collaborative positioning example *[21]*

One example of collaborative positioning would be satellite navigation combined with the recipients of the data cooperating to aide accuracy of the location. In Figure 7 we see an example of a Global Navigation Satellite System (GNSS) being used by vehicles where the target agent collaborates with another aiding agent to gain more accurate positioning data for itself. Research suggests that this would be improve position accuracy by roughly 11% in urban areas [21], which can be a harsh context for positioning systems. This is directly applicable to construction sites which can be just as harsh for positioning.

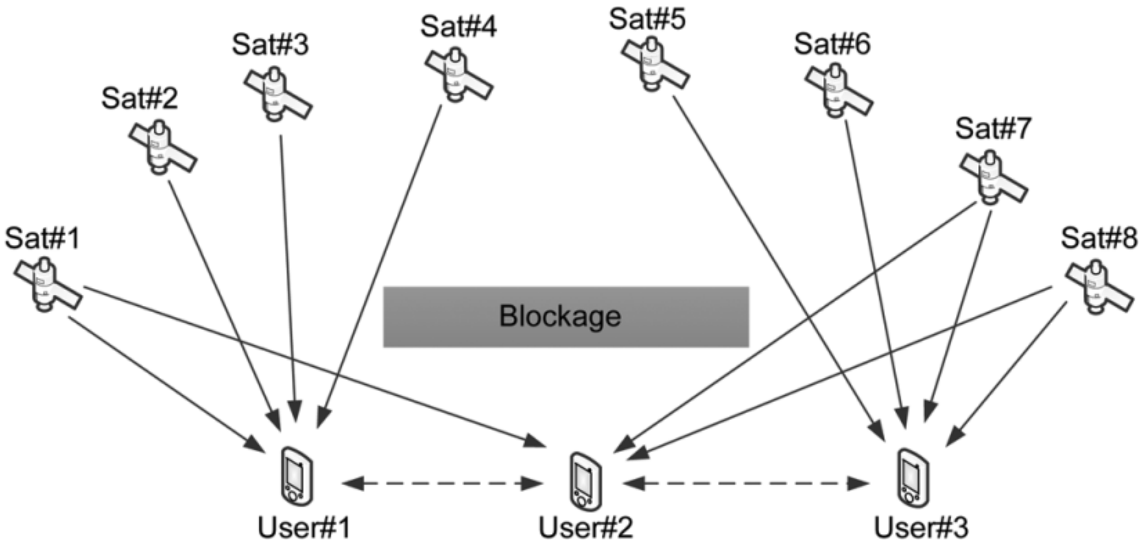

Figure 8: Collaborative positioning with GNSS and mobile devices *[22]*

In Figure 8 we see an applicable example of collaborative positioning for users or workers, when there's blockage interfering with satellite positioning. This situation is very common in construction sites, especially ones that use materials that block signals like concrete or steel. In the case of GNSS positioning, research suggests that collaborative positioning is always more accurate or equal to the accuracy of standalone positioning by GNSS [22].

Collaborative positioning is not limited to satellite navigation and it can be applied to different types of positioning methods. It can be deduced that with other forms of positioning, collaboration between the entities would always prove beneficial for the accuracy. The thought of workers and machinery collaborating to achieve more accurate location data is completely feasible.

Position collaboration over the Wi-Fi broadcasted over the communication range is already possible and it can be implemented without impacting the battery life of devices heavily [23], which suggests that collaborative positioning can be utilized on a construction site. The benefits from increased accuracy should directly correlate for the safety and efficiency of construction sites that utilize positioning data.

2.7 Sensor Fusion

Sensor fusion as the name suggests means combining the sensory data from different kinds of sources. The goal of the fusion is simply to have more information which leads to more accurate results. Sensors and sources like accelerometers, global positioning system (GPS), Microelectromechanical systems (MEMS) and more can all be fused.

Fusing Wi-Fi and UWB for example, has proven to be an effective way for high-speed positioning, which showed several improvements over the conventional methods [24].

An article about the location and tracking of first responders suggests fusing different sensors would be beneficial for accurate positioning systems [25]. With the fusion of GPS, UWB and inertial MEMS sensors the system could achieve better results for both outdoor and indoor navigation for the first responders. This information can be translated for construction use, where different sensor fusions could be utilized in outdoor and indoor navigation to cover the losses from the challenges each of the environments provide.

On construction site indoor and underground areas, it is likely that the signal for sensors like GPS is rather weak, therefore other means of sensing would be needed for accurate results. UWB, WLAN-based positioning and inertial measurements work better indoors which means fusing them would be great in the given setting. As there can be lots of obstacles and blockers for positioning signals, fusing different measurements together would ensure a better overall indoor navigation accuracy.

In complicated environments such as the indoor areas of a ship, research suggests the fusion of mobile device Wi-Fi and UWB sensors can lead to significant improvements in the accuracy [24]. The research mentioned an error range of 2-3 meters in a very complicated environment, which is promising for construction site use which most likely are not as complex as a large ship mostly made out of steel.

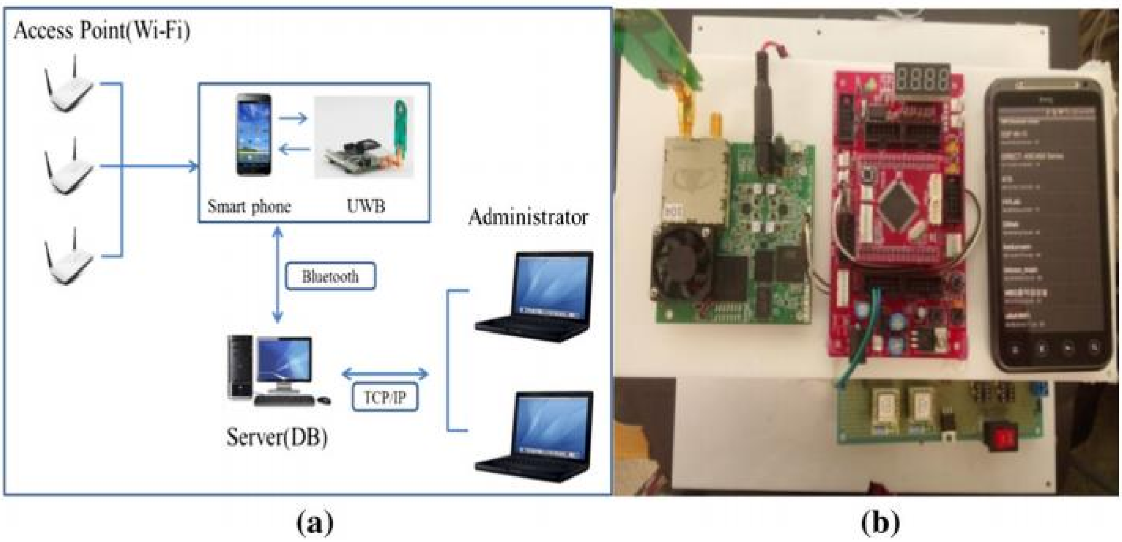

Figure 9: a) System architecture b) hardware for receiving Wi-Fi and UWB signals *[24]*

In Figure 9 we see an example of the system architecture and the hardware needed for the equipment used in indoor navigation inside the ship. The complete solution doesn't take very much space and only requires a mobile device to be carried by the entity that we want to locate. Another research also points out the benefits of indoor sensor fusion with average error being reduced 2 – 3 meters [30].

Outdoor areas of a construction site can vary in sizes and the phase of the construction also affects them. The availability of transmitters in outdoor areas might not be sufficient as placing WLAN or UWB transmitters might prove difficult if the desired goal is to cover the entire area. GPS signal is best found in open areas where the signal is not obstructed so it is worth considering fusing it with other available signals when outdoors. For example fusing inertia measurement unit (IMU)-based navigation systems with GPS have proven to be capable of reducing the mean error in location [27, 28].

As sensor fusion been proven beneficial for both indoor and outdoor uses it leads to questions about the entity locations on construction sites. Workers operate both indoors and outdoors, but certain machinery, depending on the project, might rarely go to an indoor setting. For the entities that can exist both indoors and outdoors, some logic needs to exist to determine which is the case. Geofencing could be used to determine in which setting the entity is located.

Some technologies for navigation can be expensive and require lot of space and power when looking for the most accurate variant, such as high-accuracy inertial navigation systems. Sensor fusion allows to use cheaper and power-efficient variants with less accuracy from different types, which results in better accuracy with less power used and better cost efficiency. Overall complexity of the system might be cumbersome to manage if considering covering an entire construction site with different sensor types and fusing them depending on the environment.

2.8 Smartphones

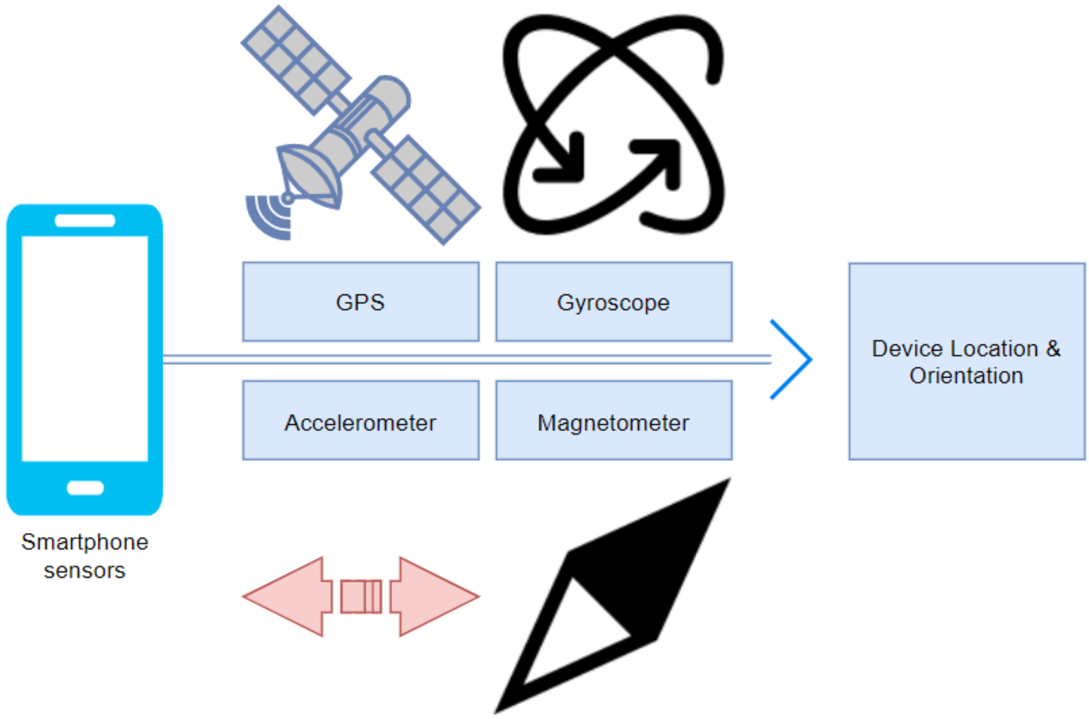

Figure 10: Common smartphone location-related sensors

Personal mobile devices come equipped with multiple common sensors as seen in Figure 10, that can be utilized in creating a location aware construction site. Most people carry a smartphone with them at all times, which is very convenient, as the sensors in the devices can be used to pick up and interpret signals from various sources. For basic navigation use the key sensors that are usually found in smartphones are magnetometer, also known as a compass, which is able to give a relative reading towards earth's magnetic pole. Usually together with a magnetometer a GPS sensor is found, which allows to determine the devices location from satellites.

