Evaluation of monitoring technologies on construction sites

Master Thesis

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I would like to thank my colleagues at the Construction and Real Estate Management Maser’s programme, they were my classmates, my friends, and my family during the past two years; this thesis was influenced by their feedback and motivation.

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Topic:

Evaluation of monitoring technologies on construction sites

This Master Thesis aims to explore the development of monitor and control processes and technologies in the Architecture, Engineering, and Construction (AEC) industry during the execution phase of construction projects, contrast it with the traditional practices, and reveal the potential feasibility of the application of new technologies on the current AEC industry.

Among the technologies that this research intends to study are 3D Cameras, Bluetooth, Computer Vision, Global Positioning Systems (GPS), Laser Scanning (LS), Radio Frequency Identification (RFID), Ultra-Wideband (UW), and Wireless Sensor Networks (WSN). This list could be modified if additional, relevant technologies are found.

This research strives to assess the potential and limitations of each technology, design a selection criterion describing the feasibility of their use, relying on variables inherent to individual construction projects, and the technologies themselves. The use of predictive solutions rather than reactive solutions via the collection and analysis of big data is also an interesting topic to explore, as well as methods to improve the technology acceptance in the AEC industry.

By performing this research, the following interrogatives shall be clarified:

- What are the current practices of monitor and control during the execution phase of construction projects?

- Which new technologies are being developed with an intended use on monitor and control during the execution phase of construction projects?
- Which are the opportunities related to the implementation these new technologies on monitor and control during the execution phase of construction projects?
- Which are the main challenges and limitations related to the implementation of these new technologies on monitor and control during the execution phase of construction projects?
- Which criterion can be used to evaluate the feasibility of implementing new technologies on monitor and control during the execution phase of specific construction projects?

The research is expected to be achieved based on a solid literature review and contact with representatives with relevant experience and positions that form part of construction companies in Finland, Germany, or any other location that may be implementing new technologies in the AEC industry if cooperation is viable. Case studies shall be obtained from those sources and subsequently analysed.

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Abstract

The present thesis describes the current state of construction site monitoring, capitalizing on flaws and their consequences, to then explore the opportunities of mitigating or eliminating these flaws by leveraging available and developing technologies in the field. A range of technologies are extracted from existing literature and individually defined and assessed in regards of their operation, performance, limitations, and potential. Data management systems are explored as the crucial interface between monitoring technologies and stakeholders, and technology acceptance is considered as a key factor in the success of implementing new monitoring technologies in construction sites. A comparative SWOT analysis including the traditional practices and monitoring technologies is designed to display the evaluation of the information in condensed structure, to aid comparison and decision making.

Keywords: Construction site, monitoring, technologies, sensors, automation

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List of Acronyms

AB	As built
AD	As designed
AEC	Architecture, engineering, and construction
AOA	Angle of arrival
AP	Access Point
AR	Augmented reality
BBS	Behavior based safety
CSS	Chirp spread spectrum
FN	False negative
FOV	Field of view
FP	False positive
GPS	Global positioning systems
ILS	Indoor location sensing
IR	Infra-red
JHA	Job hazard area
LADAR	Laser detection and ranging
LOS	Line of sight
LS	Laser scanner
NFC	Near field communication
OCR	Optical character recognition
pPC	Partial point cloud
PPC	Plan percent complete
RFID	Radio-frequency identification
RGB-D	Red, green, blue, distance (range cameras and images)
RSS	Received signal strength
RSSI	Received Signal Strength Indication
RTLS	Real time locating systems
SPI	Schedule performance index
TAM	Technology acceptance models
TDOA	Time difference of arrival
TN	True negative
TOA	Time of arrival
TOF	Time of flight
TP	True positive
UAV	Unmanned aerial vehicle
UTAUT	Unified theory of acceptance and use of technology
UWB	Ultra-wideband
SWOT	Strengths, weaknesses, opportunities, threats
WBS	Work breakdown structure
WLAN	Wireless local area network
WSN	Wireless sensor networks

1. Introduction

Monitoring and Control are essential tasks in construction management, crucial to achieve satisfactory project quality, costs, and duration, according to plan; as well as construction site safety. This study explores current monitoring practices and their inefficiencies, along with their consequences on the project performance; to then evaluate the potential of developing technologies of monitoring and control being implemented on construction sites. Innovative which could respond to the need for improved monitoring techniques in the AEC industry. To this avail, previous research regarding actual practices of construction site monitoring is examined and contrasted with the literature regarding currently available and developing site data capturing technologies.

The main interrogatives which this work strives to answer involve the description of the current monitoring practices on construction sites, the identification of available technologies for on-site monitoring, their potential and limitations, and the evaluation of technologically innovative alternatives and the current practices.

Chapter two describes the research process, the initial interrogatives which define the aim of the study, the research methods and tools utilized, the foundation and production of conclusions which fulfill the interrogatives.

Chapter three provides definition of terms more closely related to computer science; since the research is performed in the field of construction management technology, clarifying expressions involved with robotics, visualization, telecommunication, and sensor technologies proves beneficial to the development and understanding of this work.

Chapter four describes the processes defining the current monitoring practices of the AEC industry focusing on existing deficiencies and their consequences on project safety, duration, costs, and quality.

The research explores the developing monitoring technologies on chapter five, their role on other industries and the potential they offer to the construction industry, in regards of the deficiencies found on chapter four. Specific technologies are individually analyzed in regards of their definition and operation, their potential contribution to the AEC industry and their current limitations and areas of development. Previous research which aimed to study different selections of monitoring technologies are used as a reference to support this paper, however, while some of the information contained on those papers remains relevant, a significant portion is outdated or vague. On the other hand, papers striving to study a single technology or method were greater in number, and more recent, they also contained more precise information which was diligently processed to generate a profile for each technology.

Chapter six consists of a comparative SWOT analysis designed by the author, which condenses the evaluation of the previous chapters to provide a practical analysis tool for decision making and understanding towards the available monitoring options. The SWOT layout is thoroughly described, the final tables are presented and discussed.

Chapter seven introduces monitoring data management systems and their relation to on-site monitoring data, involvement of relevant stakeholders, and building information modelling. The general challenges of monitoring technologies' implementation on the construction industry are presented, along with possible strategies to mitigate or void them.

The eighth chapter concludes the research, presenting the conclusions derived from the entire process, which give answer to the initial interrogatives. Reflections on areas of improvement of this research, knowledge gaps identified, and further studies are presented as well.

This research contributes to the body of knowledge by providing a comprehensive review of the current utilization and further development of the field data capturing technologies used for automated construction monitoring. Potential areas for further research are also effectively identified.

2. Methodology

This research was founded on a specific conceptual formulation proposing the field of study and interrogatives to be addressed. To that avail, several literature reviews and analysis were performed and integrated.

An initial literature review was performed to investigate construction site monitoring current practices, define their requirements, evaluate their efficiency, and identify deficiencies in processes that could benefit from technological support.

Existing research was also used as a basis to identify and describe developing technologies, their research and development, application methods, achievements and barriers, data integration systems, and relevant implementation feasibility variables and comparison criteria.

Journal articles were gathered via ScienceDirect research directory and search engine, using keywords such as: “Construction”, “Site”, “Automation”, “Technology”, “Progress”, “Tracking”, “Monitoring”, “Data”, “Sensors”; including combinations. Additionally, academic material was retrieved from Springer Link. Both research services were provided by Metropolia University of Applied Sciences and HTW Berlin respectively.

Based on the monitoring requirements and the technologies parameters, a comparative SWOT table was designed and filled, an additional table with identical structure is presented with the sources for each specific data input. SWOT was chosen as an analysis tool due to its flexibility which allows the accommodation of multiple strategies for comparison, as well as its popularity and common understanding among academia and industry community, and for its visualization effectiveness, which is enhanced by the traffic light metaphor. The result is an intuitive, information rich instrument.

The information displayed on the table is analyzed, identifying patterns and contrasts along the technologies and their characteristics. This SWOT table intends to become a basis for decision making regarding adequate site data capturing technologies to specific project conditions, it also exposes the current knowledge gaps which could be addressed by future research.

A final literature exploration is performed to describe monitoring data management systems, building information modelling, visualization importance and alternatives, as well as challenges related to technology acceptance and how to address them to promote the implementation of new technologies in the construction industry.

3. Definition of terms

On this chapter specific terms are defined to serve as a basis for the development and understanding of the following chapters. This research work is presented under subjects related to Construction Management Technologies, however, it is closely related to Computer Science, therefore a preliminary clarification of technical terms related robotics, visualization, telecommunication, and sensor technologies proves beneficial to the development and understanding of this work.

There are also terms which allow multiple interpretations, in this case providing the description used in this research is also appropriate. The author recommends readers to notice this section rather than to skip it, scan through the listed terms and selectively read those definitions of terms which are unfamiliar, this will facilitate the understanding of the following sections.

Accuracy

Accuracy is an essential criterion to be taken into account when evaluating a monitoring technology and is defined as “the statistical difference between the estimate or measurement of a quantity and the true value of that quantity” (Awolusi, Marks, & Hallowell, 2018).

Algorithm

An algorithm is a defined procedure composed by steps that intends to solve a problem or perform a specific task (Weik, Algorithm, 2000).

Augmented Reality (AR)

Augmented Reality Denotes a live perception of a real-world environment, which elements are enriched with computer generated visuals (Tarek & Moncef, 2016).

Automation

"The investigation, design, development, and application of procedures that render processes automatic, self-moving, or self-controlling " (Weik, Automation, 2000).

Data training

Refers to the operation of providing data to a machine learning algorithm to define and improve its performance, this is a mayor aspect of computer vision (Cheng, Rashidi, Davenport, & Anderson, 2017).

Device

A physical element which can perform a task, in the context of this research work the task will generally involve interaction with a computer software (Weik, Device, 2000)

Drift

Drift is defined as the relatively slow change of a value retrieved from a system or equipment, usually affecting the accuracy of a measuring device, and corrected by calibration (Weik, Drift, 2000).

(Aerial) Drone

Formally known as unmanned aerial vehicles, abbreviated as UAVs, it is a flight enabled robot originally developed and utilized on military, now introduced to a broad range of industrial sectors (Anderson & Sessums, 2018).

Handcrafted algorithms

Algorithms which do not implement machine learning, therefore have a defined and unchanging set of tasks, unchanging performance, and low tolerance to change (Kim, Liu, Lee, & Kamat, 2019).

Kalman filter

The Kalman filter is "an optical estimator that is able to infer parameters of interest from indirect, inaccurate, and uncertain observations" (Zhu, et al., 2016)

Machine learning

The ability of a device, such as a computer, to improve its performance based on the results of its past performance (Weik, Machine learning, 2000).

Moore’s law

Refers to the prediction proposed in 1965 by Gordon Moore and later revised multiple times by himself, regarding the yearly increase of transistors per silicon chip, which relates to the size of transistors and subsequently explains the reduction in size of electronic devices (The Editors of Encyclopaedia Britannica, n.d.).

Noise

Undesired, irrelevant or misleading information captured by a system and that could negatively affect its performance (Weik, Noise, 2000).

Precision

Precision is a measure of how similar the estimates or measurements of a value are to each other, without considering the real value intended to be estimated or measured (Awolusi, Marks, & Hallowell, 2018).

Point cloud

A point cloud is defined by multiple digital points that describe the geometry of an element, each point having X, Y, and Z coordinate values (Kopsida, Brilakis, & Vela, 2015). The quality of a point cloud is can be assessed as a directly proportional function to the number of points per unit of area or volume, and the accuracy of the points’ coordinates (Rebolj, Pučko, Čuš Babič, Bizjak, & Mongus, 2017).

Robot

A robot is a device able to interact with the environment by executing algorithm, automatically or remotely controlled (Weik, Robot, 2000). On this research robots are usually mentioned as units able to assist the monitoring activity by carrying sensors throughout the construction site.

