IMPLEMENTING ALTERNATIVE TECHNOLOGIES TO IMPROVE PQI METHODOLOGY

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Preface

The present thesis was written as part of Module 12 of the Civil Engineering program, and it was developed in cooperation with the ASPARi research group.

I want to thank the Secretaría de Educación Superior, Ciencia, Tecnología e Innovación as a sponsoring entity.

Also I want to thank Seirgei Miller and Mohammad Sadeghian for their constructive feedback and support during the development of this thesis. Each comment was useful for keeping me on track and pushed me to do my best. I also want to thank the people who helped me with the interviews and gave me feedback and supporting words for completing this thesis.

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Alison Hidalgo

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Summary

The research focuses on investigating alternative technologies that can be used for tracking machinery in the construction and paving industry instead of GPS, which is the currently used technology for several industries. This GPS is part of the so-called PQi framework, which focuses on making on-site behaviour explicit to improve the quality of asphalt. This is done by tracking pavers and rollers during construction and obtaining data from other technologies to create plots that make the activities on-site visible for the asphalt crew and are used to find the aspects in which improvement should be made during the next project. The accuracy of GPS is crucial for making accurate graphs; therefore, an accuracy of 10 centimetres is needed to accomplish that. Due to the current technology presents issues regarding the loss of signal, data analysis, and costs, the idea of looking for alternatives to overcome this begun.

Therefore, during this study, the main research question that was investigated was: ***"To what extent alternative technologies available in the market can be implemented for tracking machinery with the same or similar accuracies as the currently used GPS technology in the PQi process in order to reduce the costs and functionality issues".*** To be able to answer this question, four sub-questions were formulated to make the research process more organised and understandable. The sub-questions were: (1) Which alternative technologies (standard and non-standard) available in the market are suitable to be applied in the asphalt industry? (2) What are the current issues of using standard GPS technologies in the asphalt industry? (3) What are the pro's, cons and barriers of using standard GPS and these alternative technologies? (4) Which alternative(s) perform better or equal compared to standard GPS solutions?.

After using three different methodologies: Literature review, semi-structured interviews with industry experts, and Analytical Hierarchy Process (AHP), it was found that the available technologies used for tracking machinery that could replace GPS in the construction and paving industry are Bluetooth Low Energy (BLE), Locata Technology, Unmanned Aerial Systems (UAS), Lidar, Ultra-wideband (UWB), U-Blox, Radio Frequency Identification (RFID) and Thermal Imaging. A description of how each of them works, the advantages, challenges, limitations, and future of the technologies was elaborated.

The semi-structured interviews showed that the issues that GPS presents in the asphalt industry are the loss of signal in non-favourable environments, making it to lose accuracy. Also, according to the experts, the user-friendliness of the analysis of the data could be improved. Another result was the criteria used to choose the technology. The experts mentioned that accuracy, user-friendliness, costs, and robustness are the important aspects to consider for having a technology within their projects. Therefore, the technologies mentioned above were evaluated and compared against accuracy, robustness, reliability, and user-friendliness. The results from this analysis showed that the most suitable technology to replace GPS is U-blox, followed by Thermal imaging, Ultra-wideband, Locata, UAS, Lidar, RFID (Radio Frequency Identification) and BLE (Bluetooth Low Energy). However, since the focus of this research was to find technologies for tracking machinery that can be implemented in the PQi framework. The requirements of accuracy and costs currently used within that methodology were crucial to determining which of the aforementioned technologies can be implemented within the PQi framework. Therefore, only two technologies were suitable to be implemented within the framework instead of GPS technology because they have higher accuracies and reduced costs. Those technologies are U-Blox and Thermal Imaging.

Given these results, it was concluded that there are available technologies in the market that can replace GPS within the PQi framework because they perform with equal or even better accuracies and lower-prices. However, more research and experimentation of U-blox and Thermal Imaging within the

asphalt and paving industry should be done. This is recommended because it is important to know how exactly the aforementioned technologies perform in real-life applications. Additionally, with the experimentation and more research, the issues that these technologies might have when using them in real life can be found.

Samenvatting

Het onderzoek focust zich op het onderzoeken van alternatieve technologieën die gebruikt kunnen worden voor het volgen van machines in de constructie en asfaltering industrie in plaats van GPS. GPS is op het moment de meest gebruikte techniek in verschillende industrieën. Deze GPS is een deel het zogeheten PQi framework, wat zich focust op het expliciet maken van het gedrag op de bouwplaats om de kwaliteit van het asfalt te verbeteren. Dit wordt gedaan door de machines te volgen tijdens het bouwproces en data te verzamelen via andere technologieën. Van deze data worden plots gemaakt om de activiteiten op de bouwplaats zichtbaar te maken voor de werknemers en om verbeterpunten te vinden waar tijdens het volgende project naar gekeken kan worden. De accuraatheid van de GPS is cruciaal voor het maken van accurate grafieken. Daarom is er een accuraatheid nodig met een maximale afwijking van 10 centimeter. Vanwege de huidige technologieën zijn er problemen zichtbaar zoals; het verlies van signaal, data analyse en kosten. Het moment is nu daar om te gaan zoeken naar alternatieven om deze problemen aan te pakken.

Daarom, tijdens deze studie, is de hoofd onderzoeksvraag geweest: "Tot welke hoogte alternatieve technologieën die aanwezig zijn in de markt geïmplementeerd kunnen worden voor het volgen van machines met dezelfde accuraatheid als de huidige gebruikte GPS technologie in het PQi proces met als doel het verminderen van kosten en functionele problemen''. Om deze vraag te beantwoorden zijn er vier sub-vragen opgesteld om het onderzoeksproces georganiseerder en begrijpelijker te maken. De sub-vragen zijn: (1) Welke alternatieve technologieën (standaard en niet standaard) zijn er beschikbaar op de markt en geschikt om toe te passen in de asfalt industrie? (2) Wat zijn de huidige problemen met het gebruik van standaard GPS technologieën in de asfalt industrie? (3) Wat zijn de voor- en nadelen en belemmeringen van het gebruik van standaard GPS en de alternatieve technologieën? (4) Welke alternatieven presteren beter of gelijk aan de standaard GPS techniek?

Na het gebruik van drie verschillende methodes: Literatuurstudie, semigestructureerde interviews met experts uit de industrie en Analytisch hiërarchie Proces (AHP) bleek het dat de beschikbare technologieën die gebruikt kunnen worden voor het volgen van machines als vervanging van GPS zijn: Bluetooth Low Energy (BLE), Locata technologie, Unmanned (onbemande) Aerial Systems (UAS), Lidar, Ultra-wideband (UWB), U-Blox, Radio Frequency Identification (RFID) and Thermo Imaging. Een omschrijving van hoe elke van deze technologieën werkt, wat de voor- en nadelen zijn, uitdagingen en limitaties en de toekomst van de technieken is gegeven.

De semigestructureerde interviews lieten zien dat de problemen met de GPS in de asfalt industrie zijn het verlies van signaal in ongunstige terrein, waar de GPS minder accuraat wordt. Ook zeggen experts dat de gebruiksvriendelijkheid van de data analyse verbeterd kan worden. Een ander resultaat was dat de criteria die gebruikt worden om de technologie te kiezen. De experts noemde dat accuraatheid, gebruiksvriendelijkheid, kosten en robuustheid belangrijke aspecten zijn om mee te nemen voor een keuze voor een technologie. De bovengenoemde alternatieven zijn getoetst tegen deze criteria. De resultaten van deze analyse liet zien dat de beste alternatief voor GPS U-blox is met daarna volgend: Thermal Imaging, Ultra-Wideband, Locata, UAS, Lidar, RFID and BLE. Daarentegen, sinds dat het focus van dit onderzoek is om technologieën te vinden voor het volgen van machines die geïmplementeerd kunnen worden binnen het PQi systeem. Daarom zijn er maar twee technieken echt bruikbaar voor implementatie ter vervanging van GPS omdat deze de hoogste accuraatheid hebben en laagste kosten. Deze twee technieken zijn U-Blox en Thermal Imaging.

Kijkend naar deze resultaten, kan er geconcludeerd worden dat er technieken beschikbaar zijn op de markt die GPS kunnen vervangen binnen het PQi systeem vanwege hun even goede of betere accuraatheid en lagere kosten. Daarentegen, is er meer onderzoek nodig naar U-Blox en Thermal

Imaging binnen de asfalt sector. Dit wordt aangeraden omdat het belangrijk is om te weten hoe de bovengenoemde technieken precies presteren in een real-life scenario. Daarbij kunnen tijdens dit onderzoek eventuele problemen bij het gebruik van deze technieken gevonden worden.

Glossary

Accuracy

It is defined as a degree to which the result obtained from a measurement corresponds to the proper value or standard and refers to the closeness of the measurement to the real value (Mackenzie, 2019).

AHP

Analytical Hierarchy Process is a multi-criteria decision-making approach that uses pairwise criteria comparison to reach a scale of preferences among sets of alternatives (Marinoni, 2004).

BLE tags/beacons

Small Bluetooth hardware component used to locate people, objects or vehicles (infsoft, 2021).

GNSS

Global Navigation Satellite System is a term which describes any satellite constellation which gives positioning, timing, and navigation services on a global or regional services (GPS.GOV, 2021).

GPS

Global Positioning System is a system employed to achieve position accuracies that range from meters to few millimetres depending on the equipment (Editorial, 2020).

HMA

Hot Mix Asphalt is a combination of aggregates bound together by asphalt cement which is a product of crude oil (Asphalt Pavement Association of Michigan, n.d.).

PQi

Process Quality Improvement (PQi) is a method used to monitor projects to improve process quality by monitoring and bringing to light variability in the Hot Mix Asphalt (HMA) construction process (ASPARi, n.d.).

Reliability

The quality of the signal emitted by the technologies of being trustworthy and performing consistently well.

Robustness

The quality or condition of how strong the signal is emitted by the technologies.

User-friendliness

Ease of use of the technologies by non-experts.

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1. Introduction

During the past two decades, the asphalt paving industry has changed enormously because several developments have occurred (Kuennen, 2017). For example, the implementation of technologies has helped to improve the quality and placement of mix asphalt, whereas the new asphalt paver designs have enabled safer, faster and even more versatile paving (Kuennen, 2017). However, the basic components of asphalt paving have not changed a lot in the past decades, and still includes the usage of specialised machines and workers' experience to perform the activities. Nevertheless, with the development and implementation of technologies in several fields, being the asphalt industry one of them, the productivity and quality of results can be improved as well as the transformation of operations. Also, it can be obtained greater efficiencies, and there is a possibility of having a real-time effect on each stage of the operational chain of the asphalt industry (Allen, 2020). Therefore, technology is helping to shape the future of the paving industry because advancements in several types of technologies such as GPS, telematics, and automation have resulted in safer, faster, more efficient, cost-effective, and less risky construction of projects (Allen, 2020).

The ASPARi knowledge network aims "to fill the gap between technology development and the education and workmanship of operator" (ASPARi, n.d.). Therefore, it uses advanced technologies to improve the paving process, which reduces variability in key parameters. With these technologies' use, operators' operational behaviour can be made explicit, leading to dialogues between asphalt team members and exchange of feedback to improve their operational choices. Therefore, by having a deeper understanding and implementing these types of technologies in the paving industry, the quality of the outcome can be improved.

1.1. Project context

The road construction sector in the Netherlands has been significantly transformed in terms of its business environment since the parliamentary inquiry into the construction sector (Miller S. R., 2010). New contracting schemes that encourage a better quality of work have been introduced by clients (Sijpersma and Buur, 2005, as cited in Miller, 2010), rougher competition and the impulse to make a distinction from their rivals have stimulated companies to push in product and process improvement (Miller S. R., 2010). In other words, companies are in need to differentiate themselves from others within the market by improving their products and processes (Miller S. R., 2010). To achieve this, Hot Mix Asphalt (HMA) paving companies look for better understanding and control of the whole paving process, performance, scheduling and planning of resources and work since this will minimise the possibility of paving failure during the guarantee period (Miller S. R., 2010). Remarkably, they are trying to achieve better process control and to do that; it is necessary to make explicit the construction process. However, doing so is not that simple because contractors do not often monitor or even map their operational strategies. Also, decisions regarding the process are made based on the experience and craftsmanship of the operators, and little or even no feedback is given to the operators about the quality of their work (Bijleveld, 2015). Additionally, according to Miller (2010), there are few efforts to map and analyse this construction process since most of the conducted researches focus on the quality of asphalt in terms of construction materials rather than the construction process itself.

Some companies seek solutions by implementing new technologies; however, their current adoption by workers of the paving industry gives the impression that it is problematic (Simons, 2007, as cited in Miller, 2010). This is because operators barely make use of the available technology (Miller S. R., 2010). Additionally, there is a lack of evidence that these technologies add value to the quality of the final products (Bijleveld, 2015). Furthermore, the implementation of technologies may be hampered by the sceptical attitude of operators concerning them. Also, there is a possibility that operators can feel their work being undervalued and might see technology as an instrument for managers to punish them (Miller, 2010, as cited in Bijleveld, 2015).

Miller (2010) developed a systematic framework called Process Quality Improvement (PQi) to overcome the above-mentioned problems. This method can be used to monitor and bring to light variability in the HMA construction process (ASPARi, n.d.). Hence, it serves as an approach to improve process quality. PQi uses technologies such as GPS and thermal imaging to measure and monitor process parameters such as temperature homogeneity, compaction consistency, and machinery location. These are essential aspects to consider in order to achieve good quality end products. The technologies mentioned above are combined with visualisations to make on-site operational behaviour explicit, which is an important feature of the framework since the gathered data and visualisations call upon a dialogue between operators, contributing to understanding their applied operational strategies and the construction process itself (Bijleveld, 2015).

1.2. Problem definition

As stated in the project context, the use of GPS helps HMA teams to track all equipment movements on the construction site. And, in doing so, attempt to reduce variability in the asphalt pavement construction process (Miller S. R., 2010). The data gathered from GPS is used to prepare Compaction Contour Plots (CCP) to show the number of passes that were applied to certain areas of the paved road, helping to have a deeper analysis of the compaction process (Miller S. R., 2010). Also, GPS data is used to produce animations to show how the work was done on the site; in other words, with the help of GPS, it is possible to capture and make explicit the operational behaviour of the operators and see how their choices affected the end product (Miller S. R., 2010).

For producing those animations and plots, high accuracy is necessary for capturing the turning movements of the roller compactors and the overlapping passes made by them. Hence, the required accuracy in mapping the positions of asphalt machinery during compaction and paving operations is 10 centimetres (Miller S. R., 2010).

It is worth mentioning that GPS can be affected by several aspects, which might reduce its accuracy. For example, one of the primary error sources in GPS is the ionosphere, which makes signals to be delayed affecting the range measurements (de Bakker, 2017). Also, other sources of error affect the positional accuracy of GPS, such as the inaccurate knowledge of the GPS satellite orbits, timing errors in the satellite and receiver clocks (Moore, 2013). Further, in several situations, the satellite signals are obstructed by surrounding buildings or other obstacles, which means that the GPS performance might be degraded; this situation is called shadowing (de Bakker, 2017). Another problem is encountered in built-up areas because GPS receivers repeatedly encounter signal reflection since signals arrive at the receiver after bouncing off an object (de Bakker, 2017). This is known as multipath and causes issues because there can be an error in the range measurement. Lastly, there could be a biased range measurement where the GPS receiver must deal with the superposition of the direct and reflected signals (de Bakker, 2017).

Fortunately, the use of high-end GPS addresses the problems mentioned above adequately; for instance, in the case of ASPARi, it uses Trimble GPS receivers (ASPARi, n.d.) which have the necessary accuracy in mapping the position of asphalt machinery. However, to achieve that accuracy, some pre-processing of the GPS data is needed to filter any noise or outliners (Miller S. R., 2010) caused by the reasons mentioned above, such as reflection or shadowing. Additionally, these devices are way too expensive compared to general-purpose GPS. Furthermore, deploying GPS devices on all equipment, labourers, and tools that require location information can increase costs (Luo, O'Brien, & Julien, 2011). Therefore, by considering all of the aforecited, the main problem is the cost followed by the usability of the currently used GPS technologies, which leads us to look for cheaper, user-friendly alternatives for localisation that have at least the same accuracies as the currently used GPS.

1.3. Research Aim and scope

The goal of this research is to contribute towards the determination of how feasible are alternative technologies that are available in the market to track machinery during on-site operations with equal or greater accuracies compared to currently used technologies by ASPARi. In order to see whether there is a possibility of using them within the PQi method. The scope of this research is to find alternative technologies used within the construction and paving industry and assess each of them with the use of criteria.

1.4. Research questions

The main research question that was proposed based on the context and causes for this research is: ***"To what extent alternative technologies available in the market can be implemented for tracking machinery with the same or similar accuracies as the currently used GPS technology in the PQi process in order to reduce the costs and functionality issues?"***.

This main question will be answered with the following sub-questions:

1. Which alternative technologies (standard and non-standard) available in the market are suitable to be applied in the asphalt industry?
2. What are the current issues of using standard GPS technologies in the asphalt industry?
3. What are the pro's, cons and barriers of using standard GPS and these alternative technologies?
4. Which alternative(s) perform better or equal compared to standard GPS solutions?

The first sub-question is asked because it is wanted to know what standard GPS technologies and non-standard alternatives are available in the market to be used in the asphalt industry for tracking machinery.

The second sub-question is asked because it is wanted to know the current issues that GPS technologies present when used in real-life operations; therefore, this information will be useful to compare it with the alternative technologies. Additionally, within this sub-question, it will be investigated why GPS has become a standard practice despite its drawbacks and no other technologies present in the market.

The third sub-question is asked since there will always be a positive and a negative side of the currently used and new technologies, which will help to make a balance between their advantages and disadvantages in order to see which of the alternatives(s) performs better over the others.