Mobile devices are capable of inertia measurements through the gyroscope and accelerometer sensors. The gyroscope measures angular velocity around three rotational axes which allows calculating how the orientation of the phone changes. The accelerometer as described earlier measures changes in acceleration in three axes. Fusing together the measurements from the accelerometer, gyroscope and magnetometer it allows the calculation of the absolute orientation of the phone.

In location aware construction sites, it makes a lot of sense to utilize the already existing location-capable personal devices in the system instead of adding something extra for the workers to carry or embedding a receiver in worker badges for example. It would be very cost-effective to build a software for mobile systems and only utilize separate receivers and transmitters for machinery and other entities. Smartphones have already proven to be effective in location systems indoors and outdoors while utilizing different types of methods, collaborative positioning and fusing sensor data [10, 12, 24].

Not only could the smartphones act as a navigational tool to track the location of the workers it could act as an early warning or alarm system for the possible dangers, which would lead to the improvement of overall construction site safety. A software could send notifications to the users of the mobile devices in different situations, such as entering a dangerous geofenced area or a danger like trucks approaching. Notifications could also be played if moving away from machinery that shouldn't be left unattended. One notable challenge with this approach is the possible noise on construction sites that might prevent a worker from hearing the notification.

Worksite efficiency can be improved with internal worksite navigation tools. If one were to find something on a large construction site without knowing where it is, it would be obvious that it could take a while. If the location of other entities such as site foremen, certain equipment and facilities like warehouses and toilets were known, a visual navigation system on the workers smartphone could lead them to where they want to go instead of guessing and asking around for the same information. Navigation using a mobile device is already very commonplace for the average smartphone user and there are plenty mobile navigation applications available.

The battery life of smartphones is currently an issue as logically the more services and features that run on the device, the more power-hungry the whole process becomes. Having to charge the device in the middle of work would not be efficient. When implementing a location aware construction site that requires mobile devices on the workers, battery consumption is important aspect to consider, since once the battery runs out there is no tracking or warning available for that entity. One solution to this would be providing power banks for the workers to extend the battery life of their devices.

2.9 Robustness, security and privacy

In a location aware construction site with multiple sensing devices there will be the chance that some of them will be connected to the internet, subjecting the system to the same security and privacy issues faced in Internet of Things (IoT). A system consisting of multitude of transmitters, receivers and devices all interconnected and collecting and sharing data of location and other things is subject to having data that falls under categories that should be protected. Many of the security and privacy-related threats fall under non-GNSS positioning.

Table 1: Non-GNSS security threats and mitigations *[29]*

Security threat	Description	Mitigation
Database corruption: reference locations	Entering wrong reference locations either intentionally or unintentionally, due to human errors or faults in positioning technology	Outlier detection and database consistency monitoring
Database corruption: wrong RSS	Due to errors in maps, floor plans or other geographical information, erroneous RSS fingerprints are generated when computing them from these sources	Outlier detection and database consistency monitoring
Environment change	RF infrastructure: Addition, removal, or location change of ANs. Propagation environment: Changes in building structure or furniture	Outlier detection and database consistency monitoring
RF interference	Decreases the quality of localization, in extreme cases prevents signal reception and localization. Examples: narrow band interference (jamming) and wide band interference (affects mostly cellular 3G)	Interference detection and warning or mitigation
Malicious nodes	Sends fake or erroneous information, e.g., spoofing	Identification and exclusion
Privacy threat to making the IoT device position known	Identity theft based of IoT device location or other vulnerabilities regarding to the loss of location privacy	Data perturbation or obfusca-tion methods
Trusted network issue	In network-centric positioning network has full control on positioning informa-tion. This can be misused by untrustable networks	Authorised access support

In Table 1 we see a summary of the main security and privacy-related threats in non-GNSS positioning for IoT devices. A key thing to notice from the table when it comes to construction sites is the environment change, as one key aspect in construction is that the site is constantly changing. This will be a challenge if reference points are used, which are common in WLAN-based location for example. The access nodes and reference points are very likely to change, thus the database for reference points needs to be closely monitored. What comes to different localization technologies seen in Table 2, the presence of environment change persists as a threat for many of the technologies that could prove useful for construction site use.

Table 2: Non-GNSS based localization technologies and their security threats *[29]*

	Technology									
Security threat	WLAN	802.11az FPS	Bluetooth	RFID	UWB	WSN	Cellular	LoRa and other LPWAN in ISM bands	NB-IoT / NB-CIoT	M2M (eMTC / LTE MTC)
Database corruption: reference locations	x	x	x	x						
Database corruption: wrong RSS	x	x	x							
Environment change	x	x	x	x	x (RSS)					
RF interference	x	x	x	x	x	x	x	x	x	x
Malicious nodes (affect unlicensed bands)	x	x	x	x	x	x				
Trusted network issue	x	x	x	x	x	x	x	x	x	x

Location-based services also come with complicated legal and policy issues, that appear in the form of spectrum requirements, standardization, privacy and data protection. These aspects need to be addressed when utilizing location on a construction site [29].

Especially with mobile devices that share their location for a system, there is personal data protection to consider. The law covers a lot about privacy and personal data protection in Europe. There is a lot of data associated with geographical positioning, either implicitly and explicitly [30]. Article 4 (1) of the General Data Protection Regulation (GDPR) (EU) considers location data as one of the 'identifiers' of personal data. This means that the location data of workers on a construction site can be classified as personal. This does not prevent data collection and utilization, but it does have some requirements including requiring consent (Art. 7 GDPR).

A survey also suggest means to protect the privacy of location aware systems. Such methods can include data perturbation and other obfuscation methods that aid preserving the privacy of such system. This could include replacing the true position of entities with a fake position when the data is transmitted. Other alternative ways include perturbation method, where the true location is embedded in noise. Other suggested ways to protect the communication between entities in the system are some cryptographic techniques, which enable more secure communication inside a IoT network. For example, the transmissions could be protected, and a cryptographic message authentication could be used with a shared key. [29]

3. POSITIONING ON WORK SITES

As a summary of the literature review from chapter 2, the findings will be summarized in the beginning of this chapter in two tables. In Table 3 there is a summary of suitability of different sensors for construction site use based on the reviewed literature. In Table 4 there is a summary of the advantages and disadvantages of fusing different sensors together in relation to construction site use.

Table 3: Suitability factors of different sensor technologies

	Technology				
Suitability factor	WLAN	UWB	GPS	IMUs	RFID
Accuracy indoors		✓			✓
Accuracy outdoors		✓	✓		✓
Viability indoors	✓	✓			✓
Viability outdoors			✓	✓	
Suited for constantly changing environment			✓	✓	
Smartphones	✓	✓	✓	✓	

RFID-based solutions can be left out from consideration as for them to work properly, they would need a separate RFID reader with a proper antenna for proper results as they do not work well enough with personal devices that the construction workers might carry with them. As expected, the indoor positioning aspect is most suited for WLAN and UWB-based solutions. For outdoor use the best use case is found with GPS combined with IMUs.

Table 4: Summary of different sensor fusions

Sensor Fusion	Advantages and disadvantages
WLAN + UWB	Existing research on suitability for indoor navigation. Decent accuracy indoors. Not properly suited for outdoor use. Doesn't do well in constantly changing environments
WLAN + GPS	GPS works best unobstructed outside while WLAN usually best accessible indoors. Not necessarily accurate enough according to research, but better than singular use of each overall [31].
WLAN + IMU	Movement measurements from IMUs are important outdoors, conflicting with WLANs mostly operating indoors. Magnetometer readings are influenced by building structures (metal).
UWB + GPS	A better variant of WLAN + GPS to overcome signal blockages with signs of good accuracy in fusion. Use of UWB outdoors can prove challenging in construction use, while GPS is likely to be blocked indoors.
UWB + IMU	Research shows that combining UWB, IMUs and GPS can prove very accurate on the field [32], the use for this fusion overall on construction site is limited.
GPS + IMU	Promising use case for outdoor uses on construction site for machinery tracking. Allows for entities to have a position, speed and a direction. Research shows that combining GPS and IMU can be very accurate [32].

Table 4 allows us to start forming an idea of the best possible sensor usage for construction site use. Indoor positioning could be handled by WLAN and UWB as they are the best suited and work well together. Outdoor navigation is very suited for GPS fused with IMU and perhaps even UWB, as research suggest excellent results from pairing the three in positioning accuracy [32]. The next section takes a dive into literature to see what of these sensors and technologies have been tested or implemented in construction site use.

3.1 Already proposed methods

Research already exists in UWB positioning systems especially indoors but uses for the technology in construction site also has some examples. An article describes the use of UWB to track a crane in real-time in order to prevent accidents and it proved very capable of accurately tracking the movements of a crane [33]. This shows great potential for UWB usage in position estimation for accident prevention. Some experimental evidence of low-cost use of the UWB-technology already exists [34], which makes the technology more appealing for construction sites as construction companies are concerned about their bottom line. Research also shows that UWB can be a viable option in a construction site for positioning with varying types of elements and blockages that occur in a normal construction project [35], which still showed decent accuracy for positioning even with occlusions from metal materials.