Sensor

For the uses on this thesis, a sensor will be defined as a device which is able to retrieve and communicate information from the environment (Weik, Sensor, 2000). All monitoring technologies inherently require the use of sensors to assess a given aspect of the construction site.

Signal

A signal is energy used during a specific time frame to transmit information, in this research it is a crucial element for monitoring system to interoperate and convey information to construction stakeholders; multiple signals can also disturb each other, and become noise (Weik, Signal, 2000)

Frequency band

Electromagnetic waves transmit signals at specific frequencies, these frequencies are grouped according to minimum and maximum limits, which influences their use and performance (e.g. military, industrial, transportation).

4. Overview of current monitoring practices

According to (Project Management Institute, 2013) Monitoring and Control consist of tracking, evaluating, and coordinating project development, identifying divergences to the plan, and performing the corrective actions when needed.

Monitor and control are key processes in construction and consist of the systematic collection and assessment of project data to ensure health and safety conditions, project quality, project completion time and cost (Callistus & Clinton, 2016). Monitoring input and output provides comprehensive knowledge regarding activity workflow, progress, and quality (Yang, Park, Vela, & Goldparvar-Fard, 2015).

Monitoring entails comparing the real, ongoing construction process with the planned progression, detecting differences to be addressed by another, closely related process, known as Control (Yang, Park, Vela, & Goldparvar-Fard, 2015).

Successful monitor and control in construction depends on sufficient, reliable, and timely supply chain of information, able to describe the current conditions, upon which the project manager can found their decisions (Awolusi, Marks, & Hallowell, 2018). Monitoring and control of construction equipment results in improved productivity, emissions, and safety (Cheng, Rashidi, Davenport, & Anderson, 2017).

4.1 Monitoring construction progress

The assessment of progress is one of the greatest challenges in project management (Zhang, et al., 2008). Some objective measures of progress include the Schedule Performance Index (SPI) and Plan Percent Complete (PPC), these can only detect issues based on the global outcome of construction, methods able to measure equipment, labor, and material performance separately are not used (Yang, Park, Vela, & Goldparvar-Fard, 2015).

A reliable assessment of progress is essential to control costs and schedule, make financial reports, evaluate productivity, and handle claims (Zhang, y otros, 2008).

Work progress assessment is essential for project monitoring and control, currently, it is estimated using manual, paper-based approaches, which are considerably time consuming (Garcia-Lopez & Fischer, 2014). Construction activities usually have a duration in the range of days, yet, traditional collection and report of data is performed monthly (Zhang, et al., 2008).

4.2 Monitoring and quality management

Quality management is an essential task in construction projects, it relies on inspections which are carried on site traditionally using a paper printed check list (Ma, et al., 2018). The information is later manually fed into a computer, and the whole process is slow and vulnerable to human error, compromising construction quality (Ma, et al., 2018). Quality management is ruled by standards which vary depending on the country, nevertheless, the compliance to these standards is guaranteed by inspections, carried out by different stakeholders after at defined construction milestones (Ma, et al., 2018). A diagram of current practices of construction quality management is depicted by figure 1.

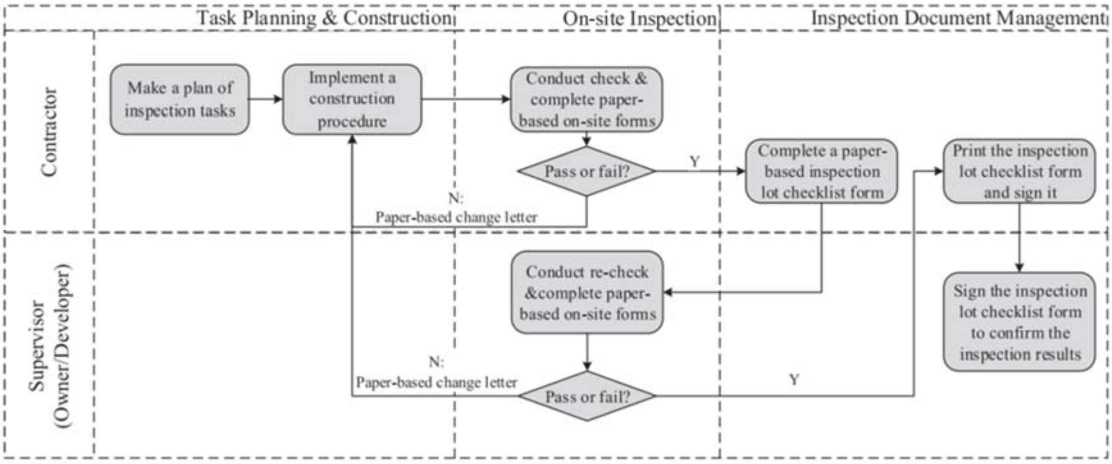


Figure 1 Current process of construction quality management. Source: (Ma, et al., 2018).

(Nahangi, Czerniawski, Haas, & Walbridge, 2019) address the specific case of prefabricated and modular elements in construction, which currently consider a degree of tolerance in their design to compensate for measurement errors originating from measuring tools, the skill of the user, the element which is measured, data transcription, and the environment conditions. These considerations limit the complexity of assemblies and even when preliminary considerations are made, these errors can still cause rework (Nahangi, Czerniawski, Haas, & Walbridge, 2019).

4.3 Monitoring and safety

Construction worksite safety is challenging due to the high number of workers in relation to the number of safety supervisors (Li, et al., 2015), as well as arduous activities performed on harsh environments (Yu, et al., 2019). Dynamism inherent to Construction sites is one of the main causes of incidents, safety regulations, equipment, and training applied on construction sites are insufficient to guarantee safety (Kim, Kim, & Kim, 2017). Workers become less aware of their environment as they perform repetitive tasks, the high levels of noise also dampen their perception (Kim, Kim, & Kim, 2017).

About four out of five construction accidents occur due to labor unsafe behavior (Yu, Guo, Ding, Li, & Skitmore, 2017). The current practice uses Behavior-Based-Safety (BBS), a method that relies on employees responsible of worksite safety who record and observe workers and give them feedback, therefore representing increased costs, and limited observation to places and workers (Yu, Guo, Ding, Li, & Skitmore, 2017).

The improvement of construction site safety would not only reduce the number and severity of accidents, but also increase morale and satisfaction among workers, and their productivity (Zhu, et al., 2016). Fatigue is closely related and can also be monitored, exhausted workers tend to develop health conditions, err during their activities, reduce their productivity, and create accidents (Yu, et al., 2019).

4.4 Weaknesses of the current practices

The monitoring systems used in the construction industry are not efficient, in comparison to those used in other industries (Kopsida, Brilakis, & Vela, 2015). The current practices are mostly manual: an expert/surveyor visits the site and documents site data manually, often using pen and paper and paper-based drawings and specification as assessment base (Yang, Park, Vela, & Goldparvar-Fard, 2015). Although the use of tablets is becoming more common, these tablets could be enabled to interact on a BIM environment, however still require the surveyor to search documents, pictures, plans, and models manually, failing to make the monitoring process any less manual, and therefore costly, time consuming, and prone to errors (Yang, Park, Vela, & Goldparvar-Fard, 2015).

The quantity of data required to be manually collected from monitoring usually affects its quality and reduces the opportunities for performance improvement (Yang, Park, Vela, & Goldparvar-Fard, 2015). Post-processing of the inspection data often reveals the need for additional data unknown at the time of the inspection, requiring additional inspections or communication with onsite personnel, further consuming time and costs (Yang, Park, Vela, & Goldparvar-Fard, 2015). As a consequence of these conditions, in contrast with the developing Technologies, the opportunities of automation grow, becoming more evident every year (Yang, Park, Vela, & Goldparvar-Fard, 2015) (Yang, Shi, & Wu, 2016).

The use of traditional approaches of monitoring and management systems result in missing, incomplete, or incorrect information (Hany, Lamine, & Gamal, 2018). These practices are unreliable, slow, expensive, and faulty (Hany, Lamine, & Gamal, 2018). A workflow of the current monitoring practices is described by figure 2.

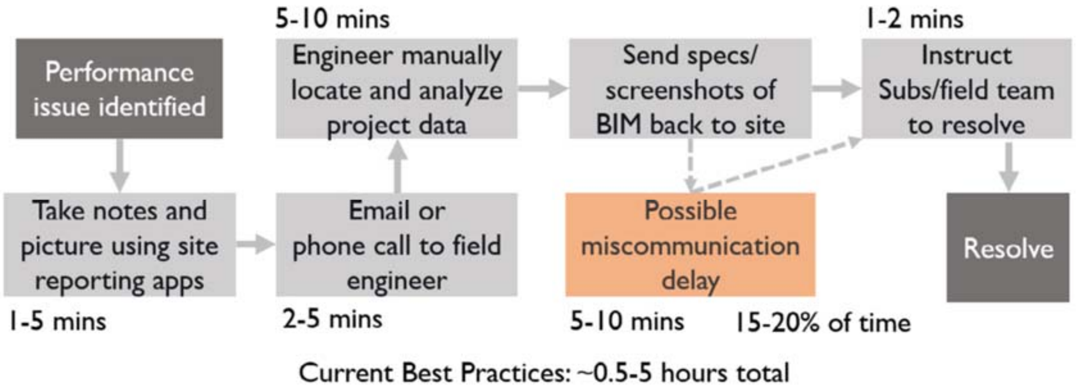


Figure 2 The workflow of control decisions on construction sites – data from BIMAnywhere and McCarthy construction based on a seminar presented at FIATECH2013. Source: (Yang, Park, Vela, & Goldparvar-Fard, 2015).

(Guo, Yu, & Skitmore, 2016) claim that monitoring problems derive from inherent features of construction data: Abstract, dynamic, and massive. However, failure to retrieve accurate and timely information from the construction site can result in delays, reworks, disputes, and claims (Kopsida, Brilakis, & Vela, 2015).

It is important to detect limitations, biases, and threats related to data collection and analysis. (Callistus & Clinton, 2016). Inspections performed by multiple supervisors present differences (Kopsida, Brilakis, & Vela, 2015).

Nowadays issues such as delays, additional costs, quality defects, and negative impacts on the environment are considered intrinsic aspects of the construction activity, and while their management strive to diminish their magnitude, there are yet no concrete solutions to them (Callistus & Clinton, 2016).

Challenging factors of current monitoring practices:

- Weak institutional capacity.
- Limited resources and budgetary allocations for monitoring and evaluation.
- Weak linkage between planning, budgeting, and monitoring and evaluation.
- Weak demand and utilization of monitoring and evaluation results.
- Poor data quality, data gaps, and inconsistencies.

Source: (Callistus & Clinton, 2016)

According to (Hany, Lamine, & Gamal, 2018), the architecture, engineering, and construction (AEC) industry is characterized by a low level of productivity, significantly attributed to weak monitoring strategies, which fail to provide a common understanding of project performance to the key stakeholders in a timely manner.

Historical data indicates that construction productivity has been reduced worldwide through the last decades (Luo, et al., 2018) (Yang, Shi, & Wu, 2016). 98% of projects are delayed an overall of 20 months behind their original schedule and their costs increase an average of 80% of the initial budget (Hany, Lamine, & Gamal, 2018). These effects are usually related to poor control initiatives, often consequence of inadequate management and the use of old technologies (Hany, Lamine, & Gamal, 2018).

The construction industry demands timely and accurate information to monitor the construction process, currently this process is performed manually, via site inspections and comparison with project documentation. Problems related to surveyor’s error, the time needed to perform the inspection, and the frequency of such inspections persist (Pučko, Šuman, & Rebolj, 2018).

5. Construction monitoring technologies

(Cheng, Rashidi, Davenport, & Anderson, 2017) claim it is of outmost priority for the construction industry to “develop efficient techniques for assessing the performance and productivity of key resources that is sufficiently flexible to handle the widely varying conditions that arise across different jobsites”. Moreover, (Yang, Shi, & Wu, 2016) have stated that “there is an urgent need of automated activity analysis of construction workers”

There is a need for the construction industry to implement new tools able to collect data for construction management (Li, et al., 2015). Such tools have been researched and show a potential to enhance logistics of material, equipment, and workers (Li, et al., 2015).