The last sub-question will help to see whether alternative technologies perform better or equal to GPS. This information will be helpful to know whether those technologies can be implemented instead of GPS in the tracking of machines within the PQi framework.

By combining these sub-questions, the main research question can be answered.

1.5. Methodology

This section introduces the methodology used to conduct the research project. The project is divided into three main chapters, where each methodology is applied to answer the research questions.

First, a literature review is applied to obtain information regarding the PQi methodology. Additionally, in this chapter, the found technologies and the currently used GPS technology are described. Topics such as their functioning, advantages, fields of application, challenges and limitations, accuracy and future use are explained. With the use of this methodology, the first and third sub-question are answered.

The second chapter focuses on the second methodology, 'Semi-structured expert interviews' (Saks & Allsop, 2013), which are used to gather information regarding the participants' experience concerning GPS use during on-site operations. The process of conducting the interview is described as well as the results obtained from it. Additionally, how the interviews were validated is explained during this chapter. This methodology is used to answer the second sub-question.

The last chapter of this research is about the comparison of the found alternative technologies and answering sub-question four. To do so, the methodology 'Analytical Hierarchy Process' developed by Saaty (1980) is used, which helps to compare alternatives based on a set of criteria. The elaboration on what this methodology entails and all the calculations made to achieve a final result are presented during this chapter.

After that, the conclusions from the research are presented, as well as the discussion and recommendations for future research.

2. Literature Review

The research method that was primarily used during the development of this assignment was the literature review. By mixing different findings and perspectives, a literature review can address research questions with an ability that no single study has (Snyder, 2019). A literature review can also give an overview in disparate and interdisciplinary areas. Therefore, this method was extensively used during the development of this report. It was chosen because it was aimed to provide an overview of the alternative technologies for localisation and tracking that can replace GPS.

Traditional literature reviews generally lack attention to detail and rigour and usually are conducted ad hoc rather than following a specific methodology; for those reasons, the quality and trustworthiness of this type of review can be questioned (Snyder, 2019). However, some guidelines for conducting literature reviews propose different types of reviews such as narrative, integrative, systematic, and meta-analysis reviews (Snyder, 2019) which helps to reduce those issues.

Snyder (2019) distinguishes between different review methodologies: systematic, semi-systematic, and integrative approaches. Between those three, the systematic review is the most accurate and rigorous approach to collect articles because it is straightforward and follows stringent rules and standards, which ensures that there is the certainty that all the relevant information will be covered (Snyder, 2019). However, this approach requires a narrow research question, meaning that it might not be suitable for all types of projects. Since reviewing every single article relevant to a broader research question or topic is not possible, another strategy is used, which is the semi-systematic or narrative review that can conceptualise differently and study within several disciplines the topic under research (Snyder, 2019). However, this approach is more problematic than the systematic one because it has fewer clear steps to follow, requiring more development and tailoring to the specific project (Snyder, 2019). Usually, researchers need to develop their own standards and even a detailed plan to guarantee the appropriate literature is correctly covered to answer their research question and be transparent about the process (Snyder, 2019). The last type of literature review is the integrative review with even fewer standards and guidelines for developing a strategy (Snyder, 2019). Therefore, it is more demanding, requires more skills, and puts more responsibility on the researchers. This leads to the impression that the integrative review approach might not be advisable to use, and compared to the systematic review, this might not hold the same amount of rigour (Snyder, 2019). However, if it is successfully conducted, a completely integrative review and even a contribution with a new conceptual model or theory can be achieved (Snyder, 2019).

By considering all those as mentioned above, the most suitable methodology to be used during this research was semi-systematic review because the research questions under study are not narrow enough; instead, they look for several topics such as the alternative technologies for GPS, and also it aims to collect data of several fields of study. Another reason for choosing this approach was the limited amount of time for completing the bachelor assignment. If a systematic approach would have been chosen, it would have taken more than a year to complete it (University of Minnesota, 2021). Lastly, the integrative review was not used because it requires expert researchers with advanced skills such as superior conceptual thinking to be transparent and document the process of analysis simultaneously (Snyder, 2019).

The organisational method for the literature review was the thematic review of the literature (University of Southern California, 2021) because this literature is organised around a certain topic or issue (University of Southern California, 2021) which in this case, the topics were the different alternative technologies that were found.

The process of conducting the literature review was done by following the four steps proposed by Snyder (2019): designing, conducting, analysing, and writing up the review.

For designing the review, the purpose of the literature review was to find whether there are alternative technologies that can replace GPS. To do so, the search strategy used to find the relevant literature was using search terms related to the topic, for instance, PQi methodology, asphalt improvement, asphalt industry, GPS, alternative technologies to GPS, technologies in the construction industry, technologies in paving industry, technologies in the industry, technologies for tracking, technologies for localisation. Later, based on the findings obtained from this, additional search terms were included such as (name of the alternative technology) in the construction industry, (name of the alternative technology) in the paving industry, (name of the alternative technology) in the industry, (name of the alternative technology) for tracking, (name of the alternative technology) for localisation.

The inclusion criterion was publication date (no older than the year 2000), meaning that the publications must be published from 2000 onwards to be considered part of the research because technologies are constantly changing; therefore, up-to-date information is essential. Another criterion was the language of the information, meaning that only the publications in English were considered. For conducting the review, the most used approach was based on reading the publication year first and then the abstract, depending on that an article was chosen or discarded. For the third phase, the analysis phase, the thematic analysis was used because of the different technologies found; therefore, the data obtained from the literature review was clustered depending on the type of technology found. Additionally, the pros, cons, and barriers of each of them were also aimed to be researched; therefore, the data was needed to be clustered depending on the theme. For the last phase, which is writing the review, the following chapters were structured to show all the information found in a more straightforward form.

2.1. Process Quality Improvement (PQi) Methodology

Process Quality Improvement (PQi) was developed by Miller (2010) and is used in the ASPARi monitored projects to improve process quality; this is done by monitoring and bringing to light variability in the Hot Mix Asphalt (HMA) construction process (ASPARi, n.d.). PQi uses technologies such as GPS and thermal imaging to measure and monitor process parameters such as temperature homogeneity, compaction consistency, and machinery location. These are essential aspects to consider in order to achieve good quality end products. Furthermore, the technologies mentioned earlier are combined with visualisations to make on-site operational behaviour explicit, which is an important feature of the framework since the gathered data and visualisations call upon a dialogue between operators, contributing to understanding their applied operational strategies during the construction process (Bijleveld, 2015).

A common cycle of this PQi methodology can be seen in the figure below.

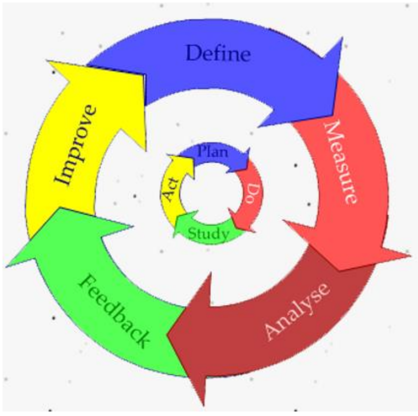

Figure 1: PQi methodology cycle (ASPARi, n.d.)

As can be seen from Figure 1, the cycle has five stages. The first stage is preparation and definition, which involves getting data from the site conditions and a preparatory meeting with the HMA team. The second stage is the data collection, where the machine movements are monitored as well as the weather conditions, temperature and nuclear density profiling, and other meaningful events (ASPARi, n.d.). This stage is vital since the application of several instruments and technologies is made to monitor important factors for the final product; for instance, a GPS receiver with an accuracy of 10 centimetres is used during this stage to track machinery such as dozers, pavers, and rollers.

The following stage of the PQi process is about analysing the obtained data to prepare animations and visualisations. This leads to the last stage, the feedback session, where all the results are discussed, and the images and animations are shown to all the people involved in the project (ASPARi, n.d.).

2.2. Technologies

As was mentioned before, the technology currently used within the PQi framework for tracking machinery is GPS with an accuracy of ± 10 centimetres. However, GPS is not the only technology capable of tracking assets because out there, there are alternative technologies used for tracking. Some of them even give more significant benefits than GPS. The technologies that will be discussed during the following sections are Bluetooth Low Energy (BLE) technology, Locata Technology, Unmanned Aerial Systems (UAS), Lidar, Ultra-wideband, U-Blox, Radio Frequency Identification (RFID), and Infrared Thermography. These were chosen because they are being used for tracking and localisation of assets in the construction industry. Therefore, due to its harsh nature, there could be a possibility to use them in the paving industry. An explanation of how each technology works (including GPS) will be given, followed by the fields of application, limitations, accuracy, and how the future use might look like for these technologies.

2.2.1. GPS

GPS is a system employed to achieve position accuracies that range from meters to few millimetres depending on the equipment (Editorial, 2020) and consist of a constellation of 24 Earth-orbiting satellites in operation and three extras in the case of failure of one of them. This satellite network was developed and implemented by the U.S. military as a military navigation system, but soon it opened up to everybody else (Brain & Harris, 2020). Each of these satellites makes two complete rotations every day, and they are arranged in a way that at any time, anywhere on Earth, there are at least four satellites visible in the sky (Brain & Harris, 2020). The GPS receivers use the radio signals of these visible satellites to calculate the distance to each satellite and deduce its location (Brain & Harris, 2020). This is called trilateration and is a technique used to calculate the location, velocity, and elevation.

GPS is made up of three components called segments that work together to produce location information (Geotab Team, 2020). The three segments are: Space satellites that circle the earth and transmit signals; ground control which is made up of Earth-based monitor stations, master control stations, and ground antenna; the last element is the user equipment which are GPS receivers and transmitters (Geotab Team, 2020), this is illustrated in Figure 2. When people talk about GPS, they usually mean a GPS receiver which is the device that determines the location of at least three satellites above it and the distance between them by analysing the high frequency, low power radio signals from the GPS satellites which travel at the speed of light. Therefore, the receiver can determine how far have the signals travelled by timing how long it took the signal to arrive (Brain & Harris, 2020).

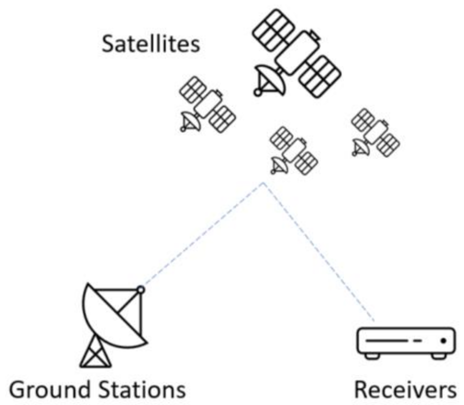

Figure 2: GPS made up of satellites, ground stations and receivers

Differential GPS (DGPS)

DGPS is a method used to enhance GPS positioning by using one or more reference stations at known locations (Khattab, Fahmy, & Wahab, 2015). The idea behind this method is to measure the GPS inaccuracy at a stationary receiver station of a known location (Brain & Harris, 2020). This can be done because the DGPS hardware at the station already knows its position; therefore, the inaccuracy of the receiver can be calculated (Brain & Harris, 2020). After that, the station broadcasts a radio signal to all DGPS-equipped receivers in the area that provides correction information (Brain & Harris, 2020). That is why DGPS receivers are more accurate than ordinary receivers (Brain & Harris, 2020).

Additionally, it is worth mentioning that differential correction can be used in real-time or post-processed, and its quality is a function of the distance between the base station and the rover (Oloufa, Ikeda, & Oda, 2003).

Fields of application

This localisation technology has become omnipresent in everyday life because it is available to civil users worldwide at no cost; additionally, it provides timing, position, and navigation accuracies that have brought incalculable benefits to people. For that reason, GPS is now the underpinning of several civil applications such as agriculture, aviation, marine, railroads, roads and highways, survey and mapping, timing, environment, meteorology, public safety and disaster relief, and recreation.

In construction, mining and off-road trucking, GPS is used to locate equipment, measure and improve asset allocation, which increases return on companies' assets (Geotab, 2020). The use of GPS technology to guide and control machinery such as dozers, motor graders, excavators, etc., has become usual in highway construction because it reduces costs and speeds project delivery (Primera Engineering, 2016). Also, the use of GPS to track machinery to make explicit the behaviour of operators has helped HMA teams to attempt to reduce variability in the asphalt pavement construction process (Miller S. R., 2010). Therefore, when tracking machinery in the paving process, choosing the correct GPS equipment that complies with the accuracy requirements is important (Zhanwu, 2020). Since this technology is used within the PQi process, it has to comply with the high accuracy requirements to obtain data from the project on-site to provide accurate and reliable measurements to prepare the animations of the on-site work.

Challenges and Limitations

GPS presents some problems when deployed in dense urban areas, vast vegetation zones, multilevel roads, tunnels (Nascimento, Kimura, Guidoni, & Villas, 2018), underground or indoors because of the loss of signal (Grgac & Paar, 2019). The problem of the multipath effect occurs when satellite signals are reflected or refracted by tall buildings and materials in the line-of-sight (LOS), resulting in poor positioning performance or even positioning failure (Sheng, Gan, Yu, & Zhang, 2020). On the other hand, the worst performance of GPS is in tunnels because of the non-line-of-sight (NLOS) with the satellites meaning that the service becomes unavailable (Nascimento, Kimura, Guidoni, & Villas, 2018).

Also, traditional high-precision GNSS systems have no scalability, which is a limitation since this scalability might be needed in the future. For instance, there might be GNSS systems built into every car that gets built (Fairhurst, Commentary: High-precision positioning is going mainstream, 2019) or either for self-driving cars or other applications. Another issue regarding scalability is that traditional GNSS services use two-way cellular communication to transmit the data between the customer device and the correction data provider. At the moment, this works because the device density is low. However, if this number grows to thousand or even millions of end-users trying to access the correction data service simultaneously, the current cellular infrastructure would have issues delivering the needed reliability (Fairhurst, Commentary: High-precision positioning is going mainstream, 2019).

The correction data that has been key to high-precision GNSS services to achieve an accuracy of centimetre-level sometimes require annual subscriptions of one hundred dollars per device. Meaning that it is confined to specific markets, countries, or even states which can mean additional roaming contracts, hence additional costs (Fairhurst, Commentary: High-precision positioning is going mainstream, 2019).

Accuracy

The accuracy varies depending on the device used. However, for this research, an accuracy of 10 centimetres will be considered because it is needed for the PQi methodology. However, the accuracy can be affected by several sources of error, such as imprecise knowledge of the GPS satellite orbits, minor timing errors in the satellite, the atmosphere, receiver biases, and multipath (Moore, 2013). These issues appear when cheap devices are employed; therefore, since accuracy is crucial is better to choose high-quality devices (GPS-SERVER, 2021) which are costly and high in power consumption.

Future

The increasing demand for automation in navigation applications such as autonomous vehicles, drones, and many others, is remarking the need for higher precision positioning solutions (Fairhurst, 2018). Therefore, the next generation of GPS satellites is expected to be fully operational in 2023; and will include better signal protection, decreased susceptibility to signal jamming, and more manoeuvrability to cover dead zones (Geotab, 2020).

2.2.2. Bluetooth Low Energy (BLE)

Bluetooth technology influences fast growth in real-time location services solutions used to track either people or assets (Bluetooth, n.d.). Its cost-effectiveness, energy-efficiency, working independently of the network, less interference, and ease to deploy indoor positioning and tracking technology facilitates the location or tracking of items, people, finding of directions, and other types of information that is useful within large buildings and facilities such as shopping malls or airports (Kingatua, 2020).

It consists of beacons (location receivers) that can be mounted on objects such as walls, ceilings, and other places from where they send radio signals at predetermined intervals (Kingatua, 2020). Even though one beacon is enough for determining the presence of an object, the accuracy increases if the number of beacons is increased (Kingatua, 2020). On average, a beacon device can transmit BLE signals to 80 meters, and this signal can trigger certain actions relevant to the location (Adarsh, 2021).

BLE beacons send out periodic signals, generally one per second (TENNA, 2020), and use a battery power supply that consumes little energy and can run for years on a single battery charge. Their price varies depending on the quality of the device. For instance, a good quality beacon costs around 20 euros per piece (Locatify, 2019). This Bluetooth beacon technology is way cheaper than other active asset tracking technologies such as RFID and GPS. In addition to the low cost, Bluetooth signals can be read by iOS and Android smartphones (see Figure 3), whereas other technologies such as RFID requires designated scanners or fixed RFID readers (AHG, Inc., n.d.). Additionally, BLE beacons are easy to install because BLE does not require any additional infrastructure and integrates with existing networks and systems (Chauhan, 2020).

It is worth mentioning that besides beacons, there are tags that use BLE technology, and independently of the acquisition of a beacon or a tag, a BLE device will work the same, which means that a beacon product can be bought and used as a tag or vice versa. These two terms do not describe different technologies, but two different applications of the same technology (Bluetooth Low Energy Technology), stationary applications are beacon-based, and on-the-move deployments are tag-based (Ciurkot, 2021).

Components used for Asset Tracking

There are three components used for asset tracking: BLE tags or beacons, which transmit a small amount of data in a short range and consumes low energy. Another component is the BLE reader, which receives data either from BLE tags or Beacons and broadcast the location of assets to the tracking platform or application, which is the third component used for asset tracking. The reader sends and displays the information of the asset management software, which the users use to report on the assets through this platform/application because it tells the exact location of the objects of interest (Chauhan, 2020). Figure 3 illustrates the relation of each component.