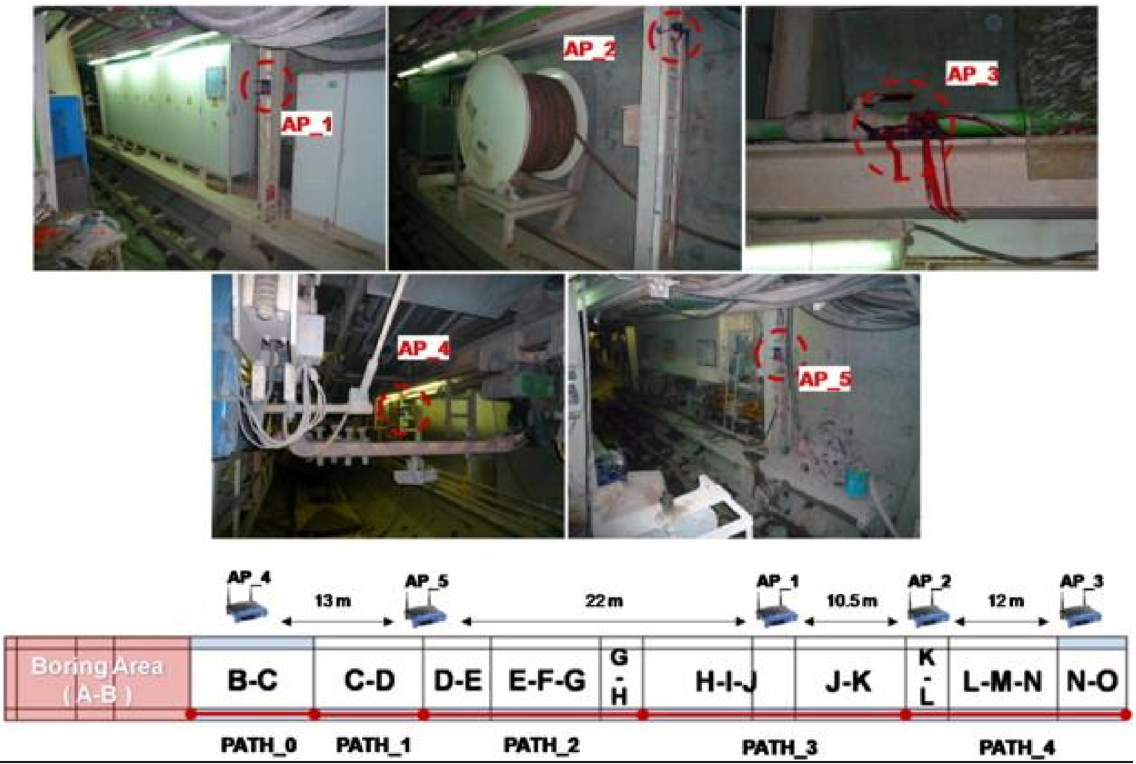

Figure 11: WLAN-positioning in an actual construction site *[36]*

For construction use, WLAN-based solutions are less documented. This might be because of the WLAN-network being usually set up in later phases of the construction instead of early phases. Placing the necessary access points before any proper room structure exists does pose some challenges, since it will take quite some time from the beginning of a construction project until the phase where buildings under construction are far enough that access points could be placed in their correct place. That does not mean the access points can’t be placed in random temporary places just for locating purposes. Some research has shown that WLAN-based positioning using fingerprints indoors, as seen in Figure 11, in an actual construction site setting can result to around 5 meters accuracy with access points evenly spread out through complex tunnel areas [36]. It was sufficient for tracking only the approximate locations of the workers within the construction site. The application of the system showed evidence of its simplicity and cost-effectiveness, but for proper use the accuracy would need to be improved.

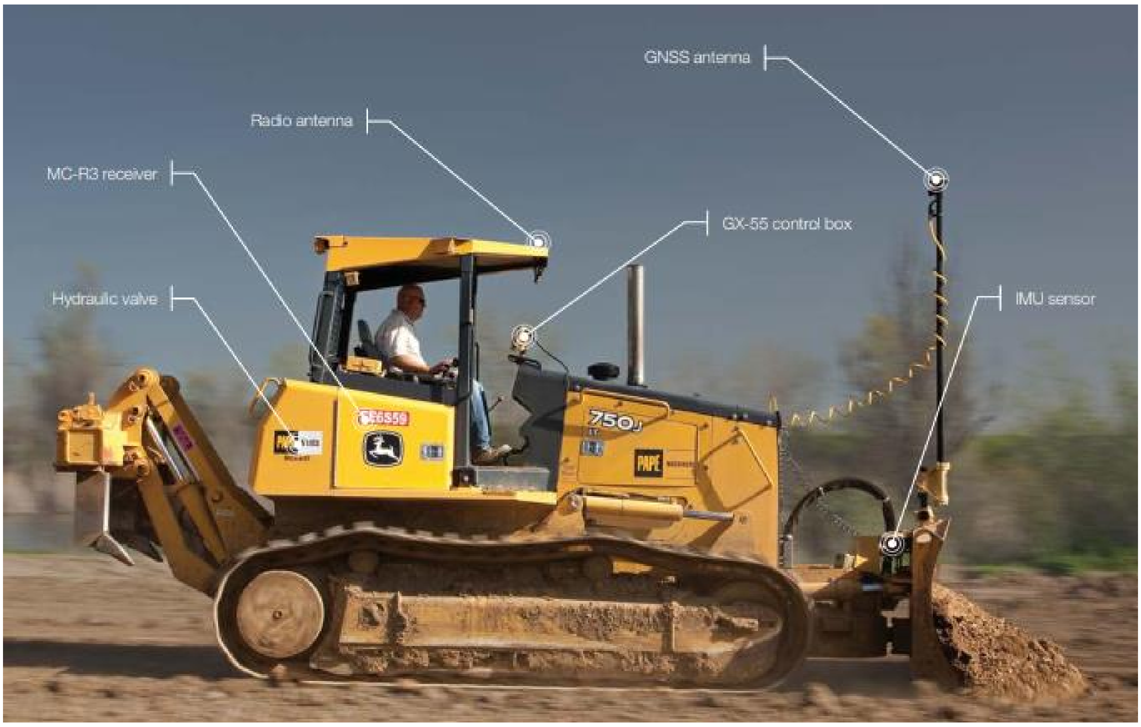

Figure 12: Topcon sensors on a dozer *[37]*

Inertia measurements on construction sites is already a reality and in use. For example, Topcon offers solutions and sensors for construction use that can be used to accurately track the movements of construction site machinery, as seen in Figure 12. They have a fully implemented solution for tracking dozers utilizing different kinds of sensors, including IMUs for example [37]. The movements, especially the speed and direction, are crucial bits of information especially for safety. IMUs combined with indoor positioning have also been researched with signs that they be used for safety monitoring and preventing accidents with an auto-warning system [38], which supports the ideas presented earlier in this thesis for possible warning systems that utilize IMUs. The most important aspect for inertia measuring seems to be safety albeit it provides some additional accuracy for positioning also, making it a great addition for construction sites. Research also suggests that IMUs can be used on construction sites to track the activities with low cost [39].

The benefits of geofencing are clear. Constructions sites are full of dangers and marking those dangers with a perimeter to keep people out is really useful as well as marking out areas that entities should stay within. A safety, health and wellbeing magazine IOSH has published information about the benefits of geofencing in construction site [40]. The article hints at automated alarm notifications that could be sent to prevent accidents, especially ones where machinery could risk collision with a worker, which goes well with earlier discussion. Geofencing also could be used to protect the expensive assets and machinery if they are detected leaving their designated area, as suggested by another article [41].

A review of the top indoor positioning systems for construction site lists the Wi-Fi as the best option for construction sites [42]. For some reason the review holds Wi-Fi to a higher standard even though it's accuracy, power consumption and response time are significantly worse compared to UWB for example. According to the review, the only aspect Wi-Fi positioning beats UWB in is the cost.

Literature about collaborative positioning, for example between mobile phones in construction site use is not vast. Research on the subject is definitely in place as collaborative positioning fused with other positioning technologies can prove to be an accurate solution for tracking position in environments such as construction sites, where there are multiple workers working in proximity of each other.

3.2 Storing data

In this section a suggestion will be made to store snapshots from the location data collected from the construction site in order to improve safety and navigational efficiency. A snapshot of the data in this case means the state of the construction site as well as location of each entity on the construction site at a given time.

The state of the construction site could for example be a virtual model of the current phase of the construction site that binds real world coordinates to virtual coordinates for data storage and analysis purposes. The model should periodically update based on the progress of the site so that the virtual and physical coordinates stay synchronized so that the data collected stays relevant. A snapshot could for example refer to a version of the modeled construction site at the time of saving. This would prove useful if reviewing older incidents or states of the construction site in the past before the construction site changed, for example a new building got erected. A snapshot would also contain the current position, potential movement vectors and orientations. Information about the positioning of entities is useful in many ways. It can be utilized for investigating incidents and acting as the last known location when there is loss of coverage for the positioning system.