> The conservative nature of the construction industry tends to cling to ineffective monitoring and controlling systems, which has severe consequences on the speed and robustness of decision-making. (Hany, Lamine, & Gamal, 2018)

(Awolusi, Marks, & Hallowell, 2018) argue that the implementation of new technologies in the construction industry is slow due to the lack of reliable data regarding their potential benefits (Awolusi, Marks, & Hallowell, 2018).

New technologies are being implemented on other industries to improve safety and productivity, however, the construction industry has integrated just a few of them (Awolusi, Marks, & Hallowell, 2018). Automation of the monitoring process aims to provide timely and reliable data to support on site control procedures (Yang, Park, Vela, & Goldparvar-Fard, 2015).

Benefits of implementing advanced monitoring technologies include faster or even immediate awareness of on-site issues, more recently updated data means better control decisions. In contrast, current practices are significantly slower, more expensive, and faulty (Yang, Park, Vela, & Goldparvar-Fard, 2015).

Monitoring data requirements include:

- Progress measurement.
- Equipment and material tracking.
- Safety planning.
- Productivity tracking.
- Causes of schedule and cost overruns.

Source: (Pučko, Šuman, & Rebolj, 2018)

(Tarek & Moncef, 2016) propose a different classification of data from construction sites among three main groups: progress, quality, and finance.

5.1 Monitoring technologies potential on safety management

Monitoring technologies can retrieve key metrics to support safety management, such as physiological data, environment data, proximity, and location (Awolusi, Marks, & Hallowell, 2018).

The environmental awareness of workers can be enhanced by using technology, therefore reducing safety risks (Kim, Kim, & Kim, 2017). Information must be timely, relevant, reliable, and well presented to have a higher potential (Kim, Kim, & Kim, 2017). Hazard level can be estimated by using the distance between workers and sources of danger (e.g. a hole, wires, equipment), then an alarm can alert the worker via their sense of touch, sight, and/or hearing (Kim, Kim, & Kim, 2017) (Awolusi, Marks, & Hallowell, 2018).

A proactive automated warning system can help the workers prepare for impending danger, reducing the number and severity of accidents (Kim, Liu, Lee, & Kamat, 2019). It is important to note that false alarms can have a negative effect on safety management (Soltanmohammadlou, Sadeghi, Hon, & Mokhtarpour-Khanghah, 2019).

There are algorithms, such as the fuzzy interference-based method, which use images to imitate the safety criteria of a safety supervisor, without human intervention (Kim, Kim, & Kim, 2017). Technologies have a significant contribution potential of information behind the workers (Kim, Kim, & Kim, 2017).

The development of computers, sensors, and telecommunications facilitates automatic retrieval of workers health indicators such as heart rate, breathing rate, and posture, which could enable a shift from reactive to proactive construction safety management (Awolusi, Marks, & Hallowell, 2018).

5.2 Monitoring technologies potential on progress assessment

By leveraging location data

Changes in the construction site are always produced by a worker or equipment (Pučko, Šuman, & Rebolj, 2018) retrieving their precise location data is a persistent critical obstacle into achieving automated construction progress monitoring (Pučko, Šuman, & Rebolj, 2018) (Valero & Adán, 2016).

Location requires the simplest data processing and can be determined using signals, based on angle of arrival (AOA), time of arrival (TOA), time difference of arrival (TDOA), or received signal strength (RSS) (Awolusi, Marks, & Hallowell, 2018).

With the eventual introduction of mobile robots to the construction site, location data is required to contribute to the flow of material on site, inspection, and surveillance (Valero & Adán, 2016).

By leveraging element and activity identification

It is important to identify existing elements, as well as missing elements to assess construction progress (Pučko, Šuman, & Rebolj, 2018). Also, the productivity of the construction sector can be improved by developing technologies of activity recognition (Luo, et al., 2018).

The behavior of construction workers can be categorized into three groups according to level of perception: “action primitives”, “actions”, and “activities” (Yang, Shi, & Wu, 2016).

An action primitive consists of simple movements involving a single limb (e.g. dipping a roller into paint). An action involves several action primitives (e.g. dipping a roller into paint, removing excess paint, smearing paint on a wall). An activity contains several actions (e.g. painting a wall involves preparing the area, applying primer, and applying paint) (Yang, Shi, & Wu, 2016).

Movements can be separated into coarse-grained and fine-grained movements, walking is an example of coarse-grained movement, while wire tying is considered fine-grained (Yang, Shi, & Wu, 2016). An example of activities breakdown according to level of detail is presented on figure 3.

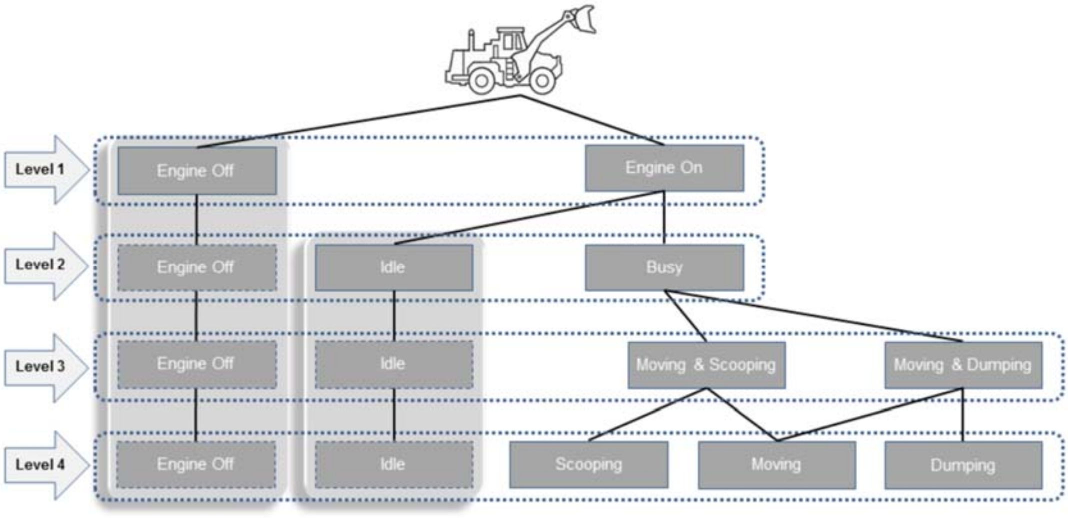


Figure 3 Level of detail in activity breakdown of a front-end loader (Akhavian, 2015)

5.3 Monitoring tools and methods requirements

Some of the most important requirements for monitoring tools and methods, according to the existing literature, are the following:

- Avoid hindering the primary work of labor and equipment (Pučko, Šuman, & Rebolj, 2018) (Awolusi, Marks, & Hallowell, 2018).

- Decisions regarding the use of technologies in construction must consider their cost and ease of use by the user-to-be stakeholders (Ma, et al., 2018).
- Power consumption and power source which allow maximum recharging/replacing times (Awolusi, Marks, & Hallowell, 2018).
- Accuracy and precision (Awolusi, Marks, & Hallowell, 2018).
- Able to retrieve relevant, timely, reliable, measurable, and verifiable data (Tarek & Moncef, 2016)

Regarding on-site location technologies, the following requirements should be met:

- Cover the entire construction site.
- Maximum error of one meter.
- Use the minimum number of devices possible.

Source: (Guo, Yu, & Skitmore, 2016)

It would be relevant to note that these general requirements are subject to the context and intended use of the technologies, for example, (Ma, et al., 2018). argue that indoor positioning technologies used with the aim to support inspections require an accuracy of up to three meters, instead of the single meter generally proposed previously.

New technologies might distract the workers from focusing on their work, or even become a hindrance for on-site processes (Kim, Kim, & Kim, 2017), therefore, devices must be able to fit their relevant locations without obstructing activities, also, they should be added to regular equipment workers use to ease their acceptance (Awolusi, Marks, & Hallowell, 2018). Multiple sensors integrated into a fewer number of devices also mitigates constraints on the implementation of technologies, while enhancing their potential (Awolusi, Marks, & Hallowell, 2018).

The frequency of battery changes has an impact on the cost and acceptance of technologies, and the capacity of batteries has a direct relation to their size, therefore, this requirement conflicts with the size and weight requirement, however, technological development is expected to further reduce the power consumption and size of devices, and enable electricity generation from the environment (e.g. solar energy, kinetic energy, heat energy) (Awolusi, Marks, & Hallowell, 2018).

One of the main challenges of monitoring technologies is their application on indoor tasks, since many of these tasks result in the changes of surfaces (e.g. paint, tiles, flooring) or relatively small and varied elements (e.g. cables, pipes) which are difficult to recognize by current technologies (Kopsida, Brilakis, & Vela, 2015).

It is imperative to clarify that the implementation of new monitoring technologies is not meant to replace the actual roles of inspectors, but to facilitate and enhance their work (Zhu, et al., 2016). Even though technologies are progressively assuming tasks traditionally performed manually by a human person, the option to perform manual changes should be generally available (Ma, et al., 2018).

5.4 Industry uses and previous case studies

For several years many construction companies have been using images and video captured by on-site cameras to support their inspections, reducing the need to visit the site, however, these files still need to be assessed by a professional (Zhang, et al., 2008).

> The localization and tracking of construction equipment (and other construction resources) is now a common practice within the construction industry. Currently, several companies (e.g. Giga Trak, Navman wireless, Fleetmatics, Linkup, Fleetilla, LiveViewGPS, etc.) offer commercial packages and services for location tracking of construction machinery. Accurately localizing and tracking construction equipment enables project managers and machine owners to better manage their assets in terms of fuel

consumptions, security concerns, and assessing the performance of operators. (Cheng, Rashidi, Davenport, & Anderson, 2017)

Commercial inspection software exist as facilitators of the inspection process (using mobile devices), they are effective in managing information, however, they do not automate the actual inspection process (Kopsida, Brilakis, & Vela, 2015).

Automatic recognition systems are commonly evaluated using the precision and recall indicators. Precision is the total of true positive (TP) results divided by the sum of this amount plus the number of false positives (FP). Recall is the total of true positive results divided by the sum of this amount plus the number of false negatives (FN) (Luo, et al., 2018).

The existing technologies for construction monitoring and control are not yet adequate to be implemented by the industry (Pučko, Šuman, & Rebolj, 2018). “There is no approach/system that has successfully automated monitoring, analyzing and controlling construction site activities to detect instantly any delays, once occurred” (Hany, Lamine, & Gamal, 2018)

The frequency of research regarding automated construction monitoring has been increasing importantly (Pučko, Šuman, & Rebolj, 2018), relying on new tools and methodologies which can be organized in two categories: Standalone Technologies and Integrated Technologies. Standalone technologies are constrained by the limitations of the single technology they utilize; therefore, an integrated approach is often preferred to combine the benefits of multiple technologies while compensating for each other’s limitations (Alizadehsalehi & Yitmen, 2019).

Stand-alone technologies are proposed as innovative and efficient solutions for monitor and control, however, due to their individual limitations, new approaches often consider the combined use of two or more technologies (Hany, Lamine, & Gamal, 2018). Combining multiple technologies results in more reliable monitoring systems, the aim is to integrate sensors that can complement each other and retrieve a wider range of information (Awolusi, Marks, & Hallowell, 2018).

Literature also classifies technologies into two groups, defined by whether there is a need for the sensors to be carried by the person or object to be monitored; those which possess this requirement are denominated ‘active; an include accelerometers, gyroscopes, GPS, RFID, and UWB, among others. Technologies which do not possess this requirement are instead denominated ‘passive’, some examples being computer vision, laser scanning, and photogrammetry (Cheng, Rashidi, Davenport, & Anderson, 2017).