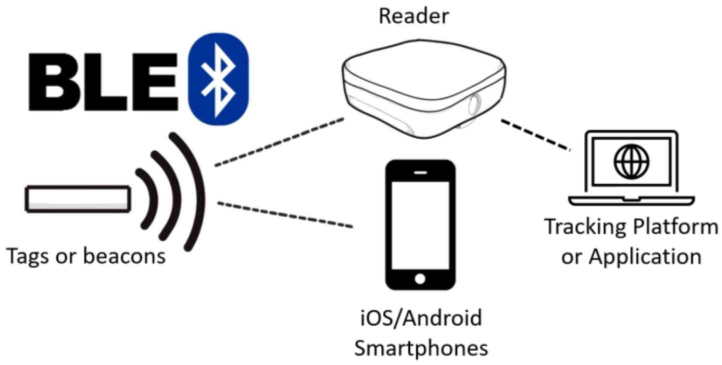

Figure 3: BLE components

Fields of Applications

This technology is used in factories, warehouses, and other facilities because it can track tools such as forklifts, trolleys, medical devices, and even people. For instance, in a hospital, the patients can be tracked and workers; this is useful because it can ensure their safety during an emergency (Kingatua, 2020).

BLE is gaining popularity in industrial applications because the industrial equipment and devices can be controlled from a smartphone as well as the readings and measurements can be automatically obtained by the use of mobile applications which can send this information directly to the cloud for processing (AHG, Inc., n.d.).

Due to its harsh environment, the BLE tracking devices can come in uncased and cased models for the tracking of construction equipment in the construction field. The cases are designed to protect the beacon; therefore, they are hardened, water-resistant, and have protection for construction or extreme conditions. In addition, the beacons can be screwed, bolted, tied, or even glued to the assets (TENNA, 2020), meaning that they could be placed in pavers and rollers to track their movements during operations.

Challenges and limitations

BLE technology supports lightning-quick connection, and for the same reason, it transmits short bursts of small packets of data followed by lightning-quick disconnection. This makes BLE limited to only particular applications where the pulsed data transmissions are not a problem. For instance, it can be used in homes to transmit if the refrigerator has raised the temperature or not; another example can be to transmit data to know whether a room is occupied or not (Wilson R. , 2014).

Additionally, Bluetooth Low Energy technology is used to transmit state data but not for streaming content (Wilson R. , 2014). Moreover, according to Onofre et al. (2016), the limitations of this technology are regarding reliability and accuracy for the application in range sensing areas. Furthermore, there are security concerns that some rogue apps could be used to track the users (Onofre et al., 2016).

Based on the limitations above mentioned and since, for the asphalt industry, the constant transmission of information is needed to know the exact location of machinery, meaning that transmission of significant amounts of data is required, this hinders its implementation within the PQi methodology for tracking pavers and rollers.

Accuracy

The Bluetooth position technology offers an accuracy of meter level and centimetre level, this depends on the configuration and enhancements applied to it (Kingatua, 2020) but in general, it can be as good as 1.5 meters approximately (Locatify, 2019). For that reason, this technology is more suitable for applications that do not require precise positioning (Kingatua, 2020).

Future

This technology is developing further because it offers more precise positioning by using tools such as magnetic field detention, gyroscope, accelerator meter, and even Near Field Communication (NFC) chips (Locatify, 2019). This could open up a possibility for implementing BLE in the paving industry in the future.

2.2.3. Locata Technology

The development of this new terrestrial radio frequency-based technology started in 2003 by the Locata Corporation with four key objectives: Availability in all environments, High reliability, High accuracy, and Cost-effectiveness (Rizos & Yang, 2019) and was designed to overcome the limitations of GNSS systems (GPS is one of this systems) (Grgac & Paar, 2019).

Locata utilises a network of ground-based transmitters; this network is also called LocataNets and consists of four or more synchronised LocataLite transceivers (Black, 2020) that cover a selected area with strong radio-positioning signals (LOCATA CORPORATION, 2014). One unique aspect of this LocataNets is the time synchronisation of the LocataLites that allows single-point positioning, which means that there are no differential methods or transmitted data corrections (Choudhury, Rizos, & Harvey, 2009).

The positional signals emitted by the LocataLites are time-synchronised via “TimeLoc”, which is a patented wireless synchronisation technology that allows Locata to broadcast GPS-like signals via asynchronous, fully autonomous ground-based network of transceivers (LOCATA CORPORATION, 2014). TimeLoc also permits a single mobile Locata receiver, also called Locata Rover, to use the synchronised signals of the LocataLites transceivers to calculate an accurate Positioning Navigation and Timing solution (Black, 2020). The LocataLites achieve this high accuracy of synchronisation wirelessly; in other words, they achieve it without atomic clocks or satellites or external control and without needing a reference network for time correction (LOCATA CORPORATION, 2014), making this solution simple and more reliable than traditional technologies. When Locata receivers (Locata Rovers) track four or more signals from different LocataLites, completely independent GPS positions are obtained (Choudhury, Rizos, & Harvey, 2009). Figure 4 shows how LocataLite Transceiver and Locata Rover looks like in real life.

Figure 4: LocataLite G4 Transceiver and Locata RV8 Rover (LOCATA CORPORATION, 2014)

In addition, the Locata transmitters can autonomously survey and initialise themselves to form a network, making LocataNets easily expandable to grant additional coverage (LOCATA CORPORATION, 2014). Another aspect is that LocataLites can autonomously join or leave networks as required, which allows for easy installation and reduce cost on maintenance (LOCATA CORPORATION, 2014). The LocataLites transmit signals in the license-free 2.4GHz that can penetrate through different materials (Choudhury, Rizos, & Harvey, 2009), making it suitable for indoor positioning as well.

Moreover, the flexibility of Locata guarantees signal integrity, even in the most demanding environments. Therefore this ability to modify the reliability and availability of the signals is beyond the reach of GPS or even any other technology that cannot control the transmitters generating the location signal (LOCATA CORPORATION, 2014). Additionally, Locata technology can be used in both indoors and outdoors environments and even in the transition zone between them and can provide continuous navigation parameters such as position, velocity, and altitude for both environments and in the transition zone (Jiang, Li, Rizos, Cai, & Shangguan, Seamless Indoor-Outdoor Navigation based on GNSS, INS and Terrestrial Ranging Techniques, 2017).

This technology can be integrated smoothly with GPS, but it can also function completely independently because it can replace GPS in a local area. This gives the world a new technology that can eliminate several GPS deficiencies and vulnerabilities such as jamming and spoofing (LOCATA CORPORATION, 2014). In addition, the Locata ground-based Positioning, Navigation, and Timing technology deliver positioning that in several scenarios surpass the performance and reliability of GPS (Black, 2020).

Fields of application

Due to its high accuracy and the potential to complement or even replace GPS in challenging environments. This technology can be applied in several field applications, such as open-cut mining. For instance, during a study conducted at DeBeers Venetia Mine in South Africa, this technology combined with Leica was installed on drills, dozers, and backpack systems and showed high positional accuracies (Rizos & Yang, 2019). Additionally, Locata can be used for deformation monitoring, for instance, the use of Locata technology to assess structural deformation.

In indoor/outdoor vehicle tracking, a prototype of Locata technology showed that the accuracies of outdoor static positioning are sub-centimetre level, and for outdoor kinematic positioning, the accuracy was at a centimetre level (Rizos & Yang, 2019).

Based on those mentioned above, this technology could be a potential alternative for replacing GPS in the PQi methodology due to its reliability, high accuracy. Also, as it was read from the above examples, it can be deployed in harsh environments as well.

Challenges and limitations

This technology faces some challenges in the presence of Radio Frequency (RF) interference due to the 2.4 GHz in which it operates; for instance, Wi-Fi signals are one of the potential interferers. However, some improvements have been made in terms of RFI rejection in newer versions of Locata (Rizos & Yang, 2019).

In terms of its implementation, the installation is complex since to configure a LocataNet with spatial diversity, there need to be several antennas mounted on concrete bases, and their coordinates have to be precisely surveyed (Rizos & Yang, 2019). Also, there is a possibility that there are some challenges concerning the configuration and power issues related to the LocataNet installation (Rizos & Yang, 2019). Moreover, another aspect that hinders the implementation of Locata is the environmental restrictions, which means that the network's geometry is restricted by the application environment (Rizos & Yang, 2019).

Lastly, it can be mentioned that some aspects that can limit Locata’s future development are the relatively high costs, incompatible user hardware, complex configuration of LocataNets as explained before, environmental constraints, and RFI (Rizos & Yang, 2019).

Accuracy

Previous research has proved the accuracy of this technology. For instance, in a test conducted by the USAF (US Air Force) in the White Sands Missile Range in New Mexico, it was proved that Locata technology has an accuracy of 6cm horizontal in the complete absence of GPS signals (LOCATA CORPORATION, 2014). Furthermore, in another study conducted by Jiang et al. (2017), Locata, GNSS and Inertial Navigation systems (which consists of accelerometers, gyroscopes and a navigation computer) were integrated by using the FKF data fusion algorithm. This new system was tested, which resulted in overall positioning accuracy of 7 centimetres indoors-outdoors; additionally, during this tests, the outdoors positioning accuracy was better than the indoors one because it resulted in 2 centimetres of accuracy (Jiang, Li, Rizos, Cai, & Shangguan, Seamless Indoor-Outdoor Navigation based on GNSS, INS and Terrestrial Ranging Techniques, 2017). Additionally, in another study conducted by Jiang, Li, & Rizos (2014), the position accuracy of Locata was better than 4 centimetres. Therefore, based on the results obtained from previous researches, it can be mentioned that the average accuracy of Locata technology is of 4 centimetres approximately.

Future

According to LOCATA CORPORATION (2014), this technology has the potential to become an essential and even fundamental part of future positioning systems because the company is taking radio-positioning technology to the next level. This means that this new technology will drive the future development of high-accuracy radio-positioning in environments with a lack of reliable and functional GPS (LOCATA CORPORATION, 2014).

However, since this technology is still under development, and, as suggested by Rizos & Yang (2019), more research should be done regarding it in terms of its errors and biases as well as the integer ambiguity of the algorithms used so the positioning accuracy and reliability of Locata standalone system can be improved (Rizos & Yang, 2019).

Lastly, since Locata Company is working on reducing costs to make this technology accessible for market users, it seems like a promising alternative to GPS in the future.

2.2.4. Unmanned Aerial System (UAS)

UAS, as its name suggests, are aircraft with no human pilots on board and were initially designed for military purposes (Zhou & Gheisari, 2018). Several terms refer to the same system of equipment operated independently of human control, such as Unmanned Aerial Vehicles (UAV) and drones (Tatum & Liu, 2017).

The system comprises the drone, the control system, ground and satellite-based equipment, communication links, and the operator to fly the aircraft effectively and efficiently (Tatum & Liu, 2017). The number of people needed to operate these devices is at least three, the pilot, the safety manager, and the mission specialist (Zhou & Gheisari, 2018).

UAS is easy to operate and has several advantages: low cost, superior accessibility, and improved safety. Additionally, they can reach vantage points that are not accessible for humans or some equipment and require low human involvement, reducing risk on job sites (Zhou & Gheisari, 2018). Also, UAS can handle some construction tasks at less time and lower cost (Zhou & Gheisari, 2018). Those are some of the reasons why there has been an amazing increase in the development and use of UAVs or drones in recent years (Nar, Amin, Banerjee, Garg, & Pardasani, 2019), making them more popular and commercially available.

These commercial devices can navigate and collect data autonomously and transfer it to a control station in real-time (Zhou & Gheisari, 2018). Also, they can be equipped with several types of sensors, such as cameras which are the most used sensor that has been incorporated to UAS in construction operations (Zhou & Gheisari, 2018). Lidar can be incorporated in UAVs as well to generate point cloud data; however, this sensor is more expensive and heavy compared with high-resolution cameras; also, experts are required to operate Lidar (Zhou & Gheisari, 2018). Another sensor that can be integrated into UAS is RFID units. Some examples of the applications of each of these sensors with drones will be discussed in the following sections.

Fields of application

The use of UAS is increasing across several industries as well as its technological advancements, which make them user-friendly and low-cost (Tatum & Liu, 2017). Due to the fast-growing market of the

Unmanned Aerial System, it has boosted its expansion to several sectors, being construction one of them (Zhou & Gheisari, 2018). For instance, some of the application of UAS in the construction industry are site inspection and surveying where spatiotemporal phenomena are obtained by using UAS; safety inspection that includes a periodic evaluation of the construction site based on a set of safety criteria; progress monitoring where the work-in-progress is evaluated using visual or thermal data collected by UAS; damage assessment where data collected by drones is used to assess the damage of buildings after disasters; and building maintenance where UAS collects visual or thermal data to evaluate building conditions (Zhou & Gheisari, 2018). Also, the construction industry uses UAVs to provide real-time reconnaissance of job sites and produce high-definition videos and images for publicity and documentation of the progress (Tatum & Liu, 2017). The images produced by UAS can be obtained daily to do the planning for the placement of stored material, flow of workers and vehicles in and around the site (Tatum & Liu, 2017). This type of data can also be used to identify possible issues regarding the installed construction or the constructability of planned installations (Tatum & Liu, 2017). Additionally, it is important to mention that three-dimensional models can be constructed using images collected by UAS because they can observe the object of interest from different angles and perspectives (Zhou & Gheisari, 2018).

In the study made by Hubbard et al. (2015, as cited in Zhou & Gheisari, 2018), a UAS with an RFDI unit was used to track materials on-site. This was done by installing an RDFI reader on the UAS and placing tags in the objects that were aimed to be tracked; in other words, the tags were placed on a route along which the UAS would fly (Zhou & Gheisari, 2018). The information obtained using RFDI was used with BIM and project supply chain management software (Hubbard et al., 2015, as cited in Zhou & Gheisari, 2018).

In the paving industry, during a study made by Zhang and Elaksher (2012, as cited in Zhou & Gheisari, 2018), UAS was used to measure surface distresses of unpaved roads. The authors found that compared with satellite and manned aircraft, the collection of data by using UAS is faster, safer and cheaper (Zhou & Gheisari, 2018).

Based on the examples mentioned above, it can be mentioned that UAS can be an alternative technology for tracking machinery during on-site paving operations.

Challenges and limitations

The wind is one of the principal limitations to UAS because it can interfere with the flight control of UAS (Zhou & Gheisari, 2018). Also, the limited manoeuvrability when operating UAS manually is an issue because the device always needs to be within operators' sight (Zhou & Gheisari, 2018).

UAS can be a cause of distraction for workers; also, there could be new safety hazards introducing by flying UAS over the construction sites (Zhou & Gheisari, 2018). Moreover, the laws of certain countries are a potential limitation of fully autonomous UAS operation (Zhou & Gheisari, 2018), as well as the limited autonomous feature and subpar obstacle avoidance (Zhou & Gheisari, 2018).

Another challenge that UAV might encounter is regarding the limitations of the extra sensor implemented. For instance, data/image processing can be an issue for photogrammetry applications because, according to Zhang and Elaksher (2012, as cited in Zhou & Gheisari, 2018), it still would need more robust methods to have a better quality of image orientation and 3D reconstruction.

Accuracy

The accuracy of using drones depends on the type of drone used and the sensor implemented on it. For instance, the accuracy of an image captured by a drone will depend on the quality of the image and the processing software; this close photogrammetric software can be reduced if the photos taken are close to each other, that is usually the limitation of ground photo collection methods (Zhou & Gheisari, 2018).

Future

In the study done by Zhou & Gheisari (2018), the results showed that the semi-autonomous and autonomous UAS performed better than manual UAS because they improved manoeuvrability and reduced the risk in UAS operations. However, they will need more supportive regulations and BIM to have UAS autonomous flights as a standard tool for construction (Zhou & Gheisari, 2018). Additionally, due to the growing market, manufacturers will offer better products at less cost (Zhou & Gheisari, 2018).

UAS can be combined with other technologies such as virtual reality (VR), augmented reality (AR), fully autonomous systems, wearable technologies, artificial intelligence(AI), machine learning (ML), etc. meaning unlimited opportunities and having a great potential for the use of drones in several fields with a combination of sensors (Zhou & Gheisari, 2018).

2.2.5. Lidar

Lidar stands for Light Detection and Ranging and is a remote sensing technology used to collect information about objects without even making physical contact with them. This is done by using light rays (Gargoum & El-Basyouny, 2017).

Lidar data is obtained by using scanning equipment that reflects the light beams off objects. In other words, the light pulse that is emitted from the sensor bounces off the target object, and then it is reflected back to the sensor (Gargoum & El-Basyouny, 2017). The distance between the scanner and the scanned object can be estimated by using the speed of light and the time it took for the reflection to return (Gargoum & El-Basyouny, 2017). The position of the scanned object can be calculated based on the distance between the scanner and the object, and the positional information of the scanner is obtained by the GNSS equipment (Gargoum & El-Basyouny, 2017).

The main steps followed in processing Lidar data are: background filtering where as many as possible points from the background objects are excluded; after the background filtering, a Region of Interest (ROI) is selected, the steps mentioned above are helpful because the detection and classification accuracy is improved and the computational costs are reduced (Zhao et al., 2019). After that, the following steps continue: object clustering where the various objects are categorised into clusters based on their similarities, the determination of these clusters is done through an algorithm; object classification; and real-time tracking the movement of a particular object in which the speed and trajectory of each object are obtained (Zhao et al., 2019). These steps are regardless of where the sensors are installed (Zhao et al., 2019).

The output data obtained from Lidar includes the location of each point in the X, Y, Z coordinates as well as their distance to the sensor, intensity, laser ID, azimuth, adjusted time, and timestamp (Zhao et al., 2019). With this information and based on the GPS location of the Lidar sensor and a reference point, the obtained points can be paired to their exact location in the real physical world (Zhao et al., 2019).

Lidar data can be collected by the use of aeroplanes (airborne) or by the use of satellites (space-borne), or even collected from the ground (terrestrial) (Gargoum & El-Basyouny, 2017). This terrestrial Lidar can be static or mobile, and during this section, the mobile Lidar will be explained because it is the one that seems more suitable for tracking machinery during road paving operations, because a narrow area is needed, otherwise if a broad area is needed, the most common instruments used to collect this data would be aeroplanes or helicopters (NOAA, 2021).