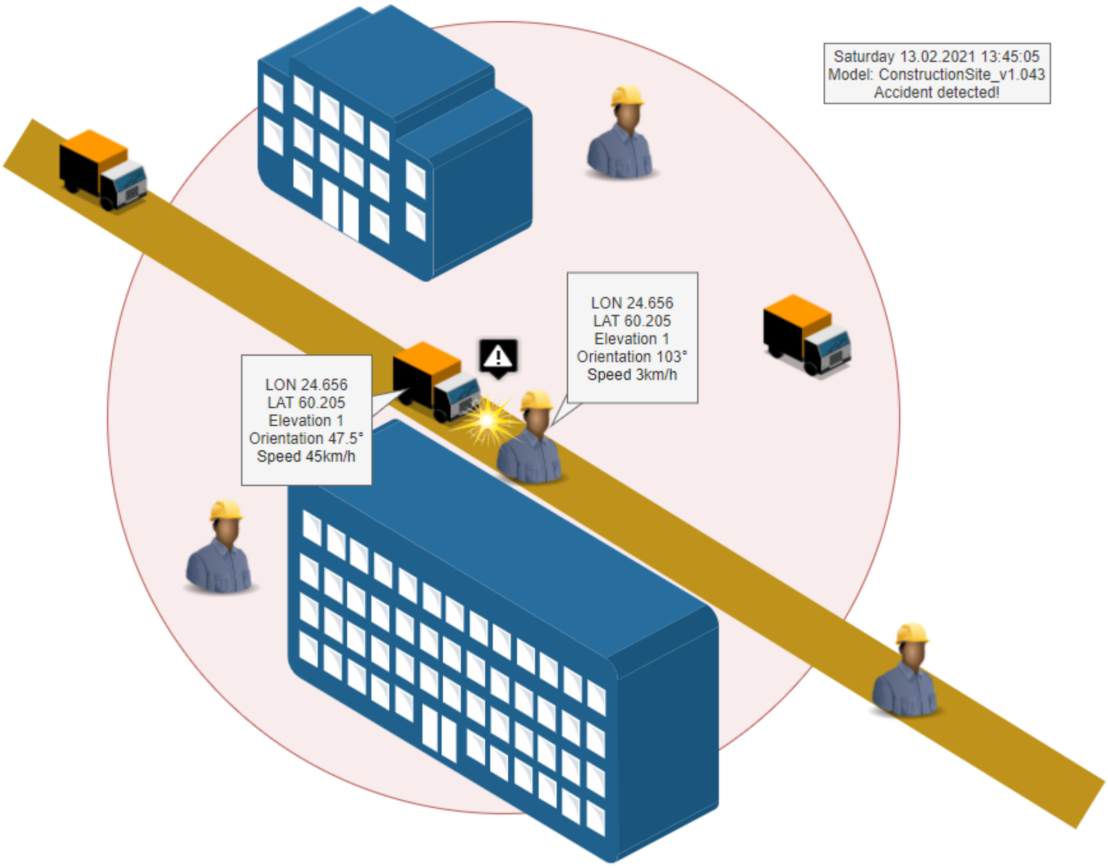

Figure 13: Snapshot of a construction site when an accident occurs

When an accident such as seen in Figure 13 or a situation which invokes an automated alarm is detected the snapshots from the near past should be permanently stored for analysis, especially within the geofenced area around the incident position. Construction site safety and security is very important to contractors and construction companies and reviewing accidents from a snapshot would be extremely beneficial for figuring out what happened. If a snapshot contains a link to the state of the construction site, for example, a 3-dimensional model of the current state when an accident happened, it could be used to virtually analyze what lead to an accident and how to prevent it in the future. Key factors could be investigated from the snapshot such as speeds, orientations of workers/equipment, pathways used on the construction site and possible line-of-sight hinderances that occur from buildings or the landscape.

A sufficient interval for snapshotting should be along the lines of 5-10 seconds, which should cover most use-cases described. It shouldn't be necessary to keep every single snapshot stored forever, instead a system could collect and store only the most recent snapshots from the past hour before deleting them. A set number of snapshots could be stored permanently for each day/week depending on the need for history data of the state of the construction site. This should keep the data usage down whilst still providing useful information about the past of the construction site for analytics. If the models of the virtualized construction site are stored, a snapshot of the state only needs to contain a reference to that version of the model that existed at the time of taking the snapshot, which would take very little resources.

3.3 Visual systems

According to the market research of Topcon Technology Finland (TTF) in the past years, a software solution that covers the discussed topics in this thesis does not exist yet. A full visual system for a smart construction site doesn’t exist yet but small parts have been implemented in different existing visual systems. A software would need to fulfill the following requirements and provide a graphical user interface for them to fully cover what is discussed in this thesis.

- Virtualization of a construction site to an accurate and up to date model or map
- Tracking the location of each moving entity in real time (worker / equipment etc.)
- Allowing virtual boundaries (geofences) to be set for the site digitally
  - Detecting what is in / entering / exiting the boundaries
- Tracking the direction and speed of entities
- Marking locations on the construction site
- Alerting a worker or equipment operator of possible danger
- Storing snapshots of location data history

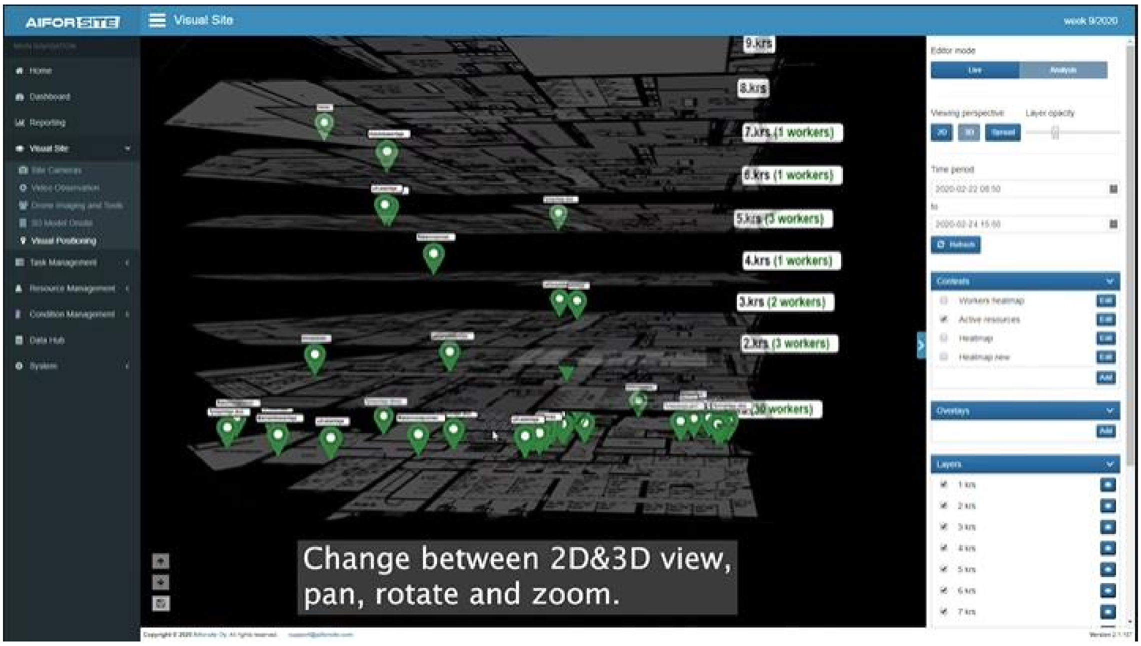

Figure 14: Visual site software by Aiforsite Oy [43]

The company Aiforsite Oy based in Espoo, Finland provides a visual system that fulfills parts of the requirements. Their solution allows creating models and maps of the construction site using drone technology. Their implementation, as seen in Figure 14, of modeling and positioning seems promising and in their video material they show evidence that they can identify the position of workers accurately on different floors of a building. Their system implementation shows evidence that a construction site can be modeled and visualized, and location can be tracked on floor-level accuracy. [43]

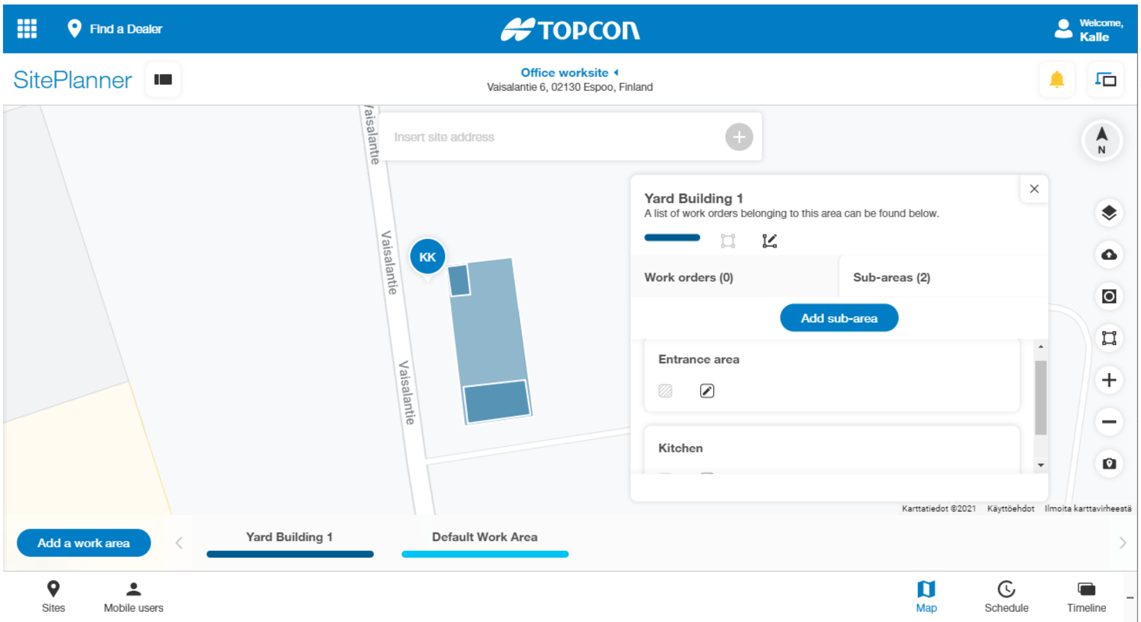

Figure 15: SitePlanner application by TTF [44]

SitePlanner is a visual scheduling tool for worksites developed by Topcon Technology Finland as seen in Figure 15, which also includes some location awareness features for construction site use. In SitePlanner, you find the ability to create virtual areas and subareas on a construction site in a 2D map interface. A bounding area can be set for the site which detects subcontractors ("KK" seen in Figure 12) inside the boundary whose location is tracked in real-time through their mobile devices from SitePlanner mobile application. Here we see evidence of a software with some form of virtual boundaries, geofencing and real-time worker tracking through their mobile device. [44]