(Awolusi, Marks, & Hallowell, 2018) argue that wearable (active) technologies can be able to automatically retrieve data to support decision making without hindering the processes in the construction site.

> The vision for the future of the construction industry is of a highly automated project management environment integrated across all phases of the project lifecycle. (Tarek & Moncef, 2016)

5.5 Monitoring technologies alternatives

There exists a variety of currently available and developing monitoring technologies suitable for construction sites, presenting them and evaluating their advantages and disadvantages could help inspectors decide which technologies fit their projects, and choose the most appropriate (Kopsida, Brilakis, & Vela, 2015).

5.5.1 Range Cameras

Also called 3D cameras or RGB-D (red, green, blue, distance), these include range sensors, such as infra-red (IR) projectors and cameras, allowing them to capture color and distance of objects and environments (Tarek & Moncef, 2016) (Kong, Liu, & Min, 2019). The added spatial information in comparison to regular cameras is not affected by changes in environment texture and illumination; and can be leveraged to reduce background noise (Kong, Liu, & Min, 2019).

Kinect is a motion sensing device developed by Microsoft and able to retrieve 3D information from human activity, recognizing human body joints and forming skeletons from its integrated camera and Infra-red sensors (Yu, Guo, Ding, Li, & Skitmore, 2017). It was originally designed as a gaming device, however, its relatively low price compared to other range cameras and its effectivity at capturing spatial data motivated its introduction into academic research (Nahangi, Czerniawski, Haas, & Walbridge, 2019). Kinect includes IR projector, IR camera, and RGB camera; depth is measured by projecting and capturing IR light then producing a 640x480-point cloud based on time of arrival, which overlaps with the RGB frame, its capturing range is from 7cm to 5m and the point density of a specific area is reduced in a proportion corresponding to the square of the distance to the device (Nahangi, Czerniawski, Haas, & Walbridge, 2019).

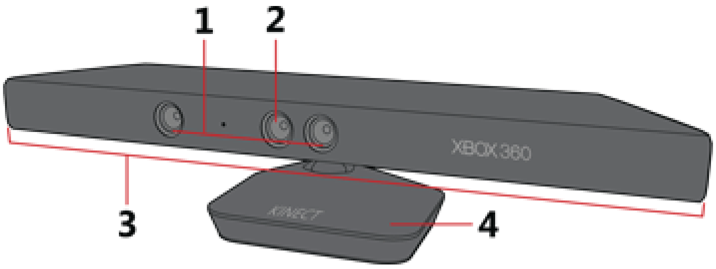


Figure 4 Kinect sensor for Xbox 360 components . Source: (Microsoft, 2019)

Figure 4 indicates the components of the Kinect device for Xbox 360:

1. Depth sensors.
2. RGB camera.
3. Microphones.
4. Motorized tilt.

Source: (Microsoft, 2019)

Kinect provides less irrelevant data, accelerating processing times; it also does not require training to identify human postures (contrary to machine learning) since these algorithms are built-in by Microsoft, and uses simple criteria, easy to understand and work with (Yu, Guo, Ding, Li, & Skitmore, 2017).

According to (Pučko, Šuman, & Rebolj, 2018) and (Kong, Liu, & Min, 2019) range cameras are cost-effective, easy to use and suitable for short rage, indoor works. However, range cameras are vulnerable to occlusions (which can be mitigated with additional sensors), as well as the analyzed parameters, depending on the intended use, for example, unsafe behavior parameters are likely to overlap with parameters of other behaviors (note that these parameters are determined as statistical ranges of values, not as single values) (Yu, Guo, Ding, Li, & Skitmore, 2017).

(Pučko, Šuman, & Rebolj, 2018) propose an idea of using 3D Cameras attached to workers' helmets and machines to retrieve partial point clouds (pPC), time, and location data.

(Yu, Guo, Ding, Li, & Skitmore, 2017) study a method of real-time identification of construction worker' unsafe behaviors by using Microsoft's Kinect to track the image-skeleton-based parameters (angles at articulations and gravity) and comparing them to parameters corresponding to three unsafe behaviors: leaning on a rail, climbing up a ladder, and dumping material. These method offers the potential to provide immediate warnings to workers, preventing accidents (Yu, Guo, Ding, Li, & Skitmore, 2017).

Range cameras' infra-red sensors require a clear line of sight and are vulnerable to sunlight, therefore, their accuracy is reduced on outdoor environments during the day (Yu, et al., 2019) (Awolusi, Marks, & Hallowell, 2018) (Zhu & Donia, 2013). Distance information often presents gaps due to reflective materials, these can significantly affect the benefits of RGB-D depending on the location of such materials (Kong, Liu, & Min, 2019).

5.5.2 Photogrammetry

Photogrammetry aims to retrieve distance data from pictures (Pučko, Šuman, & Rebolj, 2018). Videogrammetry is a derivative of photogrammetry, which aims to retrieve distance data from videos (Pučko, Šuman, & Rebolj, 2018). With distance information it can generate point clouds, which then are to be compared with as designed models to assess progress (Tarek & Moncef, 2016).

Point clouds generated via video/photogrammetry achieve acceptable accuracy and quality, while demanding significantly reduced costs compared to laser scanning (Tarek & Moncef, 2016).

The main advantages of photogrammetry are its relative low costs, automation, versatility, and the popularity of use of its hardware (cameras) among construction stakeholders (Tarek & Moncef, 2016). Their limitations include considerable computing time and vulnerability to lightning conditions (Tarek & Moncef, 2016)

Photogrammetry is typically used outdoors to obtain a point cloud of a building's façade (see figure 5), it can also be used indoors, however, the space must be large and simple to obtain reliable results (e.g. concert hall or church) (Borrmann, König, Koch, & Beetz, 2018).

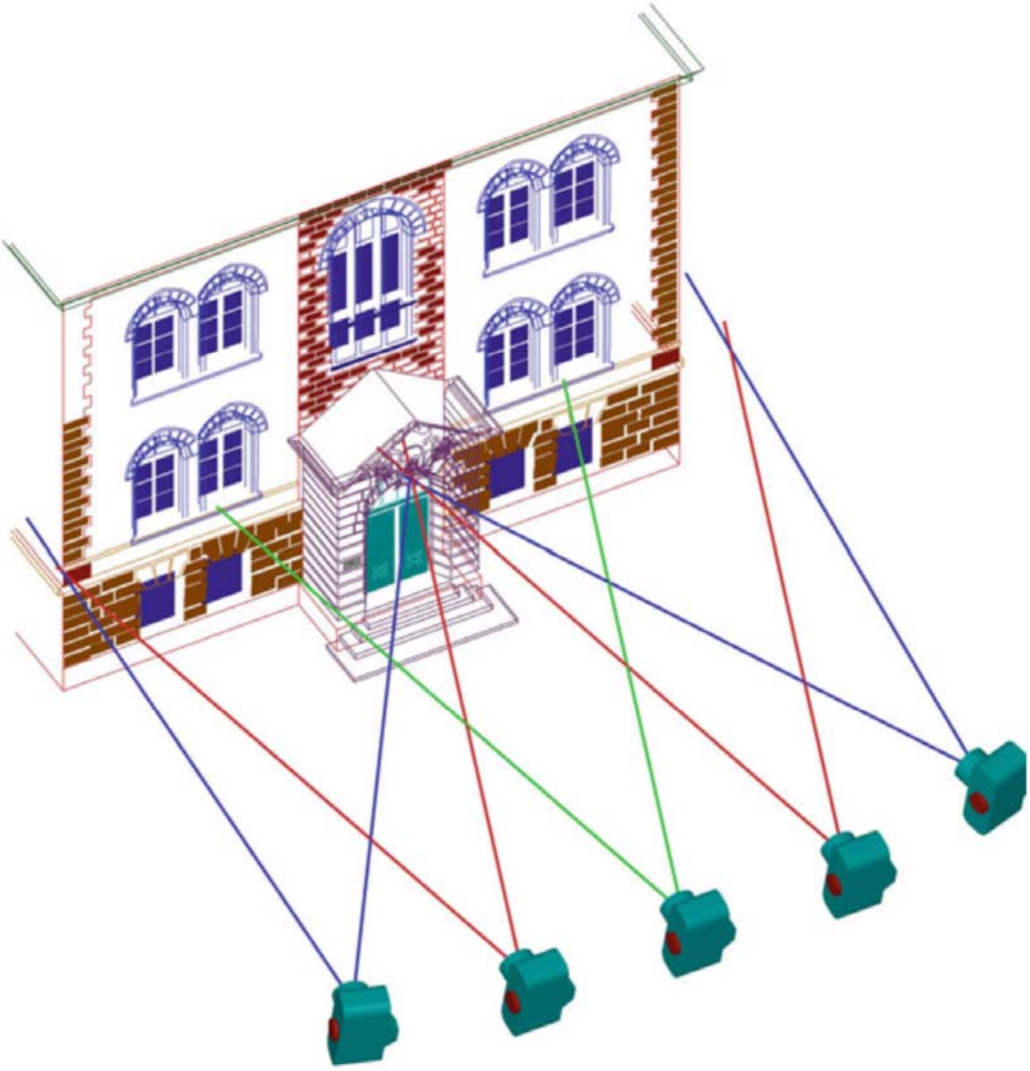


Figure 5 Set of images to be used for photogrammetry . Source: (Borrmann, König, Koch, & Beetz, 2018)

PHIDIAS is a commercial software able to perform photogrammetry analysis by triangulating multiple images with overlapping frames (Borrmann, König, Koch, & Beetz, 2018).

Photogrammetry or laser scanners can be used in combination with real time locating systems (RTLS) such that photogrammetry provides the geometric characteristics to generate a digital environment which simulates the real construction site, while the RTLS technology tracks the location of materials, equipment, or labor (Awolusi, Marks, & Hallowell, 2018).

5.5.3 Computer Vision

Computer vision technologies are being currently developed, these can harvest data from images and videos, enabling automatic detection/recognition of construction entities (Yang, Park, Vela, & Goldparvar-Fard, 2015).

On other industries computer vision has been used to develop features such as face and expression recognition, medical image analysis, and optical character recognition (OCR) (Zhang, et al., 2008).

Computer vision's development in construction has a mayor focus towards being able to localize workers, equipment, and materials automatically on a construction site to improve productivity and safety standards (see Figure 6) (Weili, Lieyun, Botao, Peter, & Hanbin, 2018).

Figure 6 Examples of data sets and labels (Kim, Liu, Lee, & Kamat, 2019).

The usual functions of computer vision are: recognition, to identify elements, features, or activities; Motion, to calculate velocity; scene reconstruction, to create a 3D model; and image restoration, to remove noise (Zhang, et al., 2008).

Due to the popularity and the development of smartphones, the quantity and quality of photos and videos taken daily on construction sites, which can be leveraged via computer vision, has increased significantly (Yang, Park, Vela, & Goldparvar-Fard, 2015). Moreover, the development of aerial robotics allows the industry to approach a wholistic data source on the exterior of buildings (Yang, Park, Vela, & Goldparvar-Fard, 2015).

Most computer vision algorithms consist of four steps. First, and object recognition method must be defined, these can be separated into three groups: recognition by parts, appearance-based recognition, and feature-based methods, the last one being the most commonly used due to its satisfying performance in complex scenes. Secondly, to define a tracking algorithm, to narrow the search space in the video. Third comes the action recognition algorithm, and lastly, the performance assessment algorithm, which registers the activity and location information (Cheng, Rashidi, Davenport, & Anderson, 2017) (Kim, Liu, Lee, & Kamat, 2019).

It is appropriate to note element recognition is a necessary prerequisite for element tracking to significantly reduce computational costs, the reason for this is detection algorithms aims to analyze the entire image frame to identify elements in every possible location, while tracking algorithms search for elements near their previous frame location (Kim, Liu, Lee, & Kamat, 2019).