Mobile Lidar integrates laser scanning equipment, GPS, and inertial navigation technologies into one system capable of collecting positioning data and intensity information about the surrounding objects (Gargoum & El-Basyouny, 2017). In mobile laser scanning, the equipment to collect data is mounted on a truck that goes through the highway collecting data to create point cloud images of the entire road segment. Figure 5 shows an example of point cloud images. Also, due to the high point density of these datasets, it allows the automated extraction of several features of the road, which otherwise would be collected manually, taking lots of time (Gargoum & El-Basyouny, 2017). Lidar data produces accurate images of roads while travelling at highway speed which leads to minimal disruption of traffic (Gargoum & El-Basyouny, 2017).

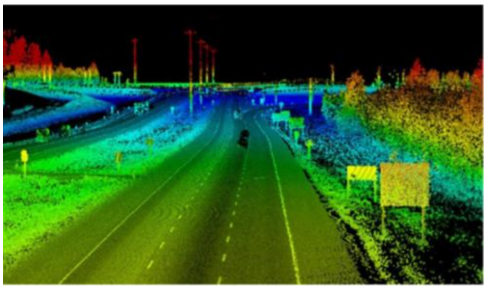

Figure 5: Lidar point cloud highway (Gargoum & El-Basyouny, 2017)

The common aspects considered for model selection of Lidar are vertical field of view, vertical resolution of laser beams, and laser channels because more laser channels mean more coverage, hence higher accuracy and higher costs as well (Zhao et al., 2019). Additionally, an important aspect of the overall performance of the Lidar application is the installation and the technical features of the device (Zhao et al., 2019).

Fields of application

Mobile Laser Scanning is applied in fields such as Tourism for virtual tour of attractions and historic preservation; research for coastal erosion, landslide assessment and unstable slopes; project planning for environmental studies, topographic mapping, roadway analysis; project development for feature extraction for CAD models and baseline data; construction for machine control and construction automation, post-construction quality control, pavement smoothness quality determination; maintenance for bridge inspection, power line clearance, vegetation management, drainage flooding; operations for emergency responses, building information modelling, land use, land zoning, traffic congestion, parking utilisation; safety for driver assistance, autonomous navigation, accident investigation, extraction of geometric properties and features for analysis; asset management for inventory mapping, modelling and inspection, automated/semiautomated extraction of signs , etc. (Gargoum & El-Basyouny, 2017).

Mobile Laser Scanning (MLS) is a common approach for obtaining data for transportation applications since the road features are obtained with a high level of detail (Williams et al., 2013, as cited in Gargoum & El-Basyouny, 2017). Additionally, MLS equipment is mounted on vehicles and captures 360-degree imagery of the roadway (Gargoum & El-Basyouny, 2017).

Based on the application fields mentioned above, this technology was chosen as an option to be an alternative technology for replacing GPS for tracking machinery in the paving industry.

Challenges and limitations

Some of the limitations include limited range, weather (Hecht, 2018), and high costs, which might hinder its acquisition if it is meant to be used in small projects (Schmehl, 2020). Also, to have a good result, high volumes of data are needed, leading to another limitation: too much data obtained by the

Lidar. That can be problematic because the team might not be adequately equipped to manipulate and process such enormous amounts of data (Schmehl, 2020).

Zhao et al. (2019) stated that due to the limited number of lasers in the Lidar sensors, point clouds' density is lower than data collected by advanced Lidar sensors (more lasers). This low density of point clouds means that specific characteristics of objects are difficult to extract. Additionally, the accuracy of the reference point can be affected due to incomplete clusters caused by occlusion and perspective shadow (Zhao et al., 2019). Finally, it is worth mentioning that there is no calibration of the data processing procedure, and without the high accuracy of GPS receivers, precise positioning cannot be achieved (Zhao et al., 2019).

Accuracy

In the study conducted by Ghallabi et al. (2018), a map-based localisation using a multilayer Lidar was proposed in combination with the Particle Filter (PF) framework. This was proven to give a lane-level localisation with a 22 centimetres cross-tracking accuracy (Ghallabi, Nashashibi, El-Haj-Shhade, & Mittet, 2018).

Based on the examples mentioned above, it can be mentioned that the accuracy of this technology depends on the number of lasers used, the processing technologies used by Lidar, and the additional technologies used in combination with Lidar. Which depends on the project's necessities and goals; however, the value of 22 centimetres accuracy will be used for future calculations.

Future

Regardless of several companies and agencies collecting Lidar data, the effort to explore its full potential is limited because either researchers do not realise the full potential of this type of data or because of the lack of expertise required to extract more information from those datasets (Gargoum & El-Basyouny, 2017). Therefore, there would be more research to explore more features, applications, limitations, and other aspects regarding Lidar in the coming years.

On the other hand, roadside Lidar sensing systems are expected to work individually, which means that they should not depend on data from other supportive sources such as GPS or high-resolution 3D maps (Zhao et al., 2019). This would give some opportunity to implement it to track the machinery in the asphalt industry and other industries.

2.2.6. Ultra-Wideband

Ultra-wideband (UWB) is a short-range radio technology that is commonly used for indoor positioning and uses short (nanosecond) bursts of electromagnetic energy in the form of short pulse radio frequency (RF) waveforms over a large bandwidth (N500 MHz) (Saidi et al., 2011). Ultra-wideband has the ability to precisely measure the time-of-flight (ToF) of a signal between a transmitter and a receiver. Moreover, this ability of performance provides the means for constructing a localisation system using several receivers by measuring the time-difference-of-arrival (TDOA) between them from several moving transmitters (tags) (Saidi et al., 2011). At least three receivers are necessary for the exact location of an object and to measure 2D location readings, whereas at least four are needed to measure 3D location readings (Cheng, Venugopal, Teizer, & Vela, 2011). Also, it is worth mentioning that there must be a direct line of sight between the receiver and the transmitter (infsoft, n.d.). Furthermore, the object of interest must be equipped with a tag that functions either with battery power or draws its power via another object (infsoft, n.d.). The process of positioning any object is that the tag sends data such as ID, ToF, timestamp to the receivers; these receivers have a fixed position and uses the running time of light to determine the distance of the asset (infsoft, n.d.), see Figure 6 for illustration of the components.

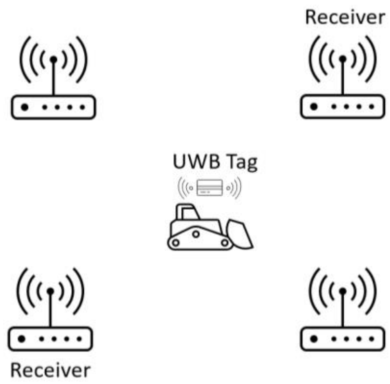

Figure 6: UWB system components

In addition, ultra-wideband has shown to have several advantages such as longer and accurate ranging, secure communication channel (RTLOC, 2020), higher measurement rate, improved measurement accuracy, and even immunity to interference from rain, fog, or clutter (Cheng, Venugopal, Teizer, & Vela, 2011).

Fields of application

Since UWB is generally used for indoor positioning, this means that it is more suitable for special industry applications (infsoft, n.d.). For instance, UWB is used in warehouse and production facilities to track machines such as forklifts with high precision (infsoft, n.d.). The tracking of assets in these vast warehouses is done by using UWB to record their location and service life; even the movement history can be retrieved (infsoft, n.d.). With this information, wrong deliveries and incorrect inventories can be prevented. Moreover, the production supply chain can be improved by applying these tracking systems and combining them with machine learning (infsoft, n.d.).

According to Cheng et al. (2011), the use of UWB for real-time location tracking in construction environments is also feasible, which means that the use of UWB localisation technologies in large, open, outdoor areas is feasible as well (Cheng et al., 2011). Additionally, during that study, the data obtained by UWB was used to do a safety analysis of the construction place. In other words, the data obtained by UWB was used for better documenting, analysing, understanding, and correcting in the best possible way the safety practices that occurred in the field, for instance, it could be determined whether the workers kept a safe distance from the cranes or not (Cheng et al., 2011).

Another UWB application includes item tracking in warehouses to improve logistics. Also, as mentioned in the previous paragraph, tracking people, equipment, and materials in a construction environment helps monitor work task status and work zone safety. UWB technology can be used in the paving industry to assess a pavement sample with good accuracy (Park & Nguyen, 2003).

Due to these fields of application, UWB was considered as a possible alternative technology to replace GPS.

Challenges and Limitations

Industrial environments where there are obstructions present a limitation for the application of UWB, making the open field an ideal environment for UWB sensing (Cheng, Venugopal, Teizer, & Vela, 2011).

In a study conducted by Saidi et al. (2011), the authors stated that the height of the measured tags dominates the 3D positioning error of UWB; in other words, the error decreases as tag elevation increases. This can be a limitation because it is not always possible to place tags in high places, hindering the performance and implementation of this technology.

According to Saidi et al. (2011), several studies that used low-powered UWB tags (from 5mw to 1 W) indicated that the real-time localisation of tags resources such as workers or machines is still feasible in partial occluded indoor environments. However, the tracking of resources in fully enclosed spaces with thick and reinforced concrete walls is not practically feasible. Nonetheless, with the new technological advancements, such as higher power UWB, nowadays, it is possible to use this technology with high accuracy indoors.

Accuracy

Combining the data from 3 receivers, results in a position accuracy of less than 30 centimetres (infsoft, n.d.). This accuracy depends on the geometric configuration of the reference point and the receivers deployed in the field (Cheng et al., 2011).

However, it is worth mentioning that several factors can affect the accuracy of the UWB, such as the receiver/reference tag position error, receiver orientation, the antenna type, and others, being the tag orientation one of the most critical factors (Saidi et al., 2011).

Future

The industry can benefit from its technology because the data obtained using UWB can be used to automate conventional work sampling techniques (Cheng et al., 2011). However, to achieve this, more detailed information than only location data will be needed, such as knowing whether a worker is carrying a tool (productive task) or not (unproductive task), but, according to Cheng et al. (2011), more research should be done regarding this topic.

Also, there is an increase in the adoption of UWB positioning, which is promising due to its massive growth with its integration in mobile phones (RTLOC, 2020).

2.2.7. U-Blox

U-Blox has developed chips and module solutions based on sensor data fusion with satellite data (Favey et al., 2011). Figure 7 shows an example of how U-Blox chips looks like in real life. The U-Blox receivers are based on the sensor fusion dead reckoning technology. This helps to keep high accuracy positioning by using information from various sensors such as gyro sensor, accelerometer and speed pulse to calculate the current position even when GPS-only positioning is difficult or impossible (Furuno, n.d.). In other words, dead reckoning is a concept used to extrapolate the position. Because when the U-Blox GPS receiver chip travels through regions of poor GPS reception and based on the last known position, the vehicle sensors give information to the receiver indicating how far and in which direction the vehicle has travelled. After that, the chip processes these data and combines it with GPS positional readings. Therefore, by doing this process, a better approximation of the object's position can be extrapolated despite of GPS satellite visibility (Favey et al., 2011). In addition to that, there are other remarkable advantages such as low cost, low power consumption, small size, high integration, and portability (Lu et al., 2019).

Figure 7: Example of a U-Blox chip NEO-M8 (U-blox, 2020)

Fields of application

U-Blox low-cost receivers are an alternative to expensive measurement devices in fields such as aerial vehicle applications, mapping surveys, geodetic monitoring, and many others (Lu et al., 2019). In addition, the low power consumption makes it ideal for power-sensitive and battery-dependent applications such as asset trackers, animal trackers, and even fitness wearables (Di Paolo Emilio, 2021).

U-Blox also offers positioning for in-car navigation systems, time synchronisation for cellular base stations; it can also be implemented on Unmanned Aerial Vehicles and track people and assets (U-blox, 2020).

The reason for including this technology as an alternative for GPS in the paving industry was that despite it is still GPS, these U-Blox chips include other types of data, making it more attractive for use in this type of industry.

Challenges and Limitations

In a study made by Rapiński (2014, as cited in Lu et al., 2019), where the observation quality and position accuracy of U-Blox LEA-6T was evaluated, it was demonstrated that the accuracy of the receiver clock limited the position performance of the low-cost receiver.

Accuracy

Several scientific articles where u-blox was tested were revised to find the accuracy of this technology. Therefore, according to Lu et al. (2019), the positioning accuracy of this technology can reach the 1-centimetre level. Furthermore, another study made by Mongredien et al. (2016, as cited in Lu et al., 2019) showed that centimetre-level position accuracy was obtained by using a u-blox receiver and differential correction information. Likewise, in the study made by Zuo et al. (2016, as cited in Lu et al., 2019), it reached a static 1.2 centimetres and dynamic 2.4 centimetres positioning accuracy by using a u-blox receiver and measurement antenna. Therefore, based on these studies, the proven accuracy of U-blox is of a centimetre level between 1-2 centimetres approximately.

Future

This new generation of GNSS devices aims to overcome the problem of scalability of traditional high-precision GNSS by implementing a new generation of GNSS hardware and new correction data services. These, combined, can facilitate the creation of cheaper, more compact, and genuinely scalable high-precision GNSS solutions making them ready for the mass market in the coming years (Fairhurst, Commentary: High-precision positioning is going mainstream, 2019). Additionally, this new generation abandons the two-way link between the customer device and the correction data service, which is the main feature of traditional high precision GNSS corrections. Instead of each device sending its own location-specific GNSS correction data, the new generation creates a real-time model of relevant errors among their whole territory; this is broadcasted by satellites and the Internet for customer devices to pick up this information (Fairhurst, Commentary: High-precision positioning is going mainstream, 2019). This opens the door to large scale mass-market applications of high-precision GNSS

2.2.8. Radio Frequency Identification (RFID)

Radio Frequency Identification is a generic term for technologies that use radio waves to identify people or objects automatically; also, RFID is an area of automatic identification (Roberts, 2006). Operational RFID systems comprise tags and readers which interact with objects and database systems (Enterprise System) to grant information and operational function (Roberts, 2006). Figure 8 illustrates the RFID system.

Figure 8: Typical RFID System (Roberts, 2006)

RFID tags are intelligent devices that are used to track products throughout the supply chain; these devices can be attached to or even implanted in almost anything (Brodie, Jacob, & Farrell, 2016). The RFDI tags were created as an improvement for bar codes because RFID tags have read and write capabilities, which means that the data stored in RFDI tags can be changed, updated, and even locked (Brodie, Jacob, & Farrell, 2016). The RFID tags transmit the data via a pre-determined radio frequency, and this information is taken and transmitted to a central database (Bonsor, 2020).

Some of the advantages of using RFID systems are the non-contact and non-line-of-sight, meaning that tags can be read through several visually and environmentally challenging conditions, for instance, snow, ice, fog, paint, grime, inside containers and vehicles. Additionally, the RFID reader can read several tags virtually instantaneously (Roberts, 2006).

Types of RFID tags

RFID tags can be categorised as active, semi-passive, and passive. Nevertheless, they also can be categorised based on how data is stored on the tag; they can be read-write, read-only, and WORM (write once, read many).

Active tags use internal batteries to power their circuits and broadcast data to the reader (Brodie, Jacob, & Farrell, 2016). Active tags generally broadcast in the frequency range between 850 MHz to 950 MHz (Brodie, Jacob, & Farrell, 2016).

Semi-passive tags are similar to active tags; they broadcast in the same frequency range and use internal batteries to power their circuits. However, this type of tag relies on the reader to supply its power for broadcasting (Bonsor & Fenlon, 2014, as cited in Brodie, Jacob, & Farrell, 2016).

Passive tags rely entirely on the reader for power and can be read up to six meters away (Brodie, Jacob, & Farrell, 2016). They are usually manufactured to be disposable, which means that they have lower production costs compared to active or semi-passive tags (Brodie, Jacob, & Farrell, 2016).

Read-write tags can be used to add or overwrite data at any time (Brodie, Jacob, & Farrell, 2016). As its names say, read-only can only be read because these tags cannot be changed from their originally installed data (Brodie, Jacob, & Farrell, 2016). Finally, WORM tags can be added additional data once; however, they cannot be overwritten (Bonsor & Fenlon, 2014, as cited in Brodie, Jacob, & Farrell, 2016).

Fields of application

In the field of tracking, these systems have been used to track vehicles, airline passengers, patients with Alzheimer and even pets (Bonsor & Fenlon, 2014, as cited in Brodie, Jacob, & Farrell, 2016). In addition, these systems are used where objects such as vehicles, animals, or even people are tagged and provides automatic location and navigational support (Roberts, 2006). Regarding industrial production, RFID tags are used to track the location of each manufactured product from the time it is made until the point of sale (Wang et al., 2007, as cited in Brodie, Jacob, & Farrell, 2016).

RFID technology is used in the construction field for equipment and tool management, inventory management, workforce management, enhancing safety, and reducing thefts (CONEXPO-CON/AGG, 2021).

Due to the application fields above mentioned, this technology was included as a possible technology for tracking machinery in the paving industry.

Challenges and limitations

A reader can fail to identify a tag, either because of the distance between the tag and the reader, the placement and direction of the tag, or the moving speed of the tag and the reader (Inoue, Hagiwara, & Yasuura, 2004). Additionally, the material density of the tagged item can be the cause of reflection and absorption variances (Schoeke, 2019).

For the massive adoption of RFID, there are some challenges such as energy-efficient data gathering and process in large scale environments, software infrastructure for supporting the Internet of Things (IoT), the business value and performance measurement, and security and privacy attacks (Zhang, Huang, & Jo, 2015).

On the other hand, there are some limitations outside the technology itself, such as marketing problems, lack of standards, and false promises. However, people involved in these fields have become aware of this and are working to solve these issues, bringing benefits to RFID (Campbell, n.d.).