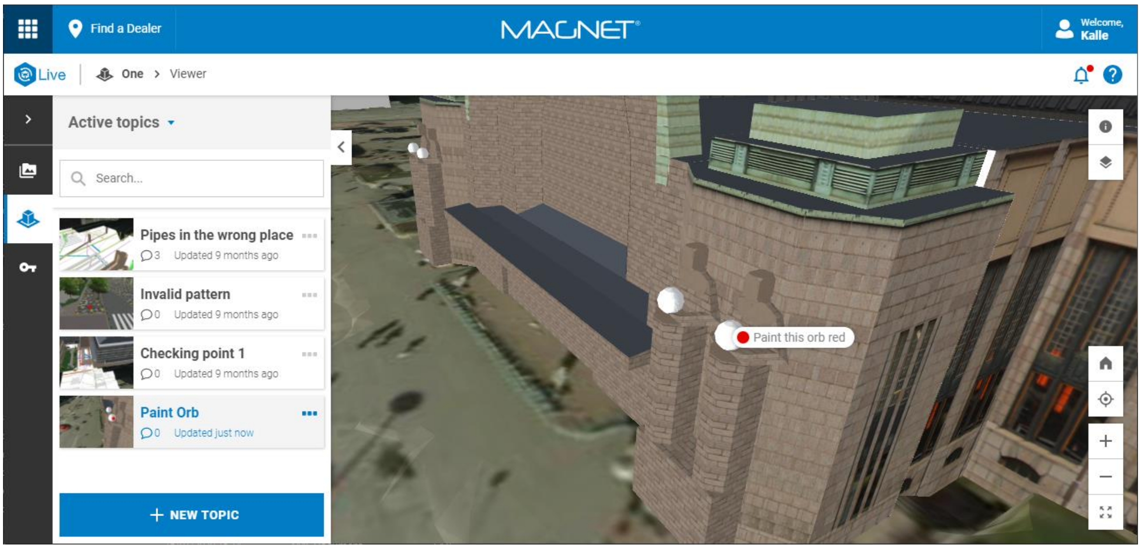

***Figure 16: MAGNET Live model software by TTF** [45, 46]*

MAGNET Live is a construction-related model inspector also developed by Topcon Technology Finland as seen in Figure 16. It allows freely navigating models with different devices and marking out points of interests using "Topics". Each model can be geographically calibrated to match the real-world coordinates to the model coordinates. Theoretically workers could use this application with a model of their construction site to find marked points of interests and get to know the environment beforehand in a virtual setting. [45, 46]

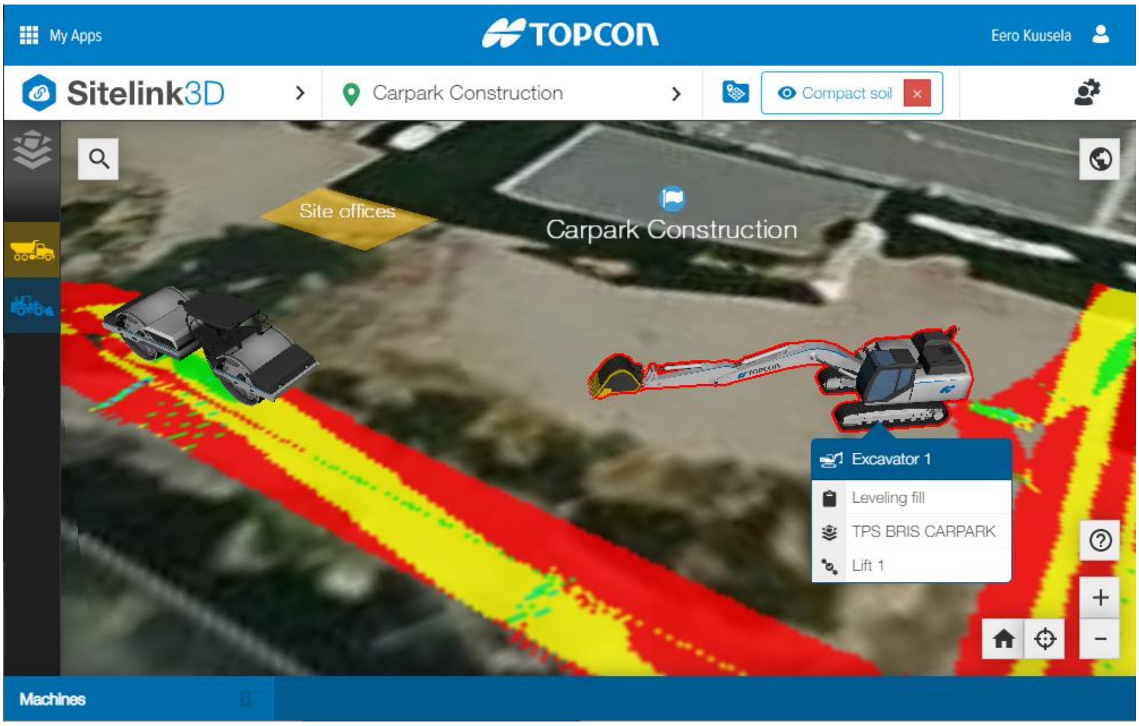

Figure 17: SiteLink3D software by Topcon *[47]*

SiteLink3D is a 3-dimensional construction management software developed by Topcon which features accurate tracking for worksite machinery as seen in Figure 17. The machinery can be equipped with different kinds of Topcon-developed and manufactured sensors such as IMUs, which allows the software to model them virtually, tracking their position, orientation, speed and even the position of the boom on an excavator for example [48]. The software is able to detect which areas the machinery is on and even make them interact with the virtual model. This shows evidence that tracking moving machinery and virtualizing them is possible and already in use.

Current visual software systems according to the market research of TTF, even if you combine them all together into a single application, do not fulfill all the requirements set and discussed in this thesis. Current solutions lack a refined solution for storing snapshots of site location data, proper velocity and direction tracking for moving entities and any form of pre-emptive warning system for accident-prevention. According to TTF there is already an existing customer demand for a software solution that covers everything said in this thesis. One issue that has been voiced by the construction companies from such systems is that they claim there is not enough evidence that taking such systems into use would be cost-effective. Further research on exactly how much money could be saved with fully location aware construction site would be in place.

3.4 Loss of coverage

In a smart location aware system one of the key aspects would be that all entities remain trackable with their location known, yet in many cases this does not actually happen and loss of coverage for positioning data occurs. Such loss can originate from hardware faults, signal losses, software faults or simply the battery running out on devices that handle the tracking. Discussion in this chapter reviews different cases of coverage loss in construction site and how they could be countered. If some individual's equipment that is connecting them to the system fails it usually renders them unable to utilize the system for navigation and for automated warnings. This is something that is hard to counteract with anything else than construction site rules and regulations on what a worker should do when faced with a problem.

In the case of a worker losing their signal, it renders them unable to receive warnings and navigate as mentioned before. For navigational efficiency on a worksite it would still be useful to find that worker, even if their current location is not known. A smart construction site is able to schedule the work in a fashion where the location of the work is known virtually. A set of questions can be made of the workers position after they have fallen off the network of positioning data.

- Which direction and what speed were they traveling?
- Were they inspecting the location of another entity?
- Were they navigating towards some target?
- Where should they be according to their schedule?
- Were they detected operating machinery?

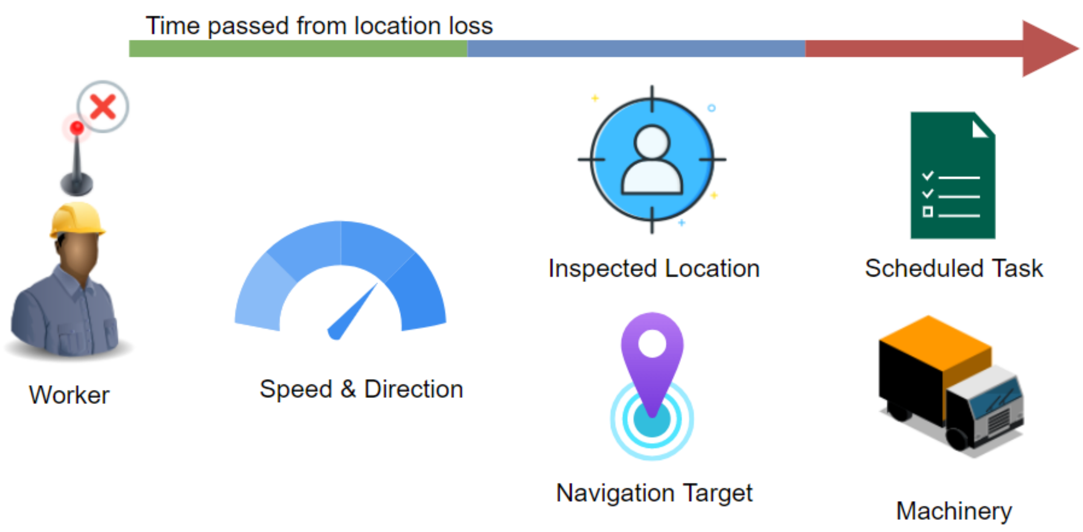

Figure 18: Locating options when signal is lost

Depending on the time passed from the signal loss, different methods become less viable as seen in Figure 18. From the initial signal loss, the best estimation for the location comes from the direction they were heading. This would only cover the first minutes after the loss of location data from the worker.

An educated guess or an estimation about workers location can be made based on what they were inspecting or where they were navigating to. If a software allows the worker to find the location of tools or other personnel on the worksite, it is not a far-fetched guess to make that that is the direction they are heading to. If they have turned on navigational features towards the entity, one can say with a relatively high chance that they are heading towards that location, so instead of trying to estimate the location of the worker whose signal was lost, the system could locate the same navigational target and most likely end up in the same place. Inspecting and navigating towards entities is also subject to time and when enough time is passed the worker might've already been where he had to be and moved on. This can also be estimated from the time it would take to travel from the position where the signal was lost to the inspected navigational target.

Least time sensitive of location estimation of a worker whose location can't be tracked is a possible location-aware scheduling system and machinery that detects their operator. If a software has accurate models of the construction site along with schedule and location data of the work that is being done, a straight forward conclusion can be made that the assigned workers for that task should be around the task location during the time it is scheduled. It is very common in construction management software to have work assigned to workers using tickets and tasks digitally. Location aware task scheduling with assigned workers has been implemented in some software already, one of the examples would be SmartSite SitePlanner developed by TTF [44].

If a worker is detected operating machinery and their signal is lost, it is a reasonable guess to make that as long as the machine is operating the same worker is still operating it. This means the shift of tracking and estimating the location of the worker can be focused on finding the machinery, likely resulting in finding the worker who has lost their signal. Rules and regulations on a construction site could be set so that the operator of machinery would not change on the fly, but instead somehow registered to the machinery through some protocol, which would allow the machine to detect if the current operator has stopped operating it.

When the real-time positioning data of heavy machinery is lost, it poses great issues for safety prevention and the suggested automated warning systems. Same applies to everything discussed about machinery operator detection with geofencing and detection if machinery leaves its designated location. At bare minimum the machinery should be able to notify the operators that their location systems are malfunctioning and some protocol to be set on how to behave and operate the machinery when systems are unable to track it. A temporary replacement for location data can be achieved from tracking the operator instead.