Videos taken from construction site present variations such as viewpoints, scale, and illumination; also, the appearance of equivalent elements (e.g. workers, and equipment) vary, therefore handcrafted algorithms, which lack adaptability and simply operate as designed, are unfit for these conditions, and machine learning is usually applied instead (Kim, Liu, Lee, & Kamat, 2019). The latter is also capable of extracting fine-grained features, which improves accuracy, however, it requires a vast volume of data and time for training, which is an mayor limitation related to this technology (Kim, Liu, Lee, & Kamat, 2019) (Hany, Lamine, & Gamal, 2018).

Visual motion capture technologies usually consist of 4 phases:

1. Collecting sample data.
2. Reducing dimension
3. Extracting relevant features
4. Comparing relevant features of sample data with test data.

Source: (Yu, Guo, Ding, Li, & Skitmore, 2017)

Google offers a computer vision application named Google Lens (Figure 7), this application is available for free, often installed from factory on Android devices, and allows users to identify text, landmarks, objects, plants, and animals from images and video (Google LLC, 2019).

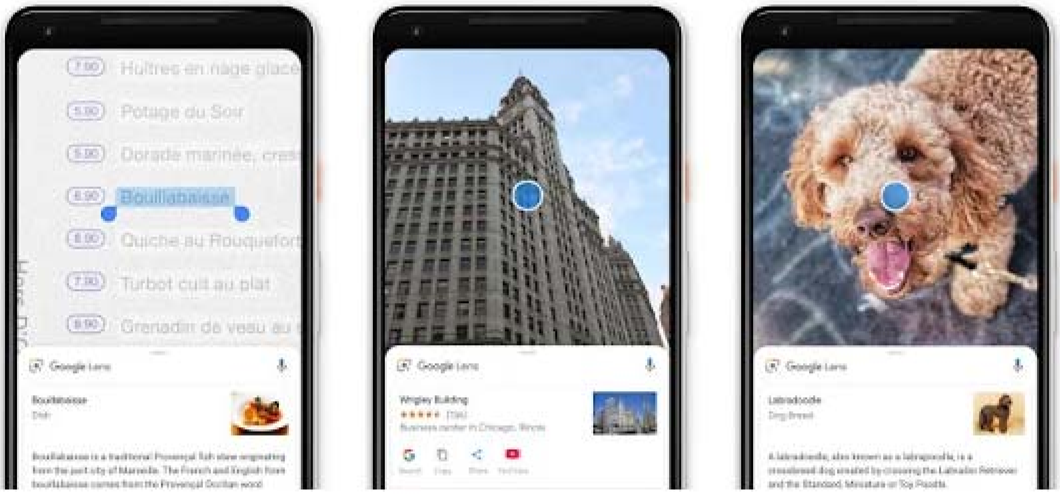


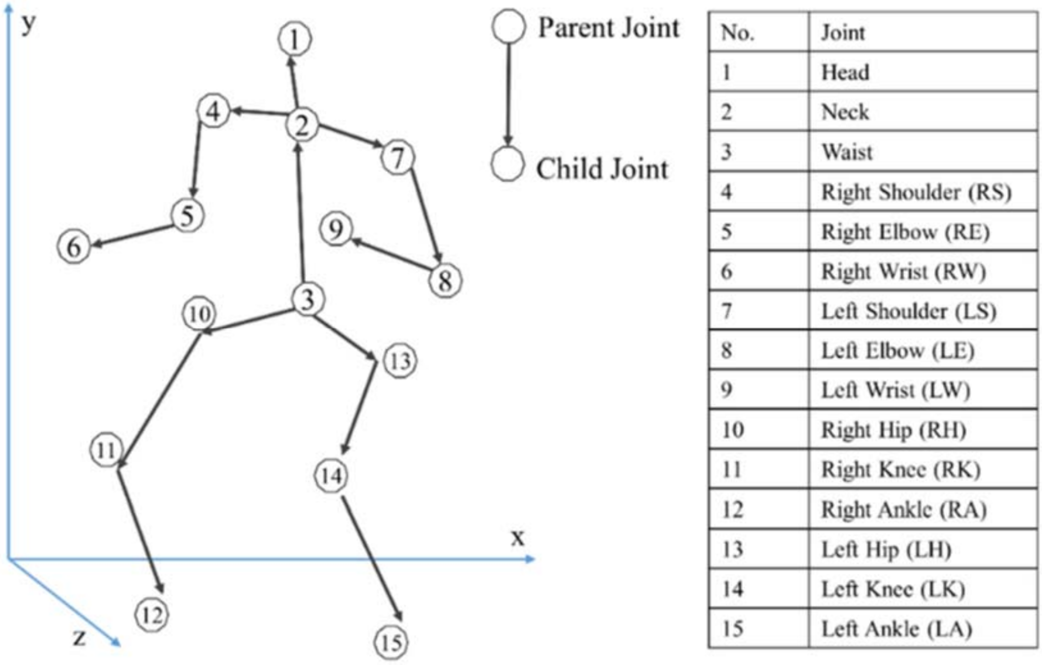
Figure 7 Google lens functions. Source: (Google LLC, 2019).

Computer vision is able to identify material, equipment (monitor of carbon footprint due to greenhouse gas emissions, benchmarking), labor, activities, safety risks (analyzing worker’s body movement, poses, safety equipment, and relative position to safety hazards) (Yang, Park, Vela, & Goldparvar-Fard, 2015).

It can also measure important process variables like working sequence and cycle time (Luo, et al., 2018).

> Alternative applications of computer vision include: monitoring progress, locating workers, occupational health assessments, quality management, and monitoring the use of personal safety equipment. (Weili, Lieyun, Botao, Peter, & Hanbin, 2018)

(Yu, et al., 2019) applied computer vision in combination with biomechanics to monitor workers' health and fatigue, by locating and tracking the individual's joints (figure 8), using body weight and center of mass to calculate torque at joints, and applying a fatigue model using the joint torque.



No.	Joint
1	Head
2	Neck
3	Waist
4	Right Shoulder (RS)
5	Right Elbow (RE)
6	Right Wrist (RW)
7	Left Shoulder (LS)
8	Left Elbow (LE)
9	Left Wrist (LW)
10	Right Hip (RH)
11	Right Knee (RK)
12	Right Ankle (RA)
13	Left Hip (LH)
14	Left Knee (LK)
15	Left Ankle (LA)

Figure 8 The simplified biomechanical human skeleton model. Source: (Yu, et al., 2019).

Computer vision can be especially useful to monitor environments with elements that cannot be tracked via the installation of sensors, such as automobiles on a highway (Zhu, et al., 2016).

Currently, a limited array of entities has been studied, including workers, excavators, dump trucks, loaders and tower cranes; as well as a limited set of activities, such as earthworks, concrete pouring, drywall installation; it is important to note that these activities have been studied in isolation from the whole construction process (Yang, Park, Vela, & Goldparvar-Fard, 2015) (Yang, Shi, & Wu, 2016).

(Zhu, et al., 2016) propose a system capable of tracking and predicting the location of workers and equipment on a construction site. They use video from multiple cameras as input, which is then analyzed by a computer vision algorithm, and then use the Kalman filter to estimate the future positions of workers and equipment; their goal is to provide a proactive early warning system to prevent collisions (Zhu, et al., 2016).

(Zhang, et al., 2008) developed an automated progress monitoring system using computer vision to semi-automate the creation and tracking of a work breakdown structure (WBS), which provides its users with an initial WBS based on design information and user inputs, and can be modified manually to better fit the project; then computer vision detects completed packages, the user can make corrections as necessary (Zhang, et al., 2008).

Motion capture technologies capture workers' images using cameras and compares these images with an image database. This requires no wearable devices; however, its results are delayed due to processing times of irrelevant information (Yu, Guo, Ding, Li, & Skitmore, 2017).

The limitations of computer vision include occlusion, poor lightning, analysis of interaction between workers and equipment, results in reduced stable tracking times, and computationally expensive algorithms (Yang, Park, Vela, & Goldparvar-Fard, 2015) (Weili, Lieyun, Botao, Peter, & Hanbin, 2018).

Cameras are affected by environment factors such as temperature, humidity, and dirt; protective measures are often needed, such as the container proposed by (Leung, Mak, & Lee, 2008). Moreover, human intervention is required to install, program, and calibrate cameras, also to change their batteries (Hany, Lamine, & Gamal, 2018).

Worker detection effectiveness depends on the size of the worker relative to the captured frames' dimensions (Weili, Lieyun, Botao, Peter, & Hanbin, 2018). Human activities present significant visual differences from individual to individual when compared to machines, therefore, automated recognition of human activities from images and videos is a challenging task, with increased datasets requirements (Yang, Shi, & Wu, 2016).

Worker's activities often involve both coarse-grained (e.g. walking) and fine-grained (e.g. wire tying) movements, however, each of them usually require different granularity of feature description to be analyzed through computer vision, tool detection could improve the precision of worker activity analysis (Yang, Shi, & Wu, 2016).

Another challenge of computer vision is assessing three dimensions of the monitored space and elements involved based on bi-dimensional input (images and video), pixel distance can be useful for safety monitoring, however, metric dimensions have more relevancy (Kim, Liu, Lee, & Kamat, 2019). Possible solutions have been explored, such as (Yu, et al., 2019) proposal to assume the ratio of the bones' length of the same individual to be constant, or (Kim, Liu, Lee, & Kamat, 2019) leverage of reference on-site elements of know dimensions to rectify images (see figure 9).

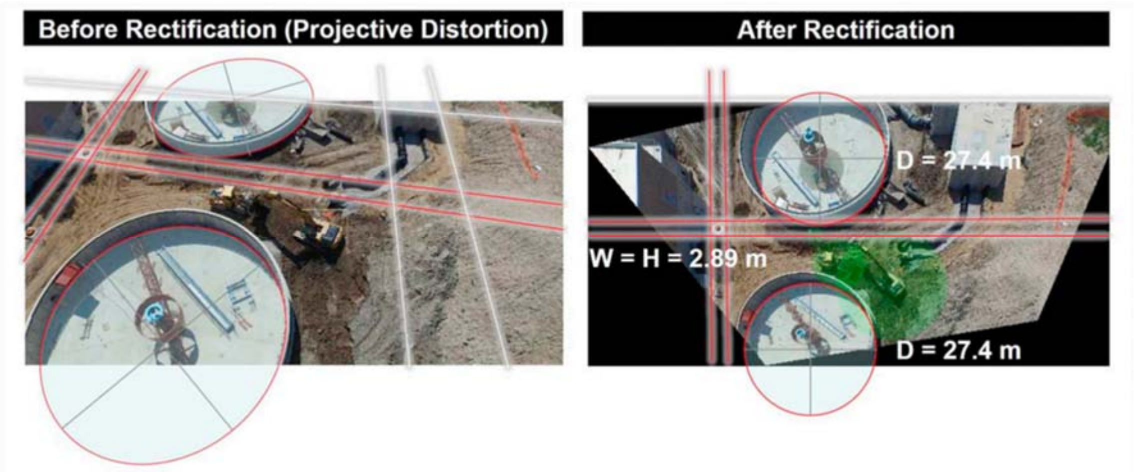


Figure 9 Projective distortion: before and after rectification (Kim, Liu, Lee, & Kamat, 2019)

(Kim, Liu, Lee, & Kamat, 2019) achieved a localization error of 0.3m while attempting to detect and measure distances between workers and equipment from video captured using an unmanned aerial vehicle (UAV). It is important to note that their processing time was of about 0.278 seconds per frame (0.028 for localization and 0.25 for rectification) which they deem unacceptable, since on-site equipment can move more than 3 meters in that time span (Kim, Liu, Lee, & Kamat, 2019).

Drones can be used for documentation, photogrammetry, range cameras, and computer vision, however, their use is often restricted depending on the country; the usual regulations are:

- Maximum weight of 5 Kg
- Fly up to 100 m high
- Line of sight to the UAV
- Avoid streets
- Avoid crowds

Source: (Borrmann, König, Koch, & Beetz, 2018)

(Yang, Park, Vela, & Goldparvar-Fard, 2015) suggest using computer vision in parallel with non-visual sensor-based tracking such as GPS, RFID, and UWB. Sampling system to analyze pictures or short clips from videos (Yang, Park, Vela, & Goldparvar-Fard, 2015).