Accuracies

Off-the-shelf RFID readers provide uncertain measurements that are capable of giving a meter accuracy (Gunatilake et al., 2021). However, this accuracy can be improved if some algorithms are implemented. For instance, in a study made by Gunatilake et al. (2021), the authors proposed a localization method for underground water pipelines and used off-the-shelf RFID components with particle filter algorithms which consisted of using both Received Signal Strength Indication (RSSI) and phase data in the measurement model to achieve high accuracy. After the experiments were done, the authors stated that their proposed system had achieved an accuracy of 15 centimetres (Gunatilake et al., 2021). It is noteworthy that the distribution of the RFID tags has an important impact on the performance of the overall technology (Zhang et al., 2021).

Future

According to Pierce (2020) there is nothing revolutionary left to discover or develop for RFID technologies. However, what can be improved are the technical aspects such as hardware reliability, read range and technology standards that open up new markets and even allow the technology to be used in fields that were not originally thought of (Pierce, 2020). Another aspect that will also open up the possibilities to use RFID is lowering the costs of this technology (Pierce, 2020).

2.2.9. Thermal Imaging

Lu, Dai, & Zaniewski (2021) proposed a thermal-based technology that used infrared cameras, laptop computers, digital video recorder and video monitor. This technology was proposed as an alternative to GPS technology in the existing Intelligent Compaction technology for the position estimation of rollers.

Some of the advantages of using infrared cameras are the utilization in unfavourable conditions such as fog, smoke, poor illumination. For instance, it can be used during the day and night because these cameras are sensitive to temperature rather than illumination. Infrared cameras can even be used in places where vapour or dust are emanated from fresh asphalt (Lu, Dai, & Zaniewski, 2021).

It is noteworthy that these type of cameras have an industrial design, meaning that they can be used in harsh environments, for instance, in extreme ambient temperature or the presence of smog, vapour and rain. Making them feasible for long term deployment in the paving construction (Lu, Dai, & Zaniewski, 2021).

Fields of application

In the study made by Vidas and Sridha (2012, as cited in Lu, Dai, & Zaniewski, 2021), the infrared camera showed its potential to be used for indoor positioning and orientation applications. Another study, made by Mouats et al. (2015, as cited in Lu, Dai, & Zaniewski, 2021), where binocular thermal imaging was used for outdoor navigation, provided improved performance in localization and orientation compared to monovular cases. After that, researchers increased the capabilities of thermal-based positioning and orientation applications by combining position data from infrared cameras and sensors such as inertial measurement unit, Lidar and even digital camera (Lu, Dai, & Zaniewski, 2021).

Since the proposed technology is not manufacturer-specific, this means that it can be applied in several rollers, either with existing Intelligent Compaction or without it, to track and map the pavement compaction process (Lu, Dai, & Zaniewski, 2021).

Challenges and Limitations

During the study made by Lu, Dai, & Zaniewski (2021), the ambient factors were not considered in the laboratory and field validation. This could be a limitation because these ambient factors might directly or indirectly affect the thermal information captured by the infrared camera, which could influence the position estimation of the rollers (Lu, Dai, & Zaniewski, 2021).

The proposed method relied on the assumption that the orientation of the infrared camera is locked during the whole time while the roller is travelling (Lu, Dai, & Zaniewski, 2021). That is not always the case; for instance, when used in dynamic rollers, they make infrared cameras oscillate, which might change the projective relationship between the image plane and the ground plane (Lu, Dai, & Zaniewski, 2021). Some equipment such as camera vibration isolators or camera stabilizers and some video stabilization techniques might be used to cope with these challenges (Lu, Dai, & Zaniewski, 2021). However, the authors of the study mentioned above suggest that more research should be done.

Accuracy

According to Lu, Dai, & Zaniewski (2021), the accuracy that this technology can achieve is 3.3 centimetres for roller’s lateral position estimation with the help of lateral position optimization (Lu, Dai, & Zaniewski, 2021).

Future

Lu, Dai, & Zaniewski (2021) stated that some tasks still need to be undertaken to have better performance and broaden the applicability of the proposed technology. For instance, more research should be done to guarantee that the developed technology is compatible with different types of rollers. Another task that should be done in the future is the evaluation of the performance of the proposed technology under diverse compaction conditions (Lu, Dai, & Zaniewski, 2021).

2.3. Summary

To summarize the afore-described technologies, the following table was made.

Table 1: Summary of the technologies

Technology	Advantages	Challenges and Limitations	Uses	Future	Accuracy (cm)
GPS	-Available anywhere on the globe -Easy to use -Updated and maintained regularly by the US government -High accuracy -Works in all weather	-Loss of signal in unfavourable environments -No scalability -Extra costs for higher accuracies -High power consumption -Not suitable for indoor positioning	-Asset allocation -Guide and control machinery -Tracking machinery	-Better signal protection -Decrease susceptibility to signal jamming -More manoeuvrability to cover dead zones	10
BLE	-Cost-effectiveness -Energy-efficiency -Work independently of the network -Easy to install -Suitable for indoor positioning	-Pulsed data transmissions -Transmits state data but does not stream content -Security concerns -Reliability and accuracy concerns if applied in range sensing areas	-Asset tracking -Control industrial equipment and devices from a smartphone	-More precise positioning	150
Locata	-Easily expandable -Suitable for indoor positioning -Can be integrated with GPS but also function independently -Surpass the performance and reliability of GPS -High reliability -High accuracy -Designed to overcome GPS limitations	-RF interference -Installation complexity -High costs -Incompatible user hardware -Complex configuration -Environmental constraints -Experts are required to operate it	-Assess structural deformation -Open-cut mining -Indoor/outdoor vehicle tracking	-High-accuracy radio-positioning environments with a lack of reliable and functional GPS -Accessible for market users due to future lowering costs	4
UAS	-Low cost -Superior accessibility -Improved safety -Reach vantage points that are not accessible for humans or some equipment -Require low human involvement -User-friendly	-Interference of flight control due to wind -Limited manoeuvrability when operated manually -Might distract workers -Laws of certain countries -Need of extra sensor	-Site inspection and surveying -Safety inspection -Progress monitoring -Damage assessment -Building maintenance -Track materials on site -Measure surface distresses of unpaved roads	-Need of supportive regulations to have UAS as a standard for construction -Can be combined with VR, AR, AI, ML	100

Lidar	-Automated extraction of features of the road -Produces highway accurate images of roads while travelling at highway speed	-Performance depends on the installation and technical features of the device -Limited range -Weather -High costs -Lots of data -Occlusion and perspective shadow - Experts are required to operate it	-Roadway analysis -Post-construction quality control -Pavement smoothness quality determination -Bridge inspection -Building information and modelling -Autonomous navigation	-More research to explore its deeper potential -Expected to work individually (no dependence on GPS)	22
UWB	-Suitable for indoor positioning -Longer and accurate ranging -Secure communication channel -Higher measurement rate -Improved measurement accuracy -Immunity to interference from rain, fog, or clutter	-Need of direct line of sight between receiver and transmitter -Industrial environments -Tracking assets in fully closed spaces is not practically feasible -Tag orientation	-Asset tracking -Safety analysis of the construction place -Assess a pavement sample with good accuracy	-Automate conventional work sampling techniques	30
U-Blox	-High accuracy -Low cost -Low power consumption -Small size -High integration and portability	-The accuracy of the receiver clock limits the position performance of the low-cost receiver	-Asset tracking -Mapping surveys -Aerial vehicle applications	-Overcome the problem of scalability of GPS -Abandons the two-way link between customer device and correction data service	1-2
RFID	-Data stored in RFID tags can be changed, updated, and even locked -Non-contact -Non-line-of-sight -Tags can be read virtually instantaneously -Energy-efficient data gathering	-Distance between reader and tag placement -Direction of the tag -Moving speed of the tag and the reader can lead to failure in reading the tag -Lack of standards	-Asset tracking -Equipment, tool, inventory, and workforce management	Improve the technical aspects of it	100
Thermal Imaging	-Utilization in unfavourable conditions such as fog, smoke, poor illumination, vapour and dust -Not manufacturer-specific -Indoor positioning	-Ambient factors can affect the thermal information captured by the infrared camera (more research is needed) -The infrared camera is locked during the whole time (assumption)	-Orientation applications -Track and map the pavement compaction process	-More research to guarantee that it is compatible with different types of rollers -Evaluation of the performance of this technology under diverse compaction conditions	3.3

3. Expert Interviews

Semi-structured interviews were conducted to have a deeper understanding of the standard GPS technologies currently used in the asphalt industry, whether there are issues present when using it and whether people are aware of the existence of alternative technologies for tracking and localization. Each interview was recorded for analysis afterwards.

There are several types of interviews, but the most commonly used for research are structured and semi-structured. Structured interviews are quantitative methods that present specific questions to test a particular hypothesis and tell less about the experience of people (Saks & Allsop, 2013). On the other hand, qualitative methods such as semi-structured interviews are used to obtain participants' experience.

Despite the benefits of structured interviews, such as the ease to quantify and replicate due to their fixed set of closed questions (McLeod, 2014). This type of interviews are not flexible, meaning that new questions cannot be asked during the interview because an interview schedule must be followed. Also, the answers from this type of interviews lack details due to the closed questions, which generates quantitative data, meaning that researchers will not know the reason behind participants' responses.

On the other hand, semi-structured interviews allow for more flexibility compared to structured interviews, meaning that these interviews have a set of guiding questions to keep the interview on track, but new questions can arise depending on how the interview evolves (Wilson, 2012). Additionally, this type of interviews present advantages such as giving access to the subjective perception of the participants and the means by which they give meaning to their experiences (Saks & Allsop, 2013). Therefore, semi-structured interviews were chosen as a research methodology for this assignment because it was aimed to explore participants' experience regarding the use and application of GPS.

3.1. Process

Seven expert interviews were held, and Thematic analysis was used to analyze the recorded data. It is a method that reflects reality by identifying, analyzing and reporting patterns in the form of themes (Snyder, 2019). A theme captures something important regarding the data concerning the research question, which in this case was *"What are the current issues of using standard GPS technologies in the asphalt industry?"*, and represents some level of patterned response or meaning within the data set (Braun, Clarke, & Terry, 2014). There are 6 phases when doing thematic analysis, which are: (1) familiarizing with the data, (2) generating initial codes, (3) searching for themes, (4) reviewing themes, (5) defining and naming themes, and (6) producing the report (Braun, Clarke, & Terry, 2014). This thematic analysis started by transcribing the interviews and reading all of them to find patterns; after that, when the patterns were identified, the themes were found, reviewed and named to be reported later in the results of the interviews.

3.2. Results

After collecting and analysing the data obtained during the interviews, there were some noteworthy themes that the participants mentioned. The results of the interviews are summarized and shown in Table 2.

Table 2: Interviews Results

Problems with GPS
It was found that the main problem that GPS presents is the loss of signal, hence, deviation of the accuracy in non-favourable environments such as in the presence of trees, in tunnels, or in heavily urban environments where many buildings are present. Another remarkable problem is regarding the analysis of data; some of the respondents mentioned that user-friendliness could be improved when analysing it.
Important criteria to consider
The majority of the respondents (85.7%) mentioned that accuracy is the most important criteria. Followed by more than a half of them (71.4%) who mentioned that the ease-to-use is also important. Costs was another criterion that was mentioned by 57.1% of the interviewees. And almost half of the participants (42.9%) mentioned that robustness of the signal is an important criterion to consider as well.
Tasks in which GPS is used
57.1% of the participants mentioned that GPS is used mostly for quality control. - "For quality control, we use it more or less on every construction site to locate where we drilled the cores". - "For the drilling the cores, it is a daily job for workers". - "All of the people who are concerned with quality control, they use the GPS on a day to day basis that is standard equipment for them".
Level of accuracy used
85.7% of the interviewees mentioned that the level of accuracy of 10 centimetres is good, but if higher accuracy (less than 10 cm) is possible, that is even better. On the other hand, if this number is higher (meter level), it becomes problematic. - "On highway projects, we need an accuracy less than 10 centimetres". - "I think we are going to 10 centimetres, but we prefer to go to either one-centimetre accuracy". - "It does not need to be one centimetre or something; ten is fine. If it is becoming a meter, then it is not fine anymore then is problematic".
Why is GPS used an no other technology?
71.4% of the participants mentioned that GPS is used because it is a well-known, easy-to-use and widely accepted technology available in the market that has been proved and used for several years. -" So GPS is the easiest and accepted of the technology available in the market. Of course, there are other options available from a technological perspective, but not as easy to use". -" Because we only buy what is there on the market and what is a tool ready to use". -" GPS has been around for, let's say, already many years. It is a very proven technique, a rather robust technique. It is a widely available technique. So you have multiple suppliers. It is a well-known standard. So even your customers accept the GPS data. So, that makes it easier".
Familiarity with alternative technologies for tracking and localisation
All participants mentioned that they are not familiar with other technologies used for localization and tracking that gave the same benefits as GPS does. -"We are not familiar with other types of system that gives the same type of output, the same quality of output". -"I am also not really familiar with other technologies". "For tracking the vehicles. I am not sure; I am not aware of another real, let's say success stories". -" No, I do not know. I'm not really aware of that."
Changing GPS for other technologies?
The overall response among the participants was 'no'. Several reasons for that were mentioned, such as upgrading the GPS, unfamiliarity with other technologies and the acceptability that GPS has.

It is clear from the above that the issues that GPS has are regarding data analysis and the loss of signal in non-favourable environments. Additionally, GPS is mainly used for quality control, and high accuracy is needed (10 centimetres).

The remarkable aspects to consider when choosing GPS or any other technology are accuracy, ease-to-use, robustness, and costs. It is important to mention that all participants are not familiar with alternative technologies for tracking and localisation. Hence, this is one reason why it has not been considered changing GPS for another technology.

3.3. Validation

In qualitative research, there is the risk that researchers might impose their personal beliefs and interests on all stages of the research process leading to the researcher's voice dominating that of the participant (Mason, 2002, as cited in Birt et al., 2016). Additionally, the results shown in the previous section (Section 3.2) are based only on expert opinions, which mean that there is a risk that the research might be biased because of the personal beliefs of respondents. Therefore, it is necessary to validate the results to reduce research bias and increase reliability.

The validation of the expert interviews was done by applying member checking, also known as respondent validation or participant validation method. Which is used to validate, verify, or assess qualitative results' trustworthiness and allow participants to add further data if the meaning of their experience has changed over time (Birt et al., 2016). This validation was done by sending the transcript document of the participant's interview and the results shown in Section 3.2. Then, they were asked to read both documents and comment whether or not they felt that the results resounded their experiences and whether there was anything they would like to change. It was emphasized that these were not the final results, meaning that there was the opportunity to influence the analysis, which permitted participants to disagree.

All of the interviewed participants checked the transcripts' data, and the results shown in Section 3.2. The result was that overall there was a good resonance, increasing confidence that the results had captured participants' experiences, thus reducing methodological concerns about possible researcher bias.

4. Analytical Hierarchy Process

The method used for comparing the alternative technologies described in Section 2.2 was the Analytical Hierarchy Process (AHP). This multi-criteria decision-making approach uses pairwise criteria comparison to reach a scale of preferences among sets of alternatives (Marinoni, 2004). In other words, all the identified criteria are compared against each other in a pairwise comparison matrix that is a measure to express the preference among the criteria. Hence, numerical values expressing a judgment of one factor's relative importance against another are assigned to each criterion (Marinoni, 2004).

This method was chosen because it can convert subjective assessments of relative importance to a set of overall scores or weights. Additionally, the advantages of AHP over other Multi-Criteria (MCA) methods are its flexibility and ability to check inconsistencies (Kasperczyk & Knickel). Moreover, AHP helps to calculate both subjective and objective evaluation measures and, at the same time, provides a useful mechanism for checking the consistency of those evaluation measures and alternatives; hence AHP reduces bias in decision making (Kasperczyk & Knickel).

For this research, the chosen criteria were: accuracy because the PQi methodology requires a centimetre-level accuracy, more specifically 10 centimetres approximately, to make the graphs accurate enough for making explicit the on-site operations. Another important criterion was the robustness of the signal emitted by the technologies. This criterion was chosen because, during the interviews, the participants mentioned that one of the main problems that GPS presents is the loss of signal in heavily urban environments, tunnels, or even in places with many trees; it is noteworthy that this criterion also includes the reliability of the signal. Likewise, the costs of each technology are important to consider since this might hinder their acquisition. Further, user-friendliness was considered because the technologies need to be easy to use by the on-site workers; this criterion also includes the installation aspect of the technology.

Since all of the criteria mentioned above is important, it is pivotal to define which of them is the most and least important. This was done by asking, “How important is criterion A relative to criterion B” and based on the scale of comparison implemented by Saaty (1980) (see Appendix A), it resulted in the following table.

Table 3: Comparison of criteria based on the scale of comparison implemented by Saaty

Criteria		Importance and intensity	
A	B	Importance	Intensity
Accuracy	Robustness	A	5: Strong or essential importance
Accuracy	Costs	A	3: Moderate importance
Accuracy	User-friendliness	A	3: Moderate importance
Robustness	Costs	B	3: Moderate importance
Robustness	User-friendliness	B	5: Strong or essential importance
Costs	User-friendliness	B	3: Moderate importance

From Table 3, it can be seen that when comparing accuracy against robustness, accuracy received a value of 5, meaning that it has strong importance over robustness. This value was decided because from the interviews, most of the people said that accuracy is an important criterion; another reason for this value is because the main research question of this assignment is to find alternative technologies with similar or greater accuracies than GPS. In the same way, accuracy was compared against cost and user-friendliness. It received a score of 3 for each case, meaning that accuracy has moderate importance over cost and user-friendliness. Again, this number was decided based on the interviewees' responses shown in section 3.2.

On the other hand, when robustness was compared against cost, it can be observed from Table 3 that cost, located in column B, has a value of 3, meaning that cost has moderate importance over robustness. This score was given because if costs are too high, it might impede the acquisition of the technologies, independently of how robust their signal is. Furthermore, user-friendliness scored 5, meaning that it has strong importance over robustness. The reason behind this choice was that the idea is that the alternative technologies need to be operated by non-expert people; otherwise, even with the most robust signal, the technology would be useless if not operated correctly. The last pairwise comparison was made between cost and user-friendliness, where the last scored 3, meaning that it has moderate importance over cost. It is noteworthy that all the values shown in Table 3 were also based on the results obtained from the interviews.