On top of suggestions made here there has been research on neural networks and deep learning and their uses to predict movements, which could be utilized in scenarios where a worker becomes unreachable. Research has already modeled human trajectories in crowded social setting with good accuracy, but this only covered brief distances [49]. Most of the research done under neural networks and path prediction seems to only cover shorter distances based on context and typical behavior [50, 51]. Utilization of neural networks on construction sites could prove useful if enough data could be collected and the predictions made for longer distances when combined with the other data mentioned in this section. Difficulties do arise from the constantly changing environment of the construction site and from the fact that every construction site varies in type, layout and size.

4. ACCIDENT PREVENTION AND SAFETY

Key aspect of accident prevention and construction site safety is geofencing and its various uses that have been described in this thesis. This section will cover some calculations to figure out relations between accuracy of construction site positioning, geofencing and an automated alarm system. With the results of the calculations conclusions can be made on what methods are suitable for positioning when accident prevention and safety is in question.

4.1 Proximity alert calculations

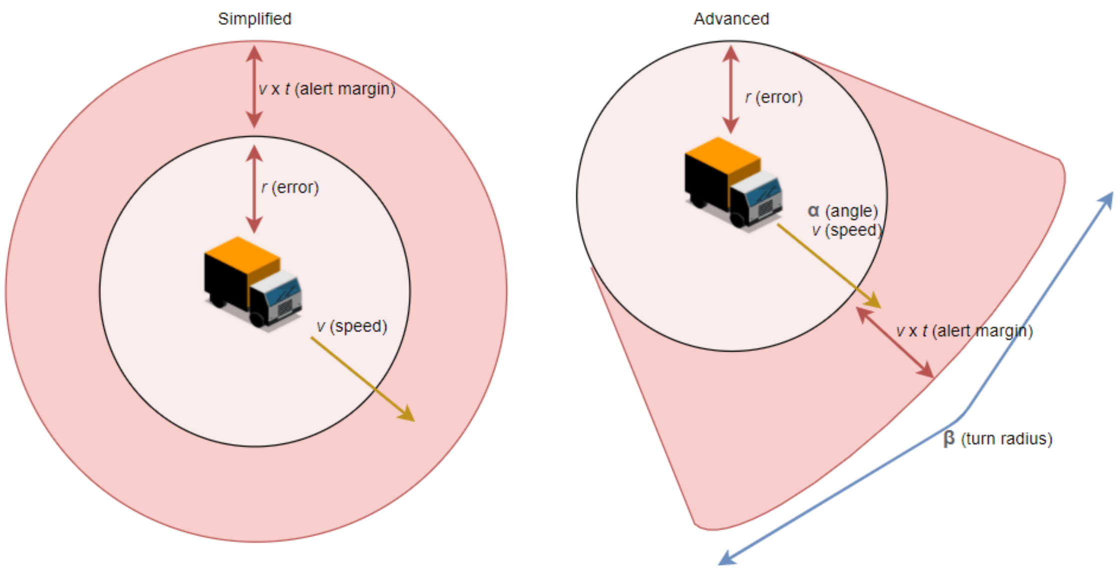

Figure 19: Simplified and advanced calculations for collision alert radius

Figure 19 shows a simplified and the actual advanced use for possible automated proximity alerts based the position and velocity of an entity on a construction site. This could be referred to as a dynamic geofence that is dependent on the velocity, direction and accuracy of the entity. The error of the positioning serves as the radius r_{error} which should accurately represent within what area the entity exits for sure and the smaller the error the smaller the radius of the circle. For this thesis an alert margin value of 5 seconds will be set for the automated warning system value t_{margin}. Based on the entity velocity v, a calculation can be made for the distance of the alert margin which is vt. This gives us a total distance from the entity point with the formula:

$$d_{alert} = vt_{margin} + r_{error}$$

In the simplified version as seen in Figure 19 this would indicate the radius around the entity which would serve as an area of danger where anything inside it would serve as justification for an automated alert. Obviously this is far from reality as entities like dozers and trucks move in a certain direction mostly affected by controlled accelerations, decelerations and position of the steering wheel, thus they have a vector indicating their velocity and direction, which can be tracked with the utilization of IMUs. Heavy machinery cannot change its movement too fast and suddenly move backwards. This leads to the automated warning area being cone shaped based on the movements of the entity, where the direction of the cone is indicated by the movement angle α of the entity and the width of the cone would be dictated by the turning radius β, which indicates the turning (steering) capabilities of a truck for example.

Table 5: Relation between speed and positioning error in alert distance

	Positioning error in meters																			
Speed	0,5 m	1,0 m	1,5 m	2,0 m	2,5 m	3,0 m	3,5 m	4,0 m	4,5 m	5,0 m	5,5 m	6,0 m	6,5 m	7,0 m	7,5 m	8,0 m	8,5 m	9,0 m	9,5 m	10,0 m
1 m/s	5,5 m	6,0 m	6,5 m	7,0 m	7,5 m	8,0 m	8,5 m	9,0 m	9,5 m	10,0 m	10,5 m	11,0 m	11,5 m	12,0 m	12,5 m	13,0 m	13,5 m	14,0 m	14,5 m	15,0 m
2 m/s	10,5 m	11,0 m	11,5 m	12,0 m	12,5 m	13,0 m	13,5 m	14,0 m	14,5 m	15,0 m	15,5 m	16,0 m	16,5 m	17,0 m	17,5 m	18,0 m	18,5 m	19,0 m	19,5 m	20,0 m
3 m/s	15,5 m	16,0 m	16,5 m	17,0 m	17,5 m	18,0 m	18,5 m	19,0 m	19,5 m	20,0 m	20,5 m	21,0 m	21,5 m	22,0 m	22,5 m	23,0 m	23,5 m	24,0 m	24,5 m	25,0 m
4 m/s	20,5 m	21,0 m	21,5 m	22,0 m	22,5 m	23,0 m	23,5 m	24,0 m	24,5 m	25,0 m	25,5 m	26,0 m	26,5 m	27,0 m	27,5 m	28,0 m	28,5 m	29,0 m	29,5 m	30,0 m
5 m/s	25,5 m	26,0 m	26,5 m	27,0 m	27,5 m	28,0 m	28,5 m	29,0 m	29,5 m	30,0 m	30,5 m	31,0 m	31,5 m	32,0 m	32,5 m	33,0 m	33,5 m	34,0 m	34,5 m	35,0 m
6 m/s	30,5 m	31,0 m	31,5 m	32,0 m	32,5 m	33,0 m	33,5 m	34,0 m	34,5 m	35,0 m	35,5 m	36,0 m	36,5 m	37,0 m	37,5 m	38,0 m	38,5 m	39,0 m	39,5 m	40,0 m
7 m/s	35,5 m	36,0 m	36,5 m	37,0 m	37,5 m	38,0 m	38,5 m	39,0 m	39,5 m	40,0 m	40,5 m	41,0 m	41,5 m	42,0 m	42,5 m	43,0 m	43,5 m	44,0 m	44,5 m	45,0 m
8 m/s	40,5 m	41,0 m	41,5 m	42,0 m	42,5 m	43,0 m	43,5 m	44,0 m	44,5 m	45,0 m	45,5 m	46,0 m	46,5 m	47,0 m	47,5 m	48,0 m	48,5 m	49,0 m	49,5 m	50,0 m
9 m/s	45,5 m	46,0 m	46,5 m	47,0 m	47,5 m	48,0 m	48,5 m	49,0 m	49,5 m	50,0 m	50,5 m	51,0 m	51,5 m	52,0 m	52,5 m	53,0 m	53,5 m	54,0 m	54,5 m	55,0 m
10 m/s	50,5 m	51,0 m	51,5 m	52,0 m	52,5 m	53,0 m	53,5 m	54,0 m	54,5 m	55,0 m	55,5 m	56,0 m	56,5 m	57,0 m	57,5 m	58,0 m	58,5 m	59,0 m	59,5 m	60,0 m
11 m/s	55,5 m	56,0 m	56,5 m	57,0 m	57,5 m	58,0 m	58,5 m	59,0 m	59,5 m	60,0 m	60,5 m	61,0 m	61,5 m	62,0 m	62,5 m	63,0 m	63,5 m	64,0 m	64,5 m	65,0 m
12 m/s	60,5 m	61,0 m	61,5 m	62,0 m	62,5 m	63,0 m	63,5 m	64,0 m	64,5 m	65,0 m	65,5 m	66,0 m	66,5 m	67,0 m	67,5 m	68,0 m	68,5 m	69,0 m	69,5 m	70,0 m
13 m/s	65,5 m	66,0 m	66,5 m	67,0 m	67,5 m	68,0 m	68,5 m	69,0 m	69,5 m	70,0 m	70,5 m	71,0 m	71,5 m	72,0 m	72,5 m	73,0 m	73,5 m	74,0 m	74,5 m	75,0 m
14 m/s	70,5 m	71,0 m	71,5 m	72,0 m	72,5 m	73,0 m	73,5 m	74,0 m	74,5 m	75,0 m	75,5 m	76,0 m	76,5 m	77,0 m	77,5 m	78,0 m	78,5 m	79,0 m	79,5 m	80,0 m
15 m/s	75,5 m	76,0 m	76,5 m	77,0 m	77,5 m	78,0 m	78,5 m	79,0 m	79,5 m	80,0 m	80,5 m	81,0 m	81,5 m	82,0 m	82,5 m	83,0 m	83,5 m	84,0 m	84,5 m	85,0 m
16 m/s	80,5 m	81,0 m	81,5 m	82,0 m	82,5 m	83,0 m	83,5 m	84,0 m	84,5 m	85,0 m	85,5 m	86,0 m	86,5 m	87,0 m	87,5 m	88,0 m	88,5 m	89,0 m	89,5 m	90,0 m
17 m/s	85,5 m	86,0 m	86,5 m	87,0 m	87,5 m	88,0 m	88,5 m	89,0 m	89,5 m	90,0 m	90,5 m	91,0 m	91,5 m	92,0 m	92,5 m	93,0 m	93,5 m	94,0 m	94,5 m	95,0 m
18 m/s	90,5 m	91,0 m	91,5 m	92,0 m	92,5 m	93,0 m	93,5 m	94,0 m	94,5 m	95,0 m	95,5 m	96,0 m	96,5 m	97,0 m	97,5 m	98,0 m	98,5 m	99,0 m	99,5 m	100,0 m
19 m/s	95,5 m	96,0 m	96,5 m	97,0 m	97,5 m	98,0 m	98,5 m	99,0 m	99,5 m	100,0 m	100,5 m	101,0 m	101,5 m	102,0 m	102,5 m	103,0 m	103,5 m	104,0 m	104,5 m	105,0 m
20 m/s	100,5 m	101,0 m	101,5 m	102,0 m	102,5 m	103,0 m	103,5 m	104,0 m	104,5 m	105,0 m	105,5 m	106,0 m	106,5 m	107,0 m	107,5 m	108,0 m	108,5 m	109,0 m	109,5 m	110,0 m