Occlusion issues are mitigated the higher the camera is placed (Kim, Kim, & Kim, 2017). (Kim, Liu, Lee, & Kamat, 2019) integrate the use of an Unmanned Aerial Vehicle (UAV) to identify elements in the construction site, and measure distance between them.

It is more difficult to extract features from videos than from images, since time and space variables need to be analyzed (Luo, et al., 2018). It is especially problematic to track multiple similar elements with interacting trajectories (Yang, Arif, Vela, Teizer, & Shi, 2010).

One of the current challenges of computer vision is the ability to 'match' the same element on multiple photos or videos taken by multiple cameras simultaneously, this is particularly difficult on construction sites due to their typical large scale, clutter, and dynamism (Zhang, Zhu, Hammad, & Aly, 2018). There are many different 'matching' methods, and they can be separated into two categories, the ones that rely on visual features, and the ones that rely on the spatial relationships between elements (Zhang, Zhu, Hammad, & Aly, 2018). Even though matching is a challenging task, it is worth noting that usual limitations of computer vision such as lighting and weather have a significantly reduced influence on results, however, matching accuracy is affected by the size of the elements (Zhang, Zhu, Hammad, & Aly, 2018). According to the experiments performed by (Zhang, Zhu, Hammad, & Aly, 2018), for construction equipment there were no matching errors, meanwhile for people and cones 1 out of 12 matches was flawed (Zhang, Zhu, Hammad, & Aly, 2018).

Computer vision shows future promise for application on the construction industry (Luo, et al., 2018). Its application is currently limited to recognition of elements and activities which are more visually evident, however, its development will increase the range of elements and activities it can assess, and in the meantime, computer vision already provides the opportunity to support project management (Zhang, et al., 2008).

5.5.4 Three-dimensional laser scanning

Also referred to as laser detection and ranging (LADAR) or just laser scanning (LS), it retrieves location data from the environment in the form of a 3D point cloud, with each point having X, Y, and Z coordinate values (Kopsida, Brilakis, & Vela, 2015). The quality of a point cloud is high if it has high point density and accuracy (Rebolj, Pučko, Čuš Babič, Bizjak, & Mongus, 2017). Smaller elements require a higher accuracy and point density to be recognized (Pučko, Šuman, & Rebolj, 2018).

There are many methods available to identify elements in point clouds, most of them are based on 3D features (e.g. Point feature histograms, point pairs, and spin images) (Pučko, Šuman, & Rebolj, 2018).

Scans can be simulated using software such as HeliOS, which allows the users to simulate the scan process and results of a modeled building without the need to access an actual construction site (Pučko, Šuman, & Rebolj, 2018).

Laser scanners often offer high accuracy; however, they are also usually expensive, bulky, require significant maintenance, and skilled users (Kopsida, Brilakis, & Vela, 2015). Laser scanners are usually not appropriate for indoor use, unless the indoor space is relatively large (e.g. Church or concert hall), they are usually employed outdoors (see figure 10) (Borrmann, König, Koch, & Beetz, 2018).

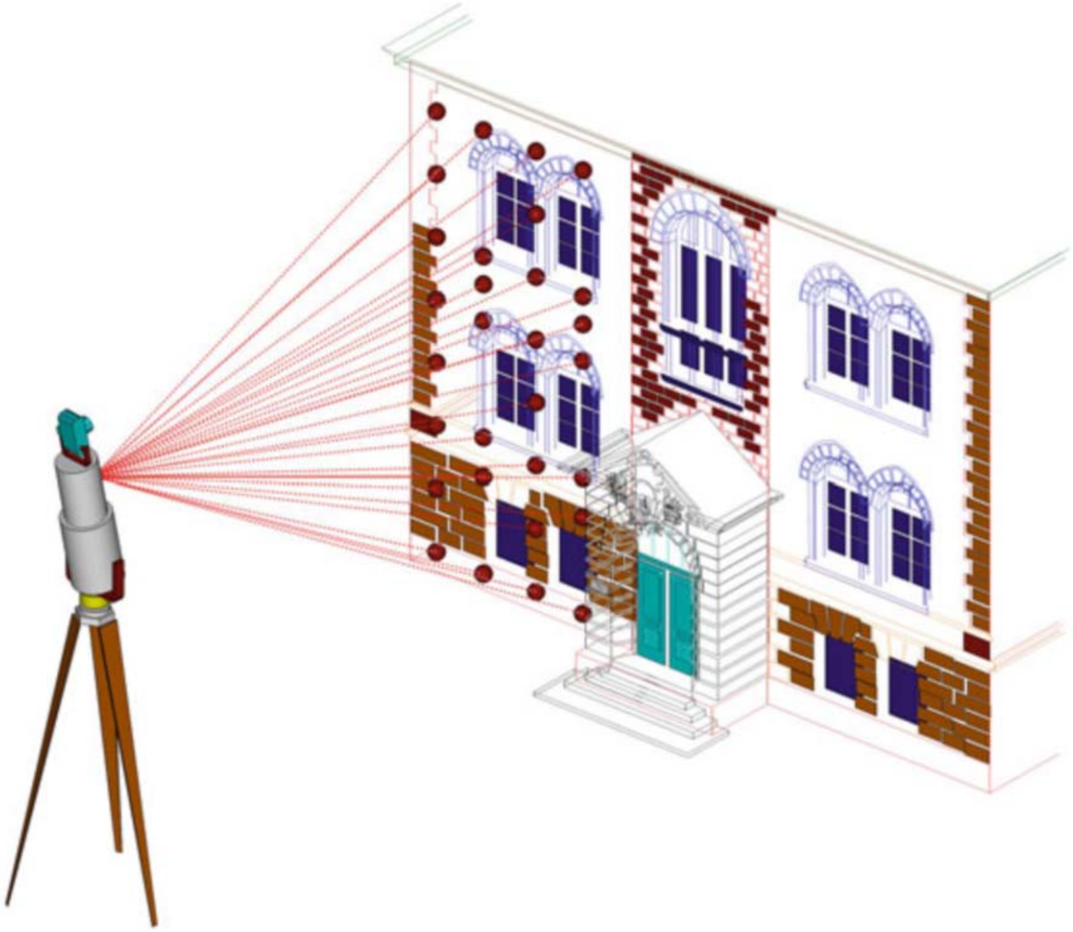


Figure 10 Outdoor laser scanning . Source: (Borrmann, König, Koch, & Beetz, 2018)

The limitations of laser scanning include long times required to perform scans (Hany, Lamine, & Gamal, 2018), important costs, clear line of sight, and complications when used inside the building (Pučko, Šuman, & Rebolj, 2018).

Laser scanning is often not feasible due to its high costs and required expertise (Hany, Lamine, & Gamal, 2018). When used in a dynamic environment - such as a construction site with equipment, material, and labor constantly moving laser scanner data can be noisy (Kopsida, Brilakis, & Vela, 2015), therefore post processing is required to remove noise from the point cloud, due to moving workers or equipment during the scan (Tarek & Moncef, 2016).

Scan-vs-BIM is a progress assessment method which comparison between the 4D As-Built (AB) model and the 4D As-Designed (AD) model, cleaning duplicates and temporary elements (Pučko, Šuman, & Rebolj, 2018).

5.5.5 Global Positioning Systems

Global Positioning Systems (GPS) is an active sensor that can be used to track the location of construction equipment (and other construction resources) and is based on the ‘time-of-arrival principle’ (TOA, also called ‘time of flight’, TOF) which uses a signal with a known propagation speed, and measures its time of propagation to calculate distance (Cheng, Rashidi, Davenport, & Anderson, 2017).

GPS is the most commonly used localization system, it provides its localization and time information as long as there are no obstructions between the device and a minimum of four satellites orbiting the earth (Cheng, Rashidi, Davenport, & Anderson, 2017). The installation of GPS systems is simple (Pradhananga & Teizer, 2013). This service is free, however, the GPS devices itself can prove costly, especially considering each tracking target must have a GPS receiver attached (Cheng, Rashidi, Davenport, & Anderson, 2017).

(Pradhananga & Teizer, 2013) propose the use of low-cost GPS devices (Figure 11) to track productivity and safety of earth moving equipment on a construction site. They manually define different zones corresponding to specific activities such as loading, unloading, and travel zone, and retrieve the time each equipment spends on each zone, as well as the times each zone is visited, and the distance between multiple equipment (Pradhananga & Teizer, 2013).

Figure 11 Low-cost GPS device. Source: (Pradhananga & Teizer, 2013)

While this technology can provide location and time data, it is still challenging to identify actions, register the time periods of activities that add value, and measure production. Furthermore, since it requires each tracking target to have a device attached, it is often considered intrusive, which is especially problematic in the case of smaller and/or rented equipment (Cheng, Rashidi, Davenport, & Anderson, 2017).

GPS accuracy ranges from 0.7m on open areas to 5m on dense urban environments (Li, et al., 2015). While GPS is the most used technology for outdoor location tracking, its accuracy and vulnerability to occlusions make it unsuitable for indoor conditions (Ma, et al., 2018).

5.5.6 Radio Frequency Identification

Known by their initials, RFID transmits information wirelessly using radio waves (Awolusi, Marks, & Hallowell, 2018). It is an active sensor technology that can be used to track the location of construction equipment (and other construction resources) and is based on the ‘time-of-arrival principle’. (Cheng, Rashidi, Davenport, & Anderson, 2017).

RFID is a reliable technology for location tracking, usually accurate enough (meters), with a solid range, and able to withstand interference by other signals (noise) (Ma, et al., 2018).

A RFID system involves tags and tag readers, also called tag detectors or signal stations (Awolusi, Marks, & Hallowell, 2018). Tags are placed on each of the elements to be identified and tracked, they consist of a power source and an antenna, their cost is relatively cheap, they can operate regardless of obstacles in between the receiver and the tags, and this receiver can be up to 100m away from the tags (Cheng, Rashidi, Davenport, & Anderson, 2017). It is important to note that one RFID reader can cost about US$2.000 (Li, et al., 2015).

Passive RFID system use one out of three frequency bands, which determines their range: low-frequency has about 30cm range, high-frequency has about 1m range, and ultra-high frequency has up to 5 meter range; range can be increased to more than 100m by using active tags (Awolusi, Marks, & Hallowell, 2018). RFID requires a minimum of three signal stations to determine the location of a tag (Kim, Kim, & Kim, 2017). The entire setup is portable and does not require any especial skills from the users (Kopsida, Brilakis, & Vela, 2015).

Regarding accuracy (Valero & Adán, 2016) found errors over 30cm and 35 degrees for position and orientation.

RFID offers the possibility to write information onto tags, allowing interaction between elements (Awolusi, Marks, & Hallowell, 2018). This technology does not require contact nor line of sight, the tags can even be placed inside materials and equipment and can store data up to several hundreds of kilobytes (Valero & Adán, 2016), they are also able to resist construction site and weather conditions (Tarek & Moncef, 2016).

While this technology can provide location and time data, it is still challenging to identify actions, register the time periods of activities that add value, and measure production. Furthermore, since it requires each tracking target to have a device attached, it often considered intrusive, which is especially problematic in the case of smaller and/or rented equipment (Cheng, Rashidi, Davenport, & Anderson, 2017).

RFID has two sub categories: active RFID, and passive RFID. The former includes a power source on their tags and works on larger ranges, the later lacks power sources on their tags, and has a reduced detection range (Kim, Kim, & Kim, 2017).

(Tarek & Moncef, 2016) state that there is a third type of RFID tags: Hybrid. Hybrid tags include a power source; however, they remain inactive until turned on by an external signal.

Skanska has used this technology to track pre-cast structural elements and use this information as a basis for progress monitoring (Kopsida, Brilakis, & Vela, 2015).