The next step of AHP is to create a matrix with all the values stated before; this matrix is known as the comparison matrix, or also called the priority matrix. The values of the comparisons were put in each cell. For instance, since accuracy scored five over robustness, a value of 5 was placed in the cell where the row of accuracy and the column of robustness encounters. Due to robustness is being perceived as less important than accuracy, its reciprocal was used ($\frac{1}{5}=0.2$) in the cell where the row of robustness and the column of accuracy encounters. The same principle was used for the remaining criteria, and since all the criteria will rank equally when compared to themselves, a value of 1 was given. The complete table can be seen below.

Table 4: Priority matrix

	Accuracy	Robustness	Costs	User-friendliness
Accuracy	1.00	5.00	3.00	3.00
Robustness	0.20	1.00	0.33	0.20
Costs	0.33	3.00	1.00	0.33
User-friendliness	0.33	5.00	3.00	1.00
Sum	1.87	14.00	7.33	4.53

4.1. Ranking of criteria

For finding the ranking of criteria, the ranking of priorities has to be found, namely the priority vector. To do so, it was necessary to normalize the priority matrix (Table 4) by dividing each entry by the sum of its column. Then, the average of each row was calculated, which resulted in the priority vector of size $n \times 1$ shown in Table 5.

Table 5: Normalized Priority Matrix

	Accuracy	Robustness	Costs	User-friendliness	Priority vector
Accuracy	0.54	0.36	0.41	0.66	0.49
Robustness	0.11	0.07	0.05	0.04	0.07
Costs	0.18	0.21	0.14	0.07	0.15
User-friendliness	0.18	0.36	0.41	0.22	0.29
Sum	1.00	1.00	1.00	1.00	1.00

From Table 5, it can be observed that the most important criterion is accuracy, followed by user-friendliness, costs and robustness. It is noteworthy that the higher the value of the priority vector, the more important the criteria.

4.2. Consistency ratio

To find if the decision preferences were consistent, the consistency ratio needed to be calculated. This was done by following some steps, which are described below.

First, by multiplying the priority vector to its corresponding column of the priority matrix and adding the values across the row, the weighted sum was obtained.

	Accuracy	Robustness	Costs	User-friendliness
Accuracy	1.00	5.00	3.00	3.00
Robustness	0.20	1.00	0.33	0.20
Costs	0.33	3.00	1.00	0.33
User-friendliness	0.33	5.00	3.00	1.00

×

Priority vector
0.49
0.07
0.15
0.29

=

Weighted sum
2.15
0.27
0.61
1.24

Figure 9: Multiplication of priority vector and priority matrix

After that, the elements of the weighted sum were divided by its corresponding values of the priority vector. Then, the average (λ_{max})of the obtained values was calculated.

Equation 1: Average of weighted values

$$\lambda_{max} = \frac{\left(\frac{2.15}{0.49}\right) + \left(\frac{0.27}{0.07}\right) + \left(\frac{0.61}{0.15}\right) + \left(\frac{1.24}{0.29}\right)}{4} = 4.2$$

With the obtained λ_{max}, the consistency index was calculated using Equation 2, where n is the number of criteria which in this case is 4. By filling in all the values, it resulted in the following result.

Equation 2: Consistency Index

$$CI = \frac{\lambda_{max} - n}{n - 1}$$

$$CI = \frac{4.2 - 4}{4 - 1} = 0.06$$

Finally, the consistency ratio can be computed by applying Equation 3. Where RI is the Random Index which is the consistency index of a randomly generated pairwise comparison matrix, and has a value of 0.9 because of the number of criteria (see Appendix B).

Equation 3: Consistency Ratio

$$CR = \frac{CI}{RI}$$

$$CR = \frac{0.06}{0.9} = 0.07$$

It is noteworthy that a consistency ratio of 10% is said to be acceptable. Therefore since the consistency ratio obtained from the above calculation was 0.07 (7%), it can be stated that the subjective judgement (pairwise comparison) is accepted.

4.3. Ranking of alternatives

Once having an acceptable consistency ratio, it is time to describe the performance of each of the alternatives, which in this case are the alternative technologies described in Section 2.2. with respect to the criteria established previously. The benchmark is the GPS currently used within the PQi methodology. Therefore, the explanation of the performance of each alternative regarding each criterion is described below. To reduce subjectiveness, quantifiable measuring units were used to determine how each alternative performed.

4.3.1. Accuracy

GPS has a centimetre level accuracy (10 centimetres) in clear open areas. Therefore, this level of accuracy is necessary for any alternative technology to be considered within the Pqi methodology. Additionally, since modern applications demand more automation, there is a clear need for reliable accuracy (Locata Corporation, n.d.)

The accuracy of each of the technologies was described in Section 2.2. However, it is important to mention that since the accuracy of UAS depends on the type of sensor used, for calculation purposes a meter accuracy was assumed. Also, for the RDIF, it was assumed an off the shelf device accuracy of 1 meter for calculation purposes. However, as was mentioned in Section 2.2.8., this accuracy can be improved if additional algorithms are used.

4.3.2. Robustness

Since measuring robustness is a difficult task due to the lack of standards and information, it was decided to use scorecards, being 1 the most robust and 5 the least. A value of 1 was given to the Locata technology because it overcomes the problems of loss of signal present when using GPS. Likewise, u-blox was given the same number because it can also deal with the loss of signal present by GPS through the use of the dead reckoning technology, explained in Section 2.2.7. Lidar got a score of 3 because the point cloud can be affected due to incomplete clusters caused by issues such as occlusion or perspective shadow (Zhao et al., 2019). BLE received a score of 4 because, according to Onofre et al. (2016), the reliability and robustness of the signal of this technology are affected when applied in range sensing areas. A value of 2 was given to UAS because this device can go to places where humans or machines cannot go making it have more robust and reliable signals than other technologies because it might not encounter problems such as occlusion; however, since this UAV needs extra sensors for localisation and tracking, this lowers the robustness and reliability of the signal, that is the reason why it scored 2 instead of 1.

UWB scored 3 because it needs a direct line of sight between the receiver and the transmitter (infsoft, n.d.), making it less reliable and less robust if an obstacle is placed between them. On the other hand, RFID scored 4 because it can have reliability problems caused by range or obstacles present (Inoue, Hagiwara, & Yasuura, 2004). Additionally, there is a possibility that the RFID tags might not be read (Zajac & Kwasniowski, 2017) either because the distance between tags and readers is too long or because of the frequency emitted. Lastly, despite the great performance and accuracy obtained by Thermal Imaging, there is still more research left regarding the applications and limitation factors that can affect the collection of data (Lu, Dai, & Zaniewski, 2021); due to these reasons, a value of 4 was given.

4.3.3. Costs

There are several costs involved during the implementation of any technology, such as equipment, installation, set-up, maintenance, software, ongoing license, and many other costs that vary depending on the project's objectives, the size of it, the personnel, time and machinery available. However, during this section, only the costs of the primary devices used in each technology, such as receivers and/or tags, will be considered to give an idea of how costly a technology might be. It is noteworthy that even the costs of only the receivers and/or tags vary depending on the brand, characteristics and accuracy. Also, it can change if there are any algorithms to correct errors or not, if they are meant to be indoors or outdoors, and other aspects that might increase or decrease their economic value. Having mentioned that, some of the costs for each technology will be described in the following paragraphs.

For the BLE technology, the price varies depending on the quality of the device; for instance, a good quality beacon costs around 20 euros per piece (Locatify, 2019). Even though one beacon is enough for determining the presence of an object, the accuracy increases if the number of beacons is increased (Kingatua, 2020).

For Locata technology, the cost of only one transceiver is 10 thousand euros approximately (Shankland, 2012). However, since this technology requires a network of at least four transceivers to function, it gives a total of 40 thousand for transceivers only.

For UAS, as it was mentioned in Section 2.2.4, it can be equipped with GPS, Lidar, cameras, and other sensors. Therefore, the cost of only the drone is 1000 euros approximately (indiamart, n.d.). Of course, this price will go up depending on the extra device needed for the project purposes, for instance, if a high-resolution camera is meant to be used to track the machinery in the asphalt paving process, the cost of the drone should be added to the cost of the camera.

According to Korosec (2019), the industry norm for a single top-of-the-range Lidar is 62000 euros approximately. However, as it was mentioned during Section 2.2.5, the price can vary depending on the number of laser present in the device.

For UWB, the price is 37 euros per tag, and per receiver, it is 240 euros approximately (Sirin Software, 2018). However, this technology needs at least 3 receivers to function; therefore, this gives a total of 720 for receivers only, plus the price of one tag gives a cost of 757 euros. This value can go up if more tags are needed.

The cost of a u-blox chip is around 210 euros per chip (GNSS OEM Store, n.d.).

For RFID, the approximate cost of a reader is 2500 euros, and the price of the tags vary depending on the type, for instance, if an active tag is meant to be used, its price would be between 5-12 euros approximately, whereas a passive tag will cost less than a euro (Ray, 2020). Therefore, it was considered the value of one reader and one active tag for calculation purposes, which resulted in a total of 2512 euros approximately.

During the study made by Lu, Dai, & Zaniewski (2021), the technology developed, which included an infrared camera, had a cost of 4200 euros approximately.

4.3.4. User-friendliness

Due to the difficulty that represents having a measuring unit for user-friendliness, it was decided that scorecards will be used. A score of 1 means the most user-friendly, whereas a score of 5 represents the least. Therefore the performance of each alternative technology will be explained below.

Since BLE signals can be read by iOS and Android smartphones, this technology points in favour of user-friendliness. Additionally, BLE beacons are easy to install because BLE does not require any additional infrastructure and integrates with existing networks and systems (Chauhan, 2020). However, since this technology is not the most suitable to be applied outdoors, it results in a value of 3.

The LocataLites achieve their high accuracy of synchronization wirelessly. In other words, they achieve it without atomic clocks or satellites or external control and without needing a reference network for time correction (LOCATA CORPORATION, 2014), making this solution more simple. In addition, the Locata transmitters can autonomously survey and initialize themselves to form a network, making LocataNets easily expandable to grant additional coverage (LOCATA CORPORATION, 2014). Another aspect is that LocataLites can autonomously join or leave networks as required (LOCATA CORPORATION, 2014). However, it needs experts to operate it, limiting the use of this technology for on-site workers and people who do not know anything about it. Also, to configure a LocataNet with spatial diversity, there need to be several antennas mounted on concrete bases, and their coordinates have to be precisely surveyed (Rizos & Yang, 2019). Additionally, there is a possibility that there are some challenges concerning the configuration and power issues related to the LocataNet installation (Rizos & Yang, 2019). Moreover, the implementation of Locata can be hindered by environmental restrictions, which means that the network's geometry is restricted by the application environment (Rizos & Yang, 2019). For these reasons, the performance of Locata scored 4.

UAS obtained a score of 1 because they are compact and can be remotely controlled by anyone. Additionally, these devices are also accessible to spaces that are not possible reachable by man and require low human involvement, reducing risk on job sites. Also, this technology does not require any extra infrastructure to function and can navigate and collect data in an autonomous way and transfer it to a control station in real-time (Zhou & Gheisari, 2018).

Lidar got a score of 2 because Scanning Lidar uses only one detector, making it relatively easy to calibrate. Also, it can be placed on the top of the machinery and survey the field job, which means that it is user-friendly because the user only needs to be concerned about the light sensitivity, timing for one detector (Christian & Cryan, 2013), and to analyze the data afterwards.

Since one of the most important aspects to consider when using UWB is the tag orientation (Saidi et al., 2011). This can hinder user-friendliness because the tags need to be adequately placed; otherwise, problems with accuracy might be encountered, making it less easy to implement. Therefore, a score of 3 was given to this technology.

Due to its small size, u-blox can be placed almost everywhere to track people and assets. In addition, these chips scored 1 in user-friendliness because of their size and ease of installing on any devices.

RFID scored 4 because it requires designated scanners or fixed RFID readers placed at strategic locations (AHG, Inc., n.d.), making it less user-friendly compared to other technologies such as BLE.

The technology of thermal imaging allows the video stream to be straightforwardly read and transmitted from the infrared camera to a laptop which grants the user with real-time feedback during the installation, which helps to find the most optimal field of view of the camera (Lu, Dai, & Zaniewski, 2021). Thus, the score of this technology for user-friendliness was 1.

4.3.5. Overview performance of technologies

To better visualise each technology's performance concerning each criterion, the following table was made.

Table 6: Performance of the alternative technologies

Criteria	Accuracy	Robustness	Costs	User-friendliness
Measuring unit	centimetres	scorecard	Euros	scorecard
BLE	150	4	20	3
Locata	4	1	40000	4
UAS	100	2	1100	1
Lidar	22	3	62000	2
Ultra-wideband	30	3	757	3
U-blox	2	1	210	1
RFID	100	4	2512	4
Thermal imaging	3.3	4	4200	1
Sum	411.3	22	110799	19

4.3.6. Calculations

To be able to compare each of the technologies, the normalization of Table 6 was needed. This was done by dividing each cell by the sum of its column. The resulting table can be observed below.

Table 7: Normalized matrix for the alternative technologies

Criteria	Accuracy	Robustness	Costs	User-friendliness
Measuring unit	centimetres	scorecard	scorecard	scorecard
BLE	0.36	0.18	0.00	0.16
Locata	0.01	0.05	0.36	0.21
UAS	0.24	0.09	0.01	0.05
Lidar	0.05	0.14	0.56	0.11
Ultra-wideband	0.07	0.14	0.01	0.16
U-blox	0.00	0.05	0.00	0.05
RFID	0.24	0.18	0.02	0.21
Thermal imaging	0.01	0.18	0.04	0.05
Sum	1.00	1.00	1.00	1.00

After that, the score of each alternative was calculated by multiplying the priority vector calculated in Section 4.1. by each row of the normalized matrix (Table 7). Having as a result, the following table.

*Table 8: Ranking of the alternatives (*the lower the score, the better the alternative)*

Possibilities	Score	Ranking
BLE	0.24	8
Locata	0.12	4
UAS	0.14	5
Lidar	0.15	6
Ultra-wideband	0.09	3
U-blox	0.02	1
RFID	0.20	7
Thermal imaging	0.04	2

4.4. Results

As it can be seen from Table 8, and based on all the chosen set of criteria, the most suitable technology to replace GPS is U-blox, followed by Thermal imaging, Ultra-wideband, Locata, UAS, Lidar, RFID and BLE. However, since the PQi methodology requires accuracies of 10 centimetres, most of the alternative technologies such as BLE, UAS, Lidar, Ultra-wideband and RFID cannot be applied within that framework.

It is noticeable that these alternatives got the last places in the ranking. The only exception was Ultra-wideband which obtained the third position in the ranking, beating Locata technology for one place. The reason for that is because Locata is more costly compared to Ultra-wideband. However, UWB does not comply with the accuracy requirements.

Moreover, the benchmark for the cost of a GPS receiver is around 10-20 thousand euros. Therefore, if the three technologies (U-blox, thermal imaging and Locata) are compared against it, only two are cheaper than the GPS; these technologies are u-blox and Thermal imaging.

Therefore the technologies that can be implemented for tracking machinery at a low cost and with similar accuracies as the currently used GPS technology within the PQi process are u-blox and thermal imaging.

5. Conclusion

For this research, four sub-questions were asked to give a final answer for the main sub-question *"To what extent alternative technologies available in the market can be implemented for tracking machinery with the same or similar accuracies as the currently used GPS technology in the PQi process in order to reduce the costs and functionality issues?"*. Therefore, the conclusion will be divided according to the sub-questions as follows.

Which alternative technologies (standard and non-standard) available in the market are suitable to be applied in the asphalt industry?

The alternative technologies that are available in the market and have been applied in the construction and asphalt industry are Bluetooth Low Energy (BLE), Locata Technology, Unmanned Aerial Systems (UAS), Lidar, Ultra-wideband (UWB), U-blox, Radio Frequency Identification (RFID) and Thermal Imaging, and were explained in Section 2.2. The literature review was used as a research methodology to find each of them and answer this question.

What are the current issues of using standard GPS technologies in the asphalt industry?

Two research methodologies were applied to answer this sub-question: Literature review and semi-structured interviews. The reason behind using both methodologies was to obtain background information of what are the issues of GPS reported in the literature and to obtain the experience of people when using it, which gave an insight into how GPS actually work and the real issues that people face when operating it in real-life applications.

It is noteworthy that at the beginning of this research and based on preliminary literature review only, it was thought that the main problems of GPS were costs and usability. However, after conducting this research and by applying the methodologies mentioned above, it was found that the main issues that GPS presents are the loss of signal in non-favourable environments such as in the presence of trees, heavily built environments and tunnels. Additionally, according to the results obtained from the interviews, the analysis of data presented issues as well. It is essential to mention that costs were mentioned to be an important aspect to consider. However, according to the experts, it is not an issue as long as the benefits obtained from a costly device pays off.

What are the pro's, cons and barriers of using standard GPS and these alternative technologies?

The answer to this sub-question was given by applying literature review. The results were elaborated in Section 2.2, where the functioning, advantages, fields of applications, challenges and limitations, accuracies and future of each technology were described.

Which alternative(s) perform better or equal compared to standard GPS solutions?

The results obtained from the interviews and the literature review were used to apply Analytical Hierarchy Process, which was the research methodology used to answer the last sub-question and the main research question. AHP was used to compare which of the alternatives performed better than GPS in terms of accuracy, costs, robustness of the signal and user-friendliness. Additionally, the GPS's accuracy and costs used within the PQi methodology were considered as a benchmark for comparison and inclusion within the methodology. Therefore, after doing all the respective calculations and discarding the technologies which did not comply with the PQi requirements. The result was that U-blox and Thermal imaging performed better than the standard GPS solutions—answering the main research question proposed at the beginning of the present report.