This thesis is limited to direct-path collision, meaning estimating the distance and time of collision if an entity keeps its course at its current velocity and direction towards detected danger. Table 5 consists of values with different speeds between $1\,m/s$ and $20\,m/s$ ($3.6\,km/h$ to $72km/h$) which should cover lot of the speeds in construction site from walking speeds to speed that is way too high for confined spaces like construction sites. The values have been calculated using the aforementioned 5 second margin for collision straight ahead from the current location of the entity. With walking speeds, we notice that the positioning error plays a big role in the actual alert distance. Table 6 consists of the ratios between positioning error and alert distance, using the formula

$$\frac{r_{error}}{d_{alert}}$$

Table 6: Relation between alert distance and positioning error

	Positioning error in meters																			
Speed	0,5 m	1,0 m	1,5 m	2,0 m	2,5 m	3,0 m	3,5 m	4,0 m	4,5 m	5,0 m	5,5 m	6,0 m	6,5 m	7,0 m	7,5 m	8,0 m	8,5 m	9,0 m	9,5 m	10,0 m
1 m/s	9,1 %	16,7 %	23,1 %	28,6 %	33,3 %	37,5 %	41,2 %	44,4 %	47,4 %	50,0 %	52,4 %	54,5 %	56,5 %	58,3 %	60,0 %	61,5 %	63,0 %	64,3 %	65,5 %	66,7 %
2 m/s	4,8 %	9,1 %	13,0 %	16,7 %	20,0 %	23,1 %	25,9 %	28,6 %	31,0 %	33,3 %	35,5 %	37,5 %	39,4 %	41,2 %	42,9 %	44,4 %	45,9 %	47,4 %	48,7 %	50,0 %
3 m/s	3,2 %	6,3 %	9,1 %	11,8 %	14,3 %	16,7 %	18,9 %	21,1 %	23,1 %	25,0 %	26,8 %	28,6 %	30,2 %	31,8 %	33,3 %	34,8 %	36,2 %	37,5 %	38,8 %	40,0 %
4 m/s	2,4 %	4,8 %	7,0 %	9,1 %	11,1 %	13,0 %	14,9 %	16,7 %	18,4 %	20,0 %	21,6 %	23,1 %	24,5 %	25,9 %	27,3 %	28,6 %	29,8 %	31,0 %	32,2 %	33,3 %
5 m/s	2,0 %	3,8 %	5,7 %	7,4 %	9,1 %	10,7 %	12,3 %	13,8 %	15,3 %	16,7 %	18,0 %	19,4 %	20,6 %	21,9 %	23,1 %	24,2 %	25,4 %	26,5 %	27,5 %	28,6 %
6 m/s	1,6 %	3,2 %	4,8 %	6,3 %	7,7 %	9,1 %	10,4 %	11,8 %	13,0 %	14,3 %	15,5 %	16,7 %	17,8 %	18,9 %	20,0 %	21,1 %	22,1 %	23,1 %	24,1 %	25,0 %
7 m/s	1,4 %	2,8 %	4,1 %	5,4 %	6,7 %	7,9 %	9,1 %	10,3 %	11,4 %	12,5 %	13,6 %	14,6 %	15,7 %	16,7 %	17,6 %	18,6 %	19,5 %	20,5 %	21,3 %	22,2 %
8 m/s	1,2 %	2,4 %	3,6 %	4,8 %	5,9 %	7,0 %	8,0 %	9,1 %	10,1 %	11,1 %	12,1 %	13,0 %	14,0 %	14,9 %	15,8 %	16,7 %	17,5 %	18,4 %	19,2 %	20,0 %
9 m/s	1,1 %	2,2 %	3,2 %	4,3 %	5,3 %	6,3 %	7,2 %	8,2 %	9,1 %	10,0 %	10,9 %	11,8 %	12,6 %	13,5 %	14,3 %	15,1 %	15,9 %	16,7 %	17,4 %	18,2 %
10 m/s	1,0 %	2,0 %	2,9 %	3,8 %	4,8 %	5,7 %	6,5 %	7,4 %	8,3 %	9,1 %	9,9 %	10,7 %	11,5 %	12,3 %	13,0 %	13,8 %	14,5 %	15,3 %	16,0 %	16,7 %
11 m/s	0,9 %	1,8 %	2,7 %	3,5 %	4,3 %	5,2 %	6,0 %	6,8 %	7,6 %	8,3 %	9,1 %	9,8 %	10,6 %	11,3 %	12,0 %	12,7 %	13,4 %	14,1 %	14,7 %	15,4 %
12 m/s	0,8 %	1,6 %	2,4 %	3,2 %	4,0 %	4,8 %	5,5 %	6,3 %	7,0 %	7,7 %	8,4 %	9,1 %	9,8 %	10,4 %	11,1 %	11,8 %	12,4 %	13,0 %	13,7 %	14,3 %
13 m/s	0,8 %	1,5 %	2,3 %	3,0 %	3,7 %	4,4 %	5,1 %	5,8 %	6,5 %	7,1 %	7,8 %	8,5 %	9,1 %	9,7 %	10,3 %	11,0 %	11,6 %	12,2 %	12,8 %	13,3 %
14 m/s	0,7 %	1,4 %	2,1 %	2,8 %	3,4 %	4,1 %	4,8 %	5,4 %	6,0 %	6,7 %	7,3 %	7,9 %	8,5 %	9,1 %	9,7 %	10,3 %	10,8 %	11,4 %	11,9 %	12,5 %
15 m/s	0,7 %	1,3 %	2,0 %	2,6 %	3,2 %	3,8 %	4,5 %	5,1 %	5,7 %	6,3 %	6,8 %	7,4 %	8,0 %	8,5 %	9,1 %	9,6 %	10,2 %	10,7 %	11,2 %	11,8 %
16 m/s	0,6 %	1,2 %	1,8 %	2,4 %	3,0 %	3,6 %	4,2 %	4,8 %	5,3 %	5,9 %	6,4 %	7,0 %	7,5 %	8,0 %	8,6 %	9,1 %	9,6 %	10,1 %	10,6 %	11,1 %
17 m/s	0,6 %	1,2 %	1,7 %	2,3 %	2,9 %	3,4 %	4,0 %	4,5 %	5,0 %	5,6 %	6,1 %	6,6 %	7,1 %	7,6 %	8,1 %	8,6 %	9,1 %	9,6 %	10,1 %	10,5 %
18 m/s	0,6 %	1,1 %	1,6 %	2,2 %	2,7 %	3,2 %	3,7 %	4,3 %	4,8 %	5,3 %	5,8 %	6,3 %	6,7 %	7,2 %	7,7 %	8,2 %	8,6 %	9,1 %	9,5 %	10,0 %
19 m/s	0,5 %	1,0 %	1,6 %	2,1 %	2,6 %	3,1 %	3,6 %	4,0 %	4,5 %	5,0 %	5,5 %	5,9 %	6,4 %	6,9 %	7,3 %	7,8 %	8,2 %	8,7 %	9,1 %	9,5 %
20 m/s	0,5 %	1,0 %	1,5 %	2,0 %	2,4 %	2,9 %	3,4 %	3,8 %	4,3 %	4,8 %	5,2 %	5,7 %	6,1 %	6,5 %	7,0 %	7,4 %	7,8 %	8,3 %	8,7 %	9,1 %

From the data of Table 6 it becomes clear just how much impact the positioning error has in walking speeds and once the travel speed is $12\ m/s$ or higher, which is likely to be an normal speed for a travelling vehicle, the effect of the error becomes less than 15 % even with a accuracy error of 10 m, which is rather poor accuracy. This indicates that the accuracy of positioning comes less important the faster an entity is moving and considering the worst case scenarios on construction site are related to loss of human life from moving machinery traveling at significant velocity, it can be deduced that the positioning accuracy is not as important when velocity is high when it comes to safety and an accuracy level of around 5 meters should be sufficient for outdoor use when tracking moving entities.

Once the accuracy is decided to be $r_{error} = 5\ m$ in outdoor use, we notice from Table 6 that the effect the accuracy has on the alert distance becomes significant (over 20%) when traveling in speeds that are $< 4\ m/s$. At these speeds it should be easy to control and maneuver equipment safely and prevent collisions considering the speed is rather slow, thus the need for alerts becomes lower.

If we compare the decided accuracy and walking speeds to a scenario where there is a dangerous area that is geofenced to keep workers out and alert would play out 10 – 15 m before the area, which is sufficient for outdoor use as it is better to let an alarm play out early instead of too late. On software side alarms should be set in a way that they do not play out constantly and would be throttled in some way and allow dismissal.

4.2 Best suited sensors

Suitable methods for positioning for moving equipment would be technologies and solutions that reach the suggested 5 m accuracy outdoors for machinery. Research has shown that the fusion between GPS and IMU can be accurate enough in longitude and latitude with Kalman filtering [52], and considering companies like Topcon already use the technology in their systems, it can be said that this is a good choice for tracking machinery and utilizing the data in a smart construction site software. This requires the moving machinery to be equipped with GPS and IMU sensors, which already exist on the market for construction use and with the correct software and implementation using Kalman filtering for example can lead to good results with existing solutions.

Utilizing existing technologies like smartphones in implementation of a smart system for construction site would be beneficial as it requires nothing more than an application on the mobile device to operate. GPS on smartphones alone can achieve various accuracies depending on what literature is read, but the typical estimation seems to be around 5 to 12 meters accuracy, but there is evidence that with some filtering it is possible to reach sub 5 meter error with GPS and the built in inertia sensors of the device [53].

In outdoor areas GPS is best available as the access to satellites is the best and the required accuracy with just GPS and inertia measurements with some filtering can be achieved for both machinery and personnel. This covers the use cases of warning of possible collision, warning of entering a dangerous area and warning if leaving machine unattended that shouldn’t be left.

Necessary accuracy of positioning indoors will be discussed more in the next section of this thesis. For safety and security related aspects the only use case discussed in this thesis indoors is geofencing for restricting or alerting workers from going to dangerous areas. This should share the same accuracy requirements as indoor navigations, which is room level accuracy.