5.5.7 Ultra-Wideband

Ultra-Wideband (UBW) is a variation of RFID that provides real time location data from several tags and receivers, it has been proven to be more accurate, and have a longer range. On the other hand, it requires a more expensive and elaborate set of receivers (Cheng, Rashidi, Davenport, & Anderson, 2017; Salehi & Yitmen, 2018).

UWB uses batteries on their tags, which means it is an active type of RFID, and it is able to precisely (cm error) determine the location of tags over long ranges and obstacles, in a power efficient manner (Kim, Kim, & Kim, 2017). It is also an active sensor, which refers to the need of tracked elements to carry a device (tags), and it uses the 'time-of-arrival' principle to track the location of construction equipment (and other construction resources) (Cheng, Rashidi, Davenport, & Anderson, 2017). UBW can track the location of tags up to 1000 meters away from the receivers (Tarek & Moncef, 2016).

Ultra-Wideband presents invulnerability to interference, which is owed to the use of a large bandwidth to transmit data (Awolusi, Marks, & Hallowell, 2018). This is an important factor that makes this technology suitable for indoor and outdoor works (Tarek & Moncef, 2016).

UWB is highly accurate (10 cm scale), performs in the presence of elements blocking the signals, and not vulnerable to interference, however, it usually demands a high investment (Ma, et al., 2018) (Li, et al., 2015). A UWB system able to track 50 workers could cost about US$150,000 (Li, et al., 2015).

While this technology can provide location and time data, it is still challenging to identify actions, register the time periods of activities that add value, and measure production. Furthermore, since it requires each tracking target to have a device attached, it often considered intrusive, which is especially problematic in the case of smaller and/or rented equipment (Cheng, Rashidi, Davenport, & Anderson, 2017).

5.5.8 Additional mentions

There were several technologies found during this research that fail to provide enough literature basis to be included in the analysis, however, they could have potential not yet exploited, and the lack of literature could point to a need for future research.

Chirp Spread Spectrum

Chirp Spread Spectrum (CSS) is a real time locating system (RTLS) that uses the time of arrival principle to estimate position, just like GPS, RFID, and UWB (Li, et al., 2015).

CSS is a relatively inexpensive technology, each module costs about 100US$, they are also small, about the size of a coin, work wirelessly, without affecting or being affected by other wireless technologies, while still being compatible to them, also, their batteries can last about 72 hours (Li, et al., 2015).

CSS modules are wireless and small, consequently, the system is simple to deploy. (Li, et al., 2015). Sixteen CSS modules were needed to produce enough signal to cover a the area of the 34th floor of a residential building in Hong Kong, with about 150m², and estimate location with 200 milliseconds frequency, 1 second delay, and 86.8cm error (Li, et al., 2015); two additional modules are required as rover and router, totaling eighteen modules and 1.800US$ investment; figures 12 and 13 describe this implementation (Li, et al., 2015).

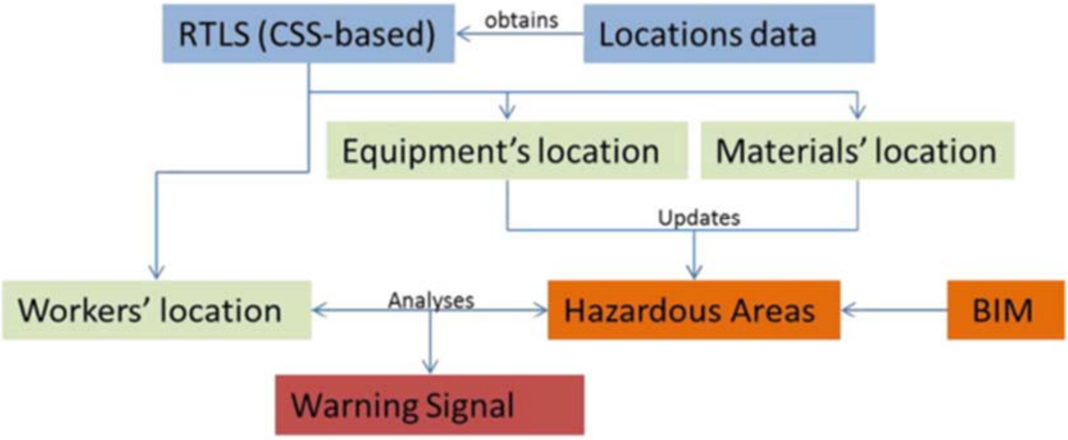


Figure 12 Flow of the CSS system developed by (Li, et al., 2015)

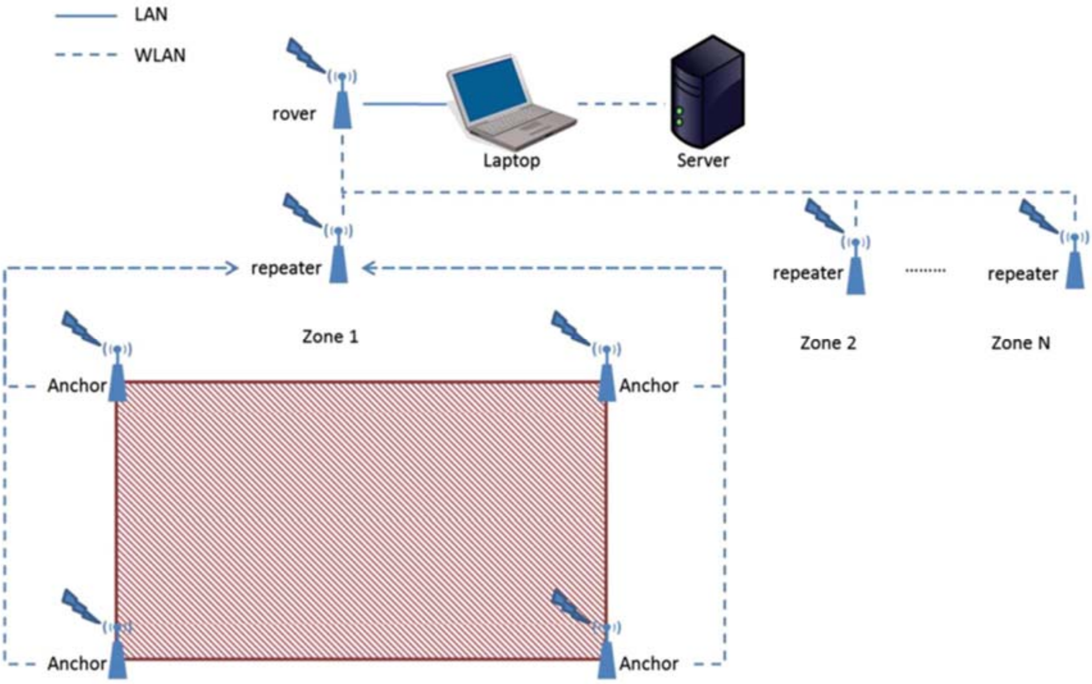


Figure 13 Setup of the CSS system developed by (Li, et al., 2015).

Microphones

(Cheng, Rashidi, Davenport, & Anderson, 2017) propose a method to identify equipment and register their activity by using microphones, registering the sound made by the engines, and the interaction between these machines and the construction site.

(Cheng, Rashidi, Davenport, & Anderson, 2017) generated a data sample of several construction equipment performing routine operations, reduced background noise, and fed the time-frequency data to a machine learning algorithm to train a classifier that can relate this data to a certain equipment activity (Cheng, Rashidi, Davenport, & Anderson, 2017).

The challenges regarding the use of this technology consist on being able to reduce unwanted background noise and recognize and differentiate the diverse sounds produced by multiple equipment. Also, to identify single activities performed by two or more construction equipment. Finally, while occlusion does not generally affect audio signals, there could be significant sound barriers or large construction sites which would require multiple microphones, and more complex algorithms (Cheng, Rashidi, Davenport, & Anderson, 2017).

Enhanced IT

These include cameras, email, microphones, mobile text messages, and have been integrated to many industries, including construction, to improve communication and data collection (Tarek & Moncef, 2016).

More recently, speech recognition has been used to minimize time and cost of inspections (Tarek & Moncef, 2016).

These technologies are relatively inexpensive and already owned by the relevant stakeholders, however, they do not provide sufficient collaboration, and require extensive user training (Tarek & Moncef, 2016).

These are adequate for small projects, which do not require automatic retrieval of large amounts of data (Tarek & Moncef, 2016).

Magnetic field

Magnetic field are created by electric current flowing on a wire coil, these magnetic fields can be placed on equipment and measured by a magnetic sensor - placed on an employee - to estimate distance to the equipment (Awolusi, Marks, & Hallowell, 2018).

This technology is used to track location, it is fairly accurate (meters), its sensors are commonly present on smartphones and its implementation doesn't require any additional hardware, however, it is vulnerable to occlusion due to elements between multiple sensors (Ma, et al., 2018). Magnetometers determine orientation, similarly to gyroscopes, however, they are commonly used together since magnetometers are less accurate for faster movements but presents zero drift over time (Awolusi, Marks, & Hallowell, 2018).

Magnetic field derived data can be hindered by metallic objects nearby magnetic fields or magnetic sensors (Awolusi, Marks, & Hallowell, 2018).

Gyroscopes and Accelerometers

These sensors provide spatial acceleration and rotation data, which can be used to determine the location and orientation of entire construction equipment or their parts over time. This information can then be used to recognize activities and measure productivity. However, since it requires each tracking target to have a device attached, it often considered intrusive, which is especially problematic in the case of smaller and/or rented equipment (Cheng, Rashidi, Davenport, & Anderson, 2017).

Wireless local area network (WLAN)

WLAN is supported by virtually all smartphones and involves the installation of network devices such a routers and repeaters. Since the use of smartphones is common for all construction stakeholders and a wireless network is also common, implementing this technology has a low cost. This technology can be used to track location, it is accurate (1-2.8 meters) but can be affected by concrete elements blocking the signals (Ma, et al., 2018).

The smartphones collect the signals from the Access Point (AP), identify it, and register their Received Signal Strength Indication (RSSI), used to estimate distance (Ma, et al., 2018). This method requires the installation of several Wi-Fi hotspots on the floor to be inspected and a calibration procedure that requires a certain amount of skill, to be performed before each inspection (Ma, et al., 2018).

Ultrasound

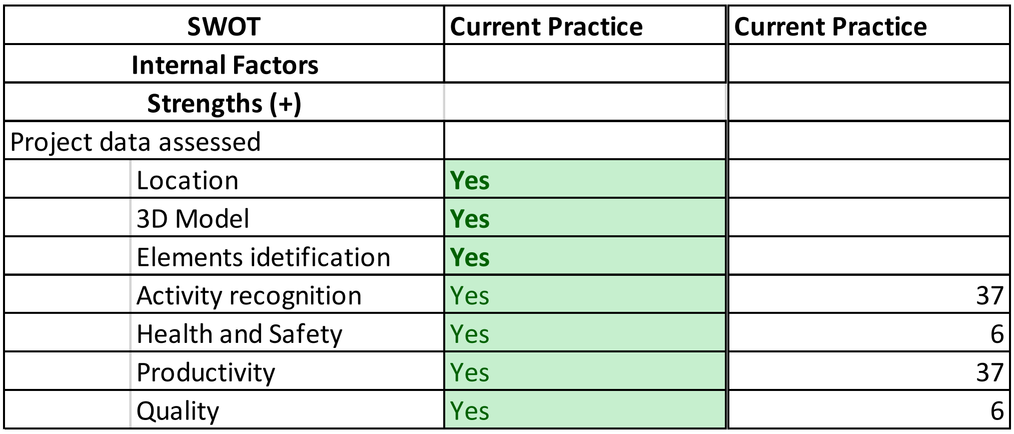
Ultrasound uses sound waves outside human hearing range to determine location, it has high accuracy (millimeters), low energy consumption, and is relatively simple and inexpensive, however, it has a short detection range, and is vulnerable to occlusions, air temperature and pressure changes, and loud noises (Ma, et al., 2018) (Awolusi, Marks, & Hallowell, 2018).