Given the obtained results, it can be concluded that there are low-priced available technologies in the market with equal or even better accuracies that can be implemented within the PQi methodology instead of GPS. However, it is noteworthy that since these technologies (U-blox and Thermal imaging) are not used as a standard practice, more experimentation and research regarding their use in the field are needed. This, to find any issues when implementing them in real-life applications. For instance, in the asphalt and paving industry for tracking machinery. Additionally, based on the analysis made during this research it can be mentioned that these are feasible alternative technologies that could replace GPS in future applications, but still more research and experimentation is needed.

6. Discussion

During this section, the weaknesses of the methodological choices will be discussed and the essential aspects that could be crucial for the report's outcome.

The semi-systematic review was an adequate approach for this research because the research questions were not narrow enough, and the available time for completing it was limited. Additionally, this type of literature review offers a base for building on previous work and helps to identify omissions or gaps in the research area. However, this approach presents some issues, such as not covering all the information available regarding a topic. Also, there is a possibility that the author may only select literature that supports his/her case. Moreover, replicating this type of literature review is regarded as having a high level of difficulty, and, sometimes, it is deemed impossible due to the lack of information on how the studies were searched and selected. Lastly, due to the nature of the narrative approach, the literature synthesis and interpretation might be prone to subjectivity.

When doing qualitative research, in this case, the semi-structured interviews, the researcher is generally the data collector and the data analyst, creating a potential for research bias. Additionally, when doing this type of research, there is a risk that researchers might impose their personal beliefs and interests on all the stages of the research, which might lead to the researchers' voice dominating the voices of the participants. However, these issues were addressed during the validation of the interviews by involving the participants in checking and confirming the results. Additionally, despite achieving the minimum amount of interviews (7 interviews), there were not several interviews conducted which might limit the deepening of the obtained results.

During the development of the Analytical Hierarch Process, some assumptions were made regarding the criteria used. For instance, since some of the alternative technologies, such as the UAS's accuracy, depends on the type of sensor coupled with it, this did not give a real accuracy for comparison. Additionally, some off-the-shelf accuracies were considered; however, some of them could be improved by applying correction algorithms. Therefore deeper research regarding these aspects should be done to have an actual value for those accuracies.

Additionally, only the receivers and tags were considered for the analysis when comparing the costs due to the lack of information regarding other costs. Additionally, the costs might vary depending on the project. However, suppose any of the found technologies are aimed to be actually implemented. In that case, the cots of equipment, installation, set-up, maintenance, software, ongoing license, and any extra costs that might appear during their implementation should be considered. This might change the outcomes of the analysis as well.

Moreover, for measuring the performance of user-friendliness and robustness, scorecards were used due to the lack of standards to measure them. Despite basing the scores on the information obtained from the literature review, there is the risk that it might include some researcher's bias because not all the available information was reviewed to have more supported scores. In addition, the only technique to verify the scores and values in the AHP was the consistency ratio used to verify the scores of the criteria. It was assumed that if this ratio was less than 10%, it is acceptable. Hence, the criteria could be used to compare any alternative. However, for verifying the final results after comparing the alternatives against the criteria, there are not available tools or methods for doing that. Therefore, more research regarding the verification of the actual results of the AHP might be helpful in future research.

Lastly, I would like to add about my experience doing this research during corona times, so after the pass of years, people who read this research can have an idea of how life was during these days. Since everything was online to avoid physical contact and reduce the spread of the virus. It was challenging and sometimes even dull to complete this research all alone in my room without having others to talk to or just seeing them working as I was. Additionally, due to these difficult times, I did not experience how it was to be 'working' for a company, the busy schedules, meetings, etc. Also, it is important to mention that all the meetings with the supervisors and interviews with the experts were held online due to corona, which sort of lost the human touch we used to have before this pandemic.

Hence, when talking about the interviews, it would have been better to interview people face to face because one can also see the body language and facial expressions when asking a question. Moreover, before conducting the interviews, I thought that every company was applying the PQi methodology as it says in theory. However, this was not true for several reasons, such as workers, money, organisation, management, and many other aspects that can influence the process in real life. Also, it was interesting to find out that because every single project is different, it can change the paving crews' organisation. Regarding the alternative technologies, an interesting finding was that experts have little or no idea about alternative technologies used for localisation and tracking, which kept me thinking about whether or not the bandwagon effect was present regarding the utilisation of GPS instead of other technologies. However, the scope of this research has nothing to do with that topic.

7. Recommendations

For future research, it is advised to check if the research methods can be validated or if there exists any tool for improving the trustworthiness of the outcomes. Also, when applying Analytical Hierarchy Process try to use criteria that can be easily quantified to avoid the possible subjectiveness of using scorecards as measuring units.

Additionally, it is advised to do either experiment or to do a field test to see how the actual performance of each of the found technologies is when applying them in real life. For instance, the accuracy level, user-friendliness, robustness of the signal, and cost can be compared against GPS performance to have more similar results to reality. This can also help learn more about the limitations of each of them in certain scenarios.

References

Adarsh, M. (2021, March 22). *Bluetooth Low Energy (BLE) Beacon Technology Made Simple: A Complete Guide to Bluetooth Beacons*. From beaconstac: https://blog.beaconstac.com/2018/08/ble-made-simple-a-complete-guide-to-ble-bluetooth-beacons/

AHG, Inc. (n.d.). *Bluetooth Asset Tracking: Internet of Things (IoT) For Monitoring Assets & Equipment*. Retrieved April, 2021 from AHG, Inc.: http://small-business-inventory-management.com/inventory-management-asset-tracking-software-guide/bluetooth-asset-tracking-iot.htm

Allen, S. (2020, June 2). *Technology Helps Asphalt Contractors Rethink How They Work*. From FOR Construction PROS.com: https://www.forconstructionpros.com/asphalt/article/21121607/technology-helps-asphalt-contractors-rethink-how-they-work

ASPARi. (n.d.). *ASPARi*. From What we do: https://en.aspari.nl/what-we-do

ASPARi. (n.d.). *Over APARi*. From ASPARi: https://en.aspari.nl/about

ASPARi. (n.d.). *The Process Quality improvement (PQi)*. From APARi: https://en.aspari.nl/methodology

Asphalt Pavement Association of Michigan. (n.d.). *What is Hot Mix Asphalt Pavement?* Retrieved August 26, 2021 from Asphalt Pavement Association of Michigan: http://www.apa-mi.org/what_is_hot_mix_asphalt_paveme.php

Asvadi, A., Girao, P., Peixoto, P., & Nunes, U. (2016). 3D Object Tracking using RGB and LIDAR Data. *2016 IEEE 19th International Conference on Intelligent Transportation Systems (ITSC)*. doi:10.1109/itsc.2016.7795718

Bhaskar, P. K., & Yong, S.-P. (2014). Image Processing Based Vehicle Detection and Tracking Method. *2014 International Conference on Computer and Information Sciences (ICCOINS)* (pp. 1-5). Kuala Lumpur, Malaysia: IEEE. From https://doi.org/10.1109/ICCOINS.2014.6868357

Bijleveld, F. R. (2015). *PROFESSIONALISING THE ASPHALT CONSTRUCTION PROCESS.* Enschede: Gildeprint. doi:10.3990/1.9789036537650

Birt, L., Scott, S., Cavers, D., Campbell, C., & Walter, F. (2016). Member Checking: A Tool to Enhance Trustworthiness or Merely a Nod to Validation? *Qualitative Health Research, 26*(13), 1802–1811. doi:10.1177/1049732316654870

Black, C. (2020, January 15). *Finding time: Accuracy test of Locata Network takes place at White Sands*. From GPS WORLD: https://www.gpsworld.com/finding-time-accuracy-test-of-locata-network-takes-place-at-white-sands/

Bluetooth. (n.d.). *Learn About Bluetooth Location Services*. Retrieved April, 2021 from Bluetooth: https://www.bluetooth.com/learn-about-bluetooth/solutions/location-services/

Bonsor, K. (2020, January 27). *How Location Tracking Works*. From HowStuffWorks: https://electronics.howstuffworks.com/everyday-tech/location-tracking1.htm

Brain, M., & Harris, T. (2020, July 27). *How GPS Receivers Work.* From howstuffworks: https://electronics.howstuffworks.com/gadgets/travel/gps.htm

Braun, V., Clarke, V., & Terry, G. (2014). Thematic Analysis. *Qualitative Research in Clinical and Health Psychology*, 95-113. From http://dx.doi.org/10.1007/978-1-137-29105-9_7

Brodie, G., Jacob, M. V., & Farrell, J. (2016). *Microwave and Radio-Frequency Technologies in Agriculture: An Introduction for Agriculturalists and Engineers.* Berlin, Germny: De Gruyter.

Business Research Methodology. (n.d.). *Types of Literature Review*. Retrieved June 10, 2021 from Business Research Methodology: https://research-methodology.net/research-methodology/types-literature-review/

Campbell, D. (n.d.). *The Future of RFID*. Retrieved June 3, 2021 from Supply Chain Market: https://www.supplychainmarket.com/doc/the-future-of-rfid-0001

Chauhan, M. (2020, September 19). *Bluetooth Low Energy (BLE): A New Asset Tracking Technique*. From Asset Infinity Blog: https://www.assetinfinity.com/blog/bluetooth-low-energy-ble-asset-tracking-technique

Cheng, T., Venugopal, M., Teizer, J., & Vela, P. A. (2011). Performance evaluation of ultra wideband technology for construction resource location tracking in harsh environments. *Automation in Construction, 20*(8), 1173-1184. From https://doi.org/10.1016/j.autcon.2011.05.001

Choudhury, M. M., Rizos, C., & Harvey, B. (2009). A survey of techniques and algorithms in deformation monitoring applications and the use of the Locata technology for such applications. *22nd International Technical Meeting of the Satellite Division of the Institute of Navigation 2009, ION GNSS 2009, 2*.

Christian, J. A., & Cryan, S. (2013). A Survey of LIDAR Technology and its Use in Spacecraft Relative Navigation. *AIAA Guidance, Navigation, and Control (GNC) Conference*, (pp. 19-22). Boston. doi:10.2514/6.2013-4641

Ciurkot, A. (2021, February 11). *What is a Beacon? The Complete Guide to Bluetooth Beacons*. From kontakt.io: https://kontakt.io/what-is-a-beacon/

CONEXPO-CON/AGG. (2021, February 4). *CONTRACTORS: FOUR WAYS TO TAKE ADVANTAGE OF RFID TECHNOLOGY*. From CONEXPO-CON/AGG: https://www.conexpoconagg.com/news/contractors-four-ways-to-take-advantage-of-rfid-te

de Bakker, P. F. (2017, January). *Reader on GPS positioning*. Retrieved February 27, 2021 from TU Delft: https://www.tudelft.nl/en/ceg/about-faculty/departments/geoscience-remote-sensing/education/bsc-education/reader-on-gps-positioning

Department for Communities and Local Government. (2009). *Multi-criteria analysis: a manual.* London: Communities and Local Government Publications. From http://eprints.lse.ac.uk/12761/1/Multi-criteria_Analysis.pdf

Di Paolo Emilio, M. (2021, January 26). *U-blox Integrates Cellular and GNSS in a Single SiP*. From EE Times: https://www.eetimes.com/u-blox-integrates-cellular-and-gnss-in-a-single-sip/

Earth Observing System. (2020, November 27). *Geospatial Technology: Changing The World In A Moment*. From Earth Observing System: https://eos.com/blog/geospatial-technology/

Earth Observing System. (2020, November 18). *Types Of Remote Sensing: Technology Changing The World*. From Earth Observing System: https://eos.com/blog/types-of-remote-sensing/

Editorial. (2020, May 13). *Top 7 location-based tracking technologies*. From roboticsbiz: https://roboticsbiz.com/top-7-location-based-tracking-technologies/

Fairhurst, P. (2018, May 14). *Bringing High Precision Positioning To The Mass Market*. From ee News Automotive: https://www.eenewsautomotive.com/design-center/bringing-high-precision-positioning-mass-market

Fairhurst, P. (2019, January 17). *Commentary: High-precision positioning is going mainstream*. From GPS WORLD: https://www.gpsworld.com/commentary-high-precision-positioning-is-going-mainstream/

Favey, E., Somieski, A., Hollenstein, C., Ammann, M., & Fenger, C. (2011, August 18). *Dead reckoning fills-in GPS navigation gap*. From ASPENCORE NETWORK: https://www.eetimes.com/dead-reckoning-fills-in-gps-navigation-gap/

Favey, E., Somieski, A., Hollenstein, C., Ammann, M., & Fenger, C. (2011, August 18). *Dead reckoning fills-in GPS navigation gap*. From EE Times: https://www.eetimes.com/dead-reckoning-fills-in-gps-navigation-gap/#

Furuno. (n.d.). *What is Dead Reckoning (DR)?* Retrieved April, 2021 from Furuno: https://www.furuno.com/en/gnss/technical/tec_dead#:~:text=It%20enables%20to%20keep%20high,utilized%20in%20automotive%20navigation%20systems

Gargoum, S., & El-Basyouny, K. (2017). Automated extraction of road features using LiDAR data: A review of LiDAR applications in transportation. *2017 4th International Conference on Transportation Information and Safety (ICTIS).* Banff, AB, Canada: IEEE. From https://doi.org/10.1109/ICTIS.2017.8047822

Geotab. (2020, May 22). *What is GPS?* From Geotab: https://www.geotab.com/blog/what-is-gps/

Geotab Team. (2020, May 22). *What is GPS?* From GEOTAB: https://www.geotab.com/blog/what-is-gps/

Ghallabi, F., Nashashibi, F., El-Haj-Shhade, G., & Mittet, M.-A. (2018). LIDAR-Based Lane Marking Detection For Vehicle Positioning in an HD Map. *2018 21st International Conference on Intelligent Transportation Systems (ITSC).* Maui, HI, USA: IEEE. From https://doi.org/10.1109/ITSC.2018.8569951

GNSS OEM Store. (n.d.). *ZED-F9P RTK GNSS receiver board with SMA Base or Rover*. Retrieved June 14, 2021 from GNSS OEM Future World: https://www.gnss.store/gnss-gps-modules/99-ublox-zed-f9p-rtk-gnss-receiver-board-with-sma-base-or-rover.html#/27-add_antenna_ann_mb-without_antenna

GPS.GOV. (2021, August 18). *Other Global Navigation Satellite Systems (GNSS)*. From GPS.GOV: https://www.gps.gov/systems/gnss/#:~:text=Global%20navigation%20satellite%20system%20(GNSS,a%20global%20or%20regional%20basis.

GPS.GOV. (n.d.). *Aviation*. Retrieved April, 2021 from GPS.GOV: https://www.gps.gov/applications/aviation/

GPS-SERVER. (2021). *Common GPS tracking device problems*. From GPS-server.net: https://www.gps-server.net/common-gps-tracking-device-problems

Grgac, I., & Paar, R. (2019). *Quality assessment of Locata positioning system.* Gothenburg: University of Gothenburg.

Gunatilake, A., Galea, M., Thiyagarajan, K., Kodagoda, S., Piyathilaka, L., & Darji, P. (2021). Using UHF-RFID Signals for Robot Localization Inside Pipelines. *1*. From https://doi.org/10.36227/techrxiv.14658795.v1

Hecht, J. (2018, January). Lidar for Self-Driving Cars. *OPTICS & PHOTONICS NEWS*. From https://www.osapublishing.org/DirectPDFAccess/65C5653E-4C6D-4F33-9EDFF89042F8A3B3_380434/opn-29-1-26.pdf?da=1&id=380434&seq=0&mobile=no

indiamart. (n.d.). *Surveillance Unmanned Aerial Vehicle*. Retrieved June 8, 2021 from indiamart: https://www.indiamart.com/proddetail/surveillance-unmanned-aerial-vehicle-22803774755.html

infsoft. (2021). *Indoor Positioning Using BLE 4 / 5 Tags*. Retrieved August 26, 2021 from infsoft: https://www.infsoft.com/technology/transmitter-hardware/ble-4-5-tags

infsoft. (n.d.). *Indoor Positioning With Ultra-Wideband*. Retrieved May 25, 2021 from infsoft: https://www.infsoft.com/technology/positioning-technologies/ultra-wideband?gclid=Cj0KCQjwwLKFBhDPARIsAPzPi-JENU9BF6n0HFvGSKlXfx-3YfdWPqmiXZy2Y2lMFcRoNfNZ9vceXaYaAoXSEALw_wcB

Inoue, S., Hagiwara, D., & Yasuura, H. (2004). A systematic approach for the reliability of RFID systems. *2004 IEEE Region 10 Conference TENCON 2004. 2*, pp. 183-186. Chiang Mai, Thailand: IEEE. From https://doi.org/10.1109/TENCON.2004.1414562

Inoue, S., Hagiwara, D., & Yasuura, H. (2004). A Systematic Approach for the Reliability of RFID Systems. doi:10.1109/TENCON.2004.1414562

Jiang, W., Li, Y., & Rizos, C. (2014). Precise Indoor Positioning and Attitude Determination using Terrestrial Ranging Signals. *Journal of Navigation, 68*, 1-17. From http://dx.doi.org/10.1017/S0373463314000551

Jiang, W., Li, Y., Rizos, C., Cai, B., & Shangguan, W. (2017, July 11). Seamless Indoor-Outdoor Navigation based on GNSS, INS and Terrestrial Ranging Techniques. *The Journal of Navigation, 70*(6), 1183-1204. From https://doi.org/10.1017/S037346331700042X

Joom. (n.d.). *Matek Systems Ublox SAM-M8Q GPS Module Support GLONASS Galileo QZSS SBAS for RC Drone FPV Racing*. Retrieved June 8, 2021 from Joom: https://www.joom.com/en/products/5bf510156ecda801015072fb