5. WORK SITE NAVIGATIONAL EFFICIENCY

At this point it has been established that sufficient accuracy for outdoor navigation for safety purposes is sub 5 meters. It is reasonable to assume that the same accuracy is sufficient for navigational purposes outdoors, as once you are within 5 meters of something, you should be able to find what you are looking for in more open space. This does not apply to indoor navigation as that 5 meters can lead to a result that places you in 3 possible different floors and two possible rooms. For example, the regulations and settings set by Ministry of the Environment in Finland demand that the minimum room height for a living/working space should be at least 2.5 meters and at least $7\,m^2$ (RT RakMK-21761). In addition to this the thickness of each floor and ceiling adds to the vertical dimensions of the construction site. If it is assumed that the minimal sized room is square shaped, and the thickness of the walls would be ignored that would mean that minimum distance to the nearest wall from the center of the room would be:

$$d_{min} = \frac{\sqrt{7}}{2} \approx 1.32\,m$$

So if we use the smallest room as a measurement we get our room level accuracy requirement of 1.32 meters, which would apply once the walls start going up in building construction, as before that the floors consist mostly of empty space and support pillars. The question becomes if such accurate positioning is possible indoors without requiring expensive and complicated systems that the construction companies do not want to use.

5.1 Suitable methods

A review that suggested WLAN as the best option for indoor use on construction sites only described an accuracy of around 10 meters [42], which is not even remotely acceptable. As one of the requirements for an effective positioning system on a construction site is floor-level accuracy, meaning at least some height-level positioning over the 2nd dimension, it suddenly is a benefit that technologies like UWB and WLAN are not so great at penetrating thicker, heavier materials like concrete and steel [15, 16]. In construction, floors are separated by thicker material like concrete to support the weight of whatever is inside that floor, allowing positioning technologies like UWB and WLAN to somewhat easily detect what floor they are in as the signal barely passes through to other floors from where the transmitter and receiver are. UWB fused with WLAN has proven to be accurate in indoor navigation in complex environments with very high accuracy well below the set requirement [24]. The architecture of the system was seen in Figure 9, showing that the system could be run on a smartphone, which is very suitable for construction site use for workers. Since UWB equipment can come in different price-ranges depending on the capabilities and power, the aforementioned research indicates that the quality of the transmitters could be scaled down by quite a lot while still staying within the set accuracy requirement.

This leads to suggesting UWB and WLAN-based positioning fusion for the use of construction sites as it has been proven more than capable for complex uses. This does pose an issue when using fingerprinting methods as the buildings do change, but the indoor changes are mostly limited to adding more floors and floors having walls added within them. Considering the literature suggests very accurate results for the fusion, it may not be necessary to place the receivers as densely as in the experiments or as suggested before, using cheaper, less powerful variants to cover floors.

5.2 Suggested system architecture and software

This leads to suggesting an architecture for a construction site positioning system, where the positioning would be divided into indoor and outdoor solutions, yet they should operate from a single software even when the sensing technology changes. The architecture will be described in Figure 20.

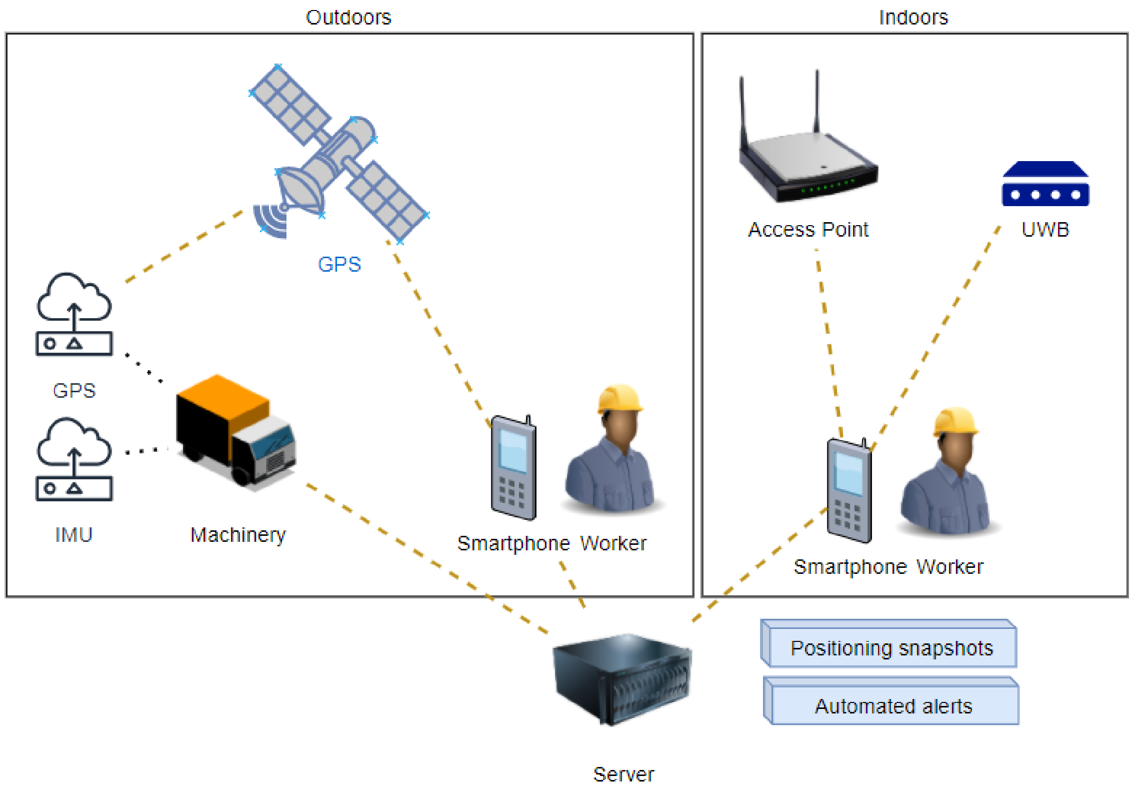

Figure 20: Suggested system architecture

For machinery it is the easiest to suggest the existing technology that has been proven to work in existing software solutions as already implemented in construction site use by Topcon. Machinery would come with mounted GPS and IMU sensing technology collecting data of the position, velocity and direction. Added benefit of machinery would be if they were capable of alerting the operator or even halting if necessary. This data would be directly passed on to the server for processing and the server should be able to communicate back with possible alerts and halt-commands.

A software would be installed on workers smartphones which would utilize GPS location when they are outdoors and UWB + WLAN connection for their position when they are inside the buildings or underground. The software would handle the tracking, sending the data to the server for processing and receiving orders from the server to alert the worker if necessary. The software should be able to display the modeled virtual version of the construction site, displaying the position of other workers, equipment and machinery in real-time.

Additionally, a software should be implemented for managing what is happening on the server and setting up geofences, updating models and so forth. A desktop or web application could be implemented that allows users to monitor the construction site in real time as well as make edits and manage the construction process.

The server would be in charge of processing the data and sending out alerts. System should alert machine/worker in the following cases:

- System detects possible collision under the safety margin of the dynamic geofence
- Worker or Machinery is detected entering dangerous geofenced area
- Machine operator leaves machine unattended leaving its proximity
- Machine leaves its designated operation area

Along with the alerts, the described snapshotting data storage should be implemented along with the management of the virtualized construction site. Server should be able to take a snapshot of the current real-time location of every entity on the site and store it in a database with a set interval. The snapshot should be connected to a virtualized model of the site that matches the construction site best at the time. A set number of snapshots should be stored from every day or week to serve as history of states of the construction site. In the case of accidents and automated alerts the associated snapshot should be stored in order to provide important information that aids in investigating the reasons of why safety or security was compromised.

Most of what is suggested here has been researched and field tested, as well as partial chunks of the described software already being implemented, indicating that it should be very possible to unify everything that exists into a system that covers the entire construction site turning it into a site that is location aware, more efficient and safer.

6. CONCLUSION

Construction companies have shown great interest in visual tools and software that assists them with the efficiency and safety of construction. Some solutions and software already exist on the markets today, but none of them provide a clear combined solution for a smart location aware construction site. Market research has shown that the there already exists a customer base ready to invest in a solution that covers full localization of a construction site.

A review of positioning technologies shows promise of cost-effective ways to accurately track machinery using sensors and solutions where location can be tracked accurately with just smartphones. The most promising solutions for positioning turned out to be related to WLAN and UWB when dealing with indoor smartphone navigation as well as GPS and IMUs being a good solution for outdoor navigation especially for machinery as well as smartphones with their built-in sensors. Currently UWB-sensors are limited to only few high-end smartphones [58]. Review also revealed that location data is classified as data from which a person can be identified, thus it falls under some regulations of privacy, requiring consent to be signed.

Storing snapshots of the state of the construction site was suggested, which means saving the locations of each entity of the construction site at a given point in time. A virtualized version of the construction site should exist in the form of a model of some sorts that would get updated as the construction progresses. A snapshot would contain the data of each individual entity containing their position, velocity and direction. The snapshots can be used to review history of the site as well as investigate accidents as data about the whereabouts of everything when something went wrong.

Sufficient accuracy for outdoor use for machinery and was determined to be 5 meters or less. This proved to be sufficient in speeds over $4\ m/s$ as the effect that the 5-meter error radius has is less than 20%. GPS combined with inertial measuring sensors has proven to be capable of achieving such accuracy for both mobile devices and machinery tracking, as mentioned before, the technology already exists for machinery, is implemented and is use on construction sites and their software.

Sufficient accuracy indoors to fulfill the criteria of room and floor level accuracy was determined to be around 1.32 meters which condones with the smallest possible room size for living / working environment according to regulations set by Ministry of the Environment in RT RakMK-21761. In order to fulfill this requirement a fusion of WLAN and UWB sensing technologies for smartphone use were selected, as they are a relatively low cost solution with potential to clear the accuracy requirement easily, also allowing to downscale in the power and quality of the transmitters.

A system architecture was suggested to be paired with the sensing technology which would connect the workers mobile devices to a server. The mobile device would collect information from the internal inertia sensors combined with GPS signal outdoors and collect WLAN and UWB signals when indoors for positioning data, which would be transmitted to the server. Machinery would collect the information with IMU and GPS-sensors and send that information to the server. An external application would need to be created to manage virtual models of the construction site, which then could be viewed on a mobile device on the construction site to monitor the state in real time leading to efficient navigation on the construction site. The system would use the collected data to prevent accidents by sending alerts to the machinery and mobile devices in cases where they are heading for collision, dangerous area or leaving something unattended.

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