Karakose, E., Gencoglu, M. T., Karakose, M., Aydin, I., & Akin, E. (2017). A New Experimental Approach Using Image Processing-Based Tracking for an Efficient Fault Diagnosis in Pantograph–Catenary Systems. *IEEE Transactions on Industrial Informatics, 13*(2), 635 - 643. From https://doi.org/10.1109/TII.2016.2628042

Kasperczyk, N., & Knickel, K. (n.d.). *The Analytic Hierarchy Process (AHP).* From http://www.ivm.vu.nl/en/Images/MCA3_tcm234-161529.pdf

Khattab, A., Fahmy, Y. A., & Wahab, A. A. (2015). High Accuracy GPS-Free Vehicle Localization Framework via an INS-Assisted Single RSU. *International Journal of Distributed Sensor Networks, 11*(5). From https://doi.org/10.1155%2F2015%2F795036

Kingatua, A. (2020, March 26). *Bluetooth Indoor Positioning and Tracking Solutions*. From Medium: https://medium.com/supplyframe-hardware/bluetooth-indoor-positioning-and-asset-tracking-solutions-8c78cae0a03

Korosec, K. (2019, March 6). *Waymo to start selling standalone LiDAR sensors*. From TechCrunch: https://techcrunch.com/2019/03/06/waymo-to-start-selling-standalone-lidar-sensors/?guce_referrer=aHR0cHM6Ly93d3cuZ29vZ2xlLmNvbS8&guce_referrer_sig=AQAAAJyRcRdIcoGY7HMMeTprwNyTPVoZlhc_kPam57BEXJghU54ch4LgyERrWdO83rsoLrWud1X7BAWBc6jp3Io5eviBsvMGbW8yNriTK-ci

Kuennen, T. (2017, June 27). *Federal Highway Administration*. From Asphalt's Generation of Change: https://www.fhwa.dot.gov/construction/pubs/hif07012/23.cfm

LOCATA CORPORATION. (2014, July). *Locata Technology Brief.* From http://www.locata.com/wp-content/uploads/2014/07/Locata-Technology-Brief-v8-July-2014-Final1.pdf

Locata Corporation. (n.d.). *Key Attributes of an alternative GPS Technology | Locata*. From Locata: http://www.locata.com/technology/key-attributes/

Locatify. (2019, October 3). *Indoor Positioning Systems based on BLE Beacons*. From Locatify: https://locatify.com/blog/indoor-positioning-systems-ble-beacons/

Lu, L., Dai, F., & Zaniewski, J. P. (2021, April 24). Automatic roller path tracking and mapping for pavement compaction using infrared thermography. *COMPUTER-AIDED CIVIL AND INFRASTRUCTURE ENGINEERING*. From https://doi.org/10.1111/mice.12683

Lu, L., Ma, L., Wu, T., & Chen, X. (2019). Performance Analysis of Positioning Solution Using Low-Cost Single-Frequency U-Blox Receiver Based on Baseline Length Constraint. *Sensors, 19*(19). From https://doi.org/10.3390/s19194352

Luo, X., O'Brien, W. J., & Julien, C. L. (2011, April). Comparative evaluation of Received Signal-Strength Index (RSSI) based indoorlocalization techniques for construction jobsites. *Advanced Engineering Informatics, 25*(2), 355-363. From https://doi.org/10.1016/j.aei.2010.09.003

Mackenzie, A. (2019, September 24). *Difference between Accuracy and Precision Measurements*. From PRECISA: https://www.precisa.co.uk/difference-between-accuracy-and-precision-measurements/

Marinoni, O. (2004, July). Implementation of the analytical hierarchy process with VBA in ArcGIS. *Computers & Geosciences, 30*(6), 637-646. From https://www.sciencedirect.com/science/article/pii/S0098300404000652?casa_token=LdQcEJifYi4AAAAA:5VbviAkv2PYKlVqG15t6WBIX9x17f0_C4gi173h-b0Y8ZJSaDPT6VoBZbFKilBthyLs4xXqiFV4

McLeod, S. (2014, February 5). *The Interview Research Method*. From Simply Psychology: https://www.simplypsychology.org/interviews.html

Miller, S. R. (2010). *HOT MIX ASPHALT CONSTRUCTION TOWARDS A MORE PROFESSIONAL APPROACH.* Ipskamp Drukkers B.V. doi:10.3990/1.9789036531283

Miller, S., ter Huerne, H., & Dorée, A. (2007). THE ASPHALT PAVING PROCESS: PLANS FOR ACTION RESEARCH. *Proceedings of 4th Nordic Conference on Construction Economics and Organization*, 37-46. Retrieved April 18, 2021 from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.99.7613&rep=rep1&type=pdf#page=40

Moore, T. (2013). A Civil Engineer's Guide to GPS and GNSS. *Geospatial Engineering Panel Briefing Sheet*. From https://www.ice.org.uk/getattachment/knowledge-and-resources/briefing-sheet/a-civil-engineers-guide-to-gps-and-gnss/Guide_to_GPS_and_GNSS_Jan_14_v4.pdf.aspx

Nar, P., Amin, S. S., Banerjee, S., Garg, V., & Pardasani, A. (2019, June 21). Autonomous Multifunctional Quadcopter for Real-Time Object Tracking and Seed Bombing in a Dynamic Environment. *Emerging Technologies for Agriculture and Environment*, 199-211. From https://link.springer.com/chapter/10.1007/978-981-13-7968-0_15

Nascimento, P. P., Kimura, B. Y., Guidoni, D. L., & Villas, L. A. (2018). An Integrated Dead Reckoning with Cooperative Positioning Solution to Assist GPS NLOS Using Vehicular Communications. *Sensors, 18*(9). From https://doi.org/10.3390/s18092895

NOAA. (2021, February 26). *What is lidar?* From National Ocean Service: https://oceanservice.noaa.gov/facts/lidar.html

NovAtel. (2020, April 9). *Uses of GPS: What are GPS Systems used for?* From Hexagon: https://blog.novatel.com/what-are-gps-systems-used-for/

Ojha, S., & Sakhare, S. (2015). Image processing techniques for object tracking in video surveillance- A survey. *2015 International Conference on Pervasive Computing (ICPC)* (pp. 1-6). Pune, India: IEEE. From https://doi.org/10.1109/PERVASIVE.2015.7087180

Oloufa, A. A., Ikeda, M., & Oda, H. (2003). Situational awareness of construction equipment using GPS, wireless and web technologies. *Automation in Construction, 12*(6), 737-748. From https://doi.org/10.1016/S0926-5805(03)00057-8

Onofre, S., Silvestre, P. M., Pimentão, J. P., & Sousa, P. (2016). Surpassing bluetooth low energy limitations on distance determination. *2016 IEEE International Power Electronics and Motion Control Conference (PEMC)*. From http://dx.doi.org/10.1109/EPEPEMC.2016.7752104

Park, J., & Nguyen, C. (2003). An ultra-wideband microwave radar sensor for characterizing pavement subsurface. *IEEE MTT-S International Microwave Symposium Digest. 2*, pp. 1443-1446. Philadelphia, PA, USA: IEEE. From https://ieeexplore.ieee.org/document/1212644

Pierce, F. (2020, May 17). *The Future of Barcoding and RFID*. From Supply Chain: https://supplychaindigital.com/logistics-1/future-barcoding-and-rfid

Primera Engineering. (2016, June 3). *GLOBAL POSITIONING SYSTEM USAGE IN ROAD CONSTRUCTION*. From Primera: https://primeraeng.com/posts/gps-usage-in-road-construction/

Ravikumar, A. (2020, June 23). *History of GPS satellites and commercial GPS tracking*. From GEOTAB: https://www.geotab.com/blog/gps-satellites/

Ray, B. (2020, November 20). *A Breakdown Of 7 RFID Costs, From Hardware To Implementation*. From Air Finder: https://www.airfinder.com/blog/rfid-cost

Rizos, C., & Yang, L. (2019). Background and Recent Advances in the Locata Terrestrial Positioning and Timing Technology. *Sensors, 19*(8), 1821. doi:10.3390/s19081821

Roberts, C. M. (2006). Radio frequency identification (RFID). *Computers & Security, 25*(1), 18-26. From https://doi.org/10.1016/j.cose.2005.12.003

RTLOC. (2020, April 6). *Technology details*. From RTLOC: https://rtloc.com/technology/

Saidi, K. S., Teizer, J., Franaszek, M., & Lytle, A. M. (2011). Static and dynamic performance evaluation of a commercially-available ultra wideband tracking system. *Automation in Construction, 20*(5), 519-530. From https://doi.org/10.1016/j.autcon.2010.11.018

Saks, M., & Allsop, J. (2013). *Researching Health* (2nd ed.). Bodmin: MPG Books Group. From https://books.google.nl/books?hl=es&lr=&id=RjPtBgAAQBAJ&oi=fnd&pg=PT117&dq=benefits+and+limitations+of+semi-structured+interviews&ots=btueBY6CZW&sig=zP4tDKTlHsAWWshc4FVnQ40_rlo#v=onepage&q=benefits%20and%20limitations%20of%20semi-structured%20interviews&f

Schmehl, A. (2020, October 2). *The Pros and Cons of LiDAR*. From KATAPULT: https://www.katapultengineering.com/blog/pro-and-cons-of-lidar

Schoeke, K. (2019, September 5). *Top 9 Reasons Why RFID is Not Working*. From RFID Reader News: https://www.scribbr.com/apa-citation-generator/new/webpage/

Shankland, S. (2012, December 13). *Locata wants to fill holes in GPS location, navigation*. From CNET: https://www.cnet.com/news/3600-for-child-tax-credit-calculate-what-your-family-will-get-starting-july-15/

Sheng, C., Gan, X., Yu, B., & Zhang, J. (2020). Precise Point Positioning Algorithm for Pseudolite Combined with GNSS in a Constrained Observation Environment. *Sensors, 20*(4). From https://doi.org/10.3390/s20041120

Sirin Software. (2018, November 9). *UWB: Cost-Effective Wireless Technology for High Accuracy*. From Sirin Software: https://sirinsoftware.com/blog/uwb-cost-effective-wireless-technology-for-high-accuracy/

Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of Business Research, 104*, 333-339. From http://dx.doi.org/10.1016/j.jbusres.2019.07.039

Tatum, M. C., & Liu, J. (2017). Unmanned Aircraft System Applications in Construction. *Procedia Engineering, 196*, 167-175. From https://doi.org/10.1016/j.proeng.2017.07.187

Technologies Used In Geospatial Science. (2020, April 23). From Geospatial science technology: https://www.geospatialscience.com.au/explore/technology/

TENNA. (2020, October 19). *Bluetooth Low Energy Technology*. From TENNA: https://www.tenna.com/technology/ble/

U-blox. (2020, June 23). *Positioning chips and modules*. From Ublox: https://www.u-blox.com/en/positioning-chips-and-modules#:~:text=u%E2%80%91blox%20offers%20position%20and,for%20people%20and%20asset%20tracking.

University of Minnesota. (2021, May 17). *Conducting a Systematic Review*. From LIBRARIES: https://libguides.umn.edu/systematicreviews

University of Southern California. (2021, June 7). *Research Guides*. From USC Libraries: https://libguides.usc.edu/writingguide/literaturereview

University of Southern California. (2021, February 23). *The Future of GIS*. From USC Dornsife Spatial Sciences Institute: https://gis.usc.edu/blog/the-future-of-gis/

Wilson, R. (2014, October 10). *The pros and cons of Bluetooth Low Energy*. From Electronics Weekly: https://www.electronicsweekly.com/news/design/communications/pros-cons-bluetooth-low-energy-2014-10/

Wilson, V. (2012). Research Methods: Interviews. *Evidence Based Library and Information Practice*.

Yousefi, R. M., & Razdari, M. A. (2015). Application of Gis and Gps in Precision Agriculture (a Review). *International Journal of Advanced Biological and Biomedical Research*, 7-9. From http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.866.3169&rep=rep1&type=pdf

Zajac, P., & Kwasniowski, S. (2017). The reliability problems of reading RFID tags in logistics warehouse systems. *MATEC Web of Conferences*. doi:10.1051/matecconf/201711205012

Zhang, D., Huang, H., & Jo, M. (2015). Future RFID technology and applications: visions and challenges. *Telecommunication Systems, 58*(3), 193–194. From https://doi.org/10.1007/s11235-014-9865-8

Zhang, K., Yu, X., Li, L., Liu, Z., Zhou, S., & Zhao, Z. (2021). A fast RFID image matching algorithm for multi-tag identification and distribution optimization. *Journal of Algorithms & Computational Technology, 15*, 1-8. From http://dx.doi.org/10.1177/17483026211012617

Zhanwu, M. (2020). Application of GPS Positioning Technology in Civil Engineering Survey. *IOP Conference Series: Earth and Environmental Science, 560*. From https://iopscience.iop.org/article/10.1088/1755-1315/560/1/012003/pdf

Zhao, J., Xu, H., Liu, H., Wu, J., Zheng, Y., & Wu, D. (2019, March). Detection and tracking of pedestrians and vehicles using roadside LiDAR sensors. *Transportation Research Part C: Emerging Technologies, 100*, 68-87. From https://doi.org/10.1016/j.trc.2019.01.007

Zhou, S., & Gheisari, M. (2018). Unmanned aerial system applications in construction: a systematic review. *Construction Innovation, 18*(4), 453-468. From https://doi.org/10.1108/CI-02-2018-0010

Appendix

Appendix A: Saaty's scale of comparison

Intensity of importance	Description
1	Equal importance
3	Moderate importance of one factor over another
5	Strong or essential importance
7	Very strong importance
9	Extreme importance
2,4,6,8	Intermediate values
Reciprocals	Values for inverse comparison

Figure 10: Scale of comparison

Appendix B: Random Index

n	RI
2	0
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.51

Figure 11: Table of Random Index

Appendix C: Calculations Consistency Ratio

=(F20*B13)+(F21*C13)+(F22*D13)+(F23*E13)

Comparison matrix, also called priority matrix

	Accuracy	Robustness	Costs	User-friendliness
Accuracy	1.00	5.00	3.00	3.00
Robustness	0.20	1.00	0.33	0.20
Costs	0.33	3.00	1.00	0.33
User-friendliness	0.33	5.00	3.00	1.00
Sum	1.87	14.00	7.33	4.53

	Accuracy	Robustness	Costs	User-friendliness	Priority vector	Weighted sum
Accuracy	0.54	0.36	0.41	0.66	0.49	F23*E13)
Robustness	0.11	0.07	0.05	0.04	0.07	0.27
Costs	0.18	0.21	0.14	0.07	0.15	0.61
User-friendliness	0.18	0.36	0.41	0.22	0.29	1.24
Sum	1.00	1.00	1.00	1.00	1.00	1.00

Figure 12: Calculation weighted sum

=G20/F20

Comparison matrix, also called priority matrix

	Accuracy	Robustness	Costs	User-friendliness
Accuracy	1.00	5.00	3.00	3.00
Robustness	0.20	1.00	0.33	0.20
Costs	0.33	3.00	1.00	0.33
User-friendliness	0.33	5.00	3.00	1.00
Sum	1.87	14.00	7.33	4.53

	Accuracy	Robustness	Costs	User-friendliness	Priority vector	Weighted sum	Divide weighte
Accuracy	0.54	0.36	0.41	0.66	0.49	2.15	=G20/F20
Robustness	0.11	0.07	0.05	0.04	0.07	0.27	4.08
Costs	0.18	0.21	0.14	0.07	0.15	0.61	4.07
User-friendliness	0.18	0.36	0.41	0.22	0.29	1.24	4.26

Figure 13: Calculation divide weight

=AVERAGE(H20:H23)

AVERAGE(**number1**; [number2]; ...)

5	Strong
7	Very st
9	Extrem
2,4,6,8	Interm
Reciprocals	Values

Comparison matrix, also called priority matrix

	Accuracy	Robustness	Costs	User-friendliness
Accuracy	1.00	5.00	3.00	3.00
Robustness	0.20	1.00	0.33	0.20
Costs	0.33	3.00	1.00	0.33
User-friendliness	0.33	5.00	3.00	1.00
Sum	1.87	14.00	7.33	4.53

	Accuracy	Robustness	Costs	User-friendliness	Priority vector	Weighted sum	Divide weight	Average
Accuracy	0.54	0.36	0.41	0.66	0.49	2.15	4.38	=AVERAGE(H20:H23)
Robustness	0.11	0.07	0.05	0.04	0.07	0.27	4.08	
Costs	0.18	0.21	0.14	0.07	0.15	0.61	4.07	
User-friendliness	0.18	0.36	0.41	0.22	0.29	1.24	4.26	
Sum	1.00	1.00	1.00	1.00	1.00	1.00		

Figure 14: Calculation average of weighted values

Appendix D: Calculation for ranking the alternatives

JM | =(F40*B40)+(F41*C40)+(F42*D40)+(F43*E40)

A	B	C	D	E	F
Criteria	Accuracy	Robustness	Costs	User-friendliness	
Measuring unit	centimeters	score card	score card	score card	Final score vector
BLE	0.36	0.18	0.00	0.16	0.49
Locata	0.01	0.05	0.36	0.21	0.07
UAS	0.24	0.09	0.01	0.05	0.15
Lidar	0.05	0.14	0.56	0.11	0.29
Ultra-wideband	0.07	0.14	0.01	0.16	
U-blox	0.00	0.05	0.00	0.05	
RFID	0.24	0.18	0.02	0.21	
Thermal imaging	0.01	0.18	0.04	0.05	
Sum	1.00	1.00	1.00	1.00	

Possibilities	Score	Ranking
BLE	F43*E40)	8
Locata	0.12	4
UAS	0.14	5
Lidar	0.15	6
Ultra-wideband	0.09	3
U-blox	0.02	1
RFID	0.20	7
Thermal imaging	0.04	2

Figure 15: Ranking of the alternatives