6. SWOT Analysis

The information gathered through this research was carefully evaluated and structured into a comparative SWOT analysis table. Strengths, weaknesses, opportunities, and threats related to developing technologies and traditional methods applied to construction site monitoring are listed on the left column, while the technologies themselves are presented on the first row.

The specific aspects composing strengths, weaknesses, opportunities, and threats are extracted from the literature on grounds of the attention each of them receives throughout the journals, the existence of such data as a result of the work of researchers is evidence of its relevance.

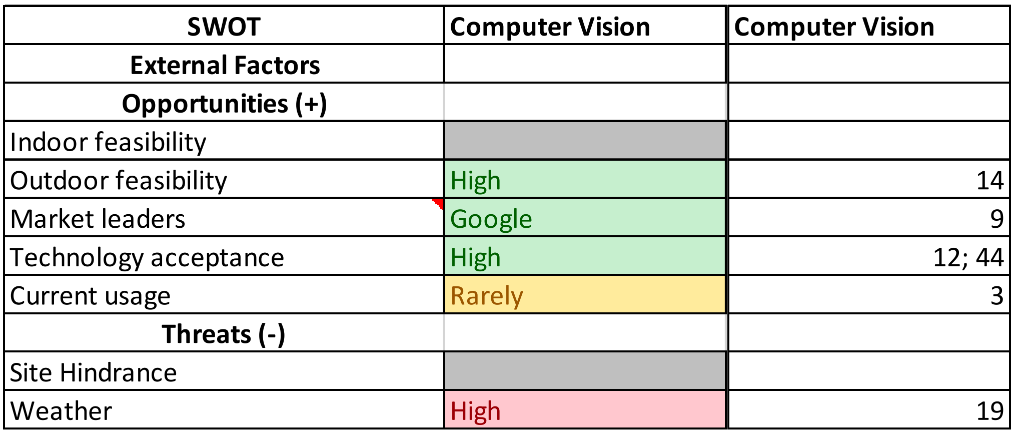
The evaluation based on the research is assigned to every cartesian coordinate cell, and a color gradient based on the metaphor of a traffic light is assigned by the author. The sources for the evaluations are presented on a second SWOT table with identical structure, there are some cases of presented data without a source, this happens when the information is common knowledge in the AEC industry, therefore, a statement made by a researcher is unexpected and not required. Information without source is presented in bold font, and a source will be missing on the source table (see example on table 1).



SWOT		**Current Practice**	**Current Practice**
Internal Factors			
Strengths (+)			
Project data assessed			
	Location	**Yes**	
	3D Model	**Yes**	
	Elements idetification	**Yes**	
	Activity recognition	Yes	37
	Health and Safety	Yes	6
	Productivity	Yes	37
	Quality	Yes	6

Table 1 Example of data without source. Elaborated by the author, sources as indicated.

This SWOT analysis presents empty cells, colored grey, corresponding to non-evident information which has not been covered by the current body of knowledge; these cells are particularly important since they clearly indicate the present knowledge gaps which could be addressed by future research (see example on table 2).



SWOT	Computer Vision	Computer Vision
External Factors		
Opportunities (+)		
Indoor feasibility	▨	
Outdoor feasibility	High	14
Market leaders	Google	9
Technology acceptance	High	12; 44
Current usage	Rarely	3
Threats (-)		
Site Hindrance	▨	
Weather	High	19

Table 2 Example of knowledge gaps. Elaborated by the author, sources as indicated.

It is important to note that even though the information presented on this SWOT intends to be a useful guideline for construction stakeholders and researchers, this information must be contrasted against specific conditions and requirements of a construction site to be properly utilized.

6.1 Layout

A SWOT analysis consists of four sections which result of the combination of two dichotomies, Internal and external; favorable and unfavorable. For the purpose of this study, and to enable the simultaneous analysis of different technologies, a generic construction site will be assumed as the environment, and the next definitions will be held:

- Internal: factors inherent to each technology and/or devices.
- External: factors defined in terms of the physical, economical, or social environment.
- Favorable: factors which positive magnitude have a positive effect on the outcome or objectives.
- Unfavorable: factors which positive magnitude have a negative effect on the outcome of objects.

6.1.1 Strengths

Project data that can be assessed by the technology/current practices

Types of data which the studied technologies are able to provide as outputs, these variables are treated as Booleans (true or false), some cases present no confirmation or denial of a certain technology being able give certain data as output (e.g. no research confirmed or denied the capability of GPS to provide health and safety data) on this cases the cell was left blanc and the author recommends assuming an implicit negative.

- Location: coordinates of the monitored elements or individuals.
- 3D Model: virtual simulation of the site surfaces and volumes.
- Elements identification: assign the corresponding denomination of units on the site.
- Activity recognition: identify operations performed by equipment or individuals.
- Health and safety: recognition, measurement, or evaluation of on-site hazards or workers' physical and mental condition.
- Productivity: assessment of progress completion.
- Quality: evaluation of progress relative to regulation or contractual standards.

Value of data

Includes variables which affect the potential benefits of leveraging specific data outputs. Results are presented in a wider range than the previous section, however, still relevant and comparable.

- Accuracy: describes the similarity between the output data and reality, for technologies which mainly measure distances or determine location it displays the offset range or maximum error, for technologies with more diverse types of outputs an experts' assessment is displayed.

- Update frequency: inversely proportional to the period between data updates, shorter times indicate high frequency, thus more timely and relevant data.
- Detection range: describes the area that each technology can monitor, ideally the entire site must be covered.
- Interoperability: Indicates the capacity of each technology to interact seamlessly with other technologies, ideally, technologies should be able to interact with the BIM environment.
- Automation level: evaluates the need for human intervention to assist the generation of output data, ideally non-existent.

Versatility

Assesses the flexibility of use of the required devices in regards of their physical characteristics, specifically size and weight.

- Hardware size: considers whether the shape of the device presents limitations of its use.
- Hardware weight: indicates whether the device can be lifted and carried by the users without the need of special measures.

6.1.2 Weaknesses

Technology requirements

These are limitations inherent to each specific technology and their usage, they are treated as Booleans (true or false), generally, the ‘true’ or ‘yes’ value on a requirement represents a disadvantage.

- Training data: machine learning requires sample data to learn, which, depending on the task, can be a significant amount, this represents a limitation both because the data is often unavailable, and because of the present need to train the technology.
- Active sensor: Indicates the need for individuals and other monitoring targets to carry or wear a device in order to be monitored.

- Line of sight: Indicates the vulnerability to occlusions, and the need of a clear line of sight between the devices and the monitored people and elements.

Implementation cost

Describes the costs related to purchasing, installing, maintaining, and replacing the monitoring systems. The results are mostly qualitative, retrieved from research journals.

Hardware requirements

Describes the set of devices generally required to utilize a specific technology.

- Quantity: Number of devices required.
- Requires batteries: States whether the devices require batteries, do not require batteries, or batteries are optional to allow for wireless use.

Installation difficulty

Describes the complexity and time required for preliminary tasks required to operate the technology.

User training requirement

Evaluates the need for preliminary training of users to be able to use the technology safely and effectively.

6.1.3 Opportunities

Indoor feasibility

Evaluates the difficulties and effectiveness related to the use of a device on an indoor space of a construction site.

Outdoor feasibility

Evaluates the difficulties and effectiveness related to the use of a device on an outdoor space of a construction site.

Market leaders

Mentions companies offering devices, spare parts, user and maintenance services related to the technologies.

Technology acceptance

Provides an assessment of the likeness of the specific technology being embraced by the industry and its stakeholders. This is based on (Jacobs, et al., 2019) and considers whether the technology can enhance health and safety on the construction site, and whether it requires employees to carry or wear devices.

Current usage

Indicates how common or how rare is for construction projects to use the studied technologies at the present time.

6.1.4 Threats

Site hindrance

Assesses whether the use of a specific technologies obstructs the primary work of labor and equipment on the construction site.

Weather

Presents an evaluation of the vulnerability of the technologies to different weather conditions and changes.

6.2 Tables and discussion

SWOT	Current Practice	Range camera	Photogrammetry	Computer Vision	Laser Scanning	GPS	RFID	UWB
Internal Factors								
Strengths (+)								
Project data assessed								
Location	**Yes**	Yes	Yes	Yes	Yes	Yes	Yes	Yes
3D Model	**Yes**	Yes	Yes	Yes	Yes			
Elements idetification	**Yes**	Yes		Yes	Yes			
Activity recognition	Yes	Yes		Yes	No	Earth works	Yes	
Health and Safety	Yes	Yes		Yes		Earth works		
Productivity	Yes	Yes		Yes	Yes	Earth works	Yes	Yes
Quality	Yes	Yes		Yes				
Value of data								
Accuracy	Low	4cm	Medium	Varies	2-5mm	0,7 to 5m	30cm	10cm
Update frequency	Monthly	limited by post-procesing	limited by post-procesing	Near-real time	limited by post-procesing	Real Time	Real Time	Real Time
Detection range	Limited by personel	7cm to 5m	Cameras' FOV	Cameras' FOV	>1 Km	Global	30cm to 5m	up to 1000m
Interoperability	N/A	BIM	BIM	BIM	BIM	BIM	BIM	BIM
Automation level	Manual	May require post procesing	Post processing required	Automated	Post processing required	Semi-automated	Automated	Automated
Versatility	**High**	Medium	High	High	Low	High	High	High
Hardware size	**Handheld**	**Handheld**	Versatile	Handheld	Large	64x40x17mm	Handheld	Wearable
Hardware weight	**Handheld**	**Handheld**	Versatile	Handheld	Heavy	55gr	Handheld	Wearable
Weakneses (-)								
Technology requirements								
Training data	**N/A**	No	**No**	Yes	**No**	**No**	**No**	**No**
Active sensor	**N/A**	No	No	No	No	Yes	Yes	Yes
Line of sight	**Yes**	Yes	Yes	Yes	Yes	Yes	No	No
Implementation Cost	High	Moderate-low	Low	Low	High	Moderate-High	Moderate	High
Hardware	Office computers, phones, tablets	Range camera	RGB Camera	Camera	Laser scanner	GPS device	Receivers and tags	Receivers and tags
Quantity	**Low**	One or more	One is enough	One or more	One is enough	High	High	High
Requires batteries	**Yes**	Wired or Wireless	Wired or Wireless	Wired or Wireless	**Yes**	Yes	Increased range	Yes
Installation difficulty	**N/A**	Low	Low	Medium	Medium	Low	>1hour	
User training requirement	**High**	Low	High	Low	High	Low	Low	
External Factors								
Opportunities (+)								
Indoor feasibility	**High**	High	Limited		Low	Not feasible	High	High
Outdoor feasibility	**High**	Low	Limited	High	High	Limited	High	High
Market leaders	**N/A**	Microsoft	PHOCAD	Google	Leica	Wintec		
Technology acceptance	**N/A**	Medium	Medium	High	Medium	Medium	Medium	Medium
Current usage	Common	Rarely	Rarely	Rarely	Rarely	Common	Rarely	Rarely
Threats (-)								
Site Hindrance	**Low**					Intrusive	Intrusive	Intrusive
Weather	**Low**	High	High	High		Low	Low	Low

Table 3 SWOT analysis of current monitoring technologies. Elaborated by the author, sources: Table 2.

SWOT	Current Practice	Range camera	Photogrammetry	Computer Vision	Laser Scanning	GPS	RFID	UWB
Internal Factors								
Strengths (+)								
Project data assessed								
Location		33	28	46	18	8	23	16
3D Model		17	33	53	18			
Elements idetification		54		48	28			
Activity recognition	48	50		49	18	26	8	
Health and Safety	7	50		46		26		
Productivity	48	28		46	28	26	18	18
Quality	7	28		46				
Value of data								
Accuracy	48	25	33	15	6	21	36	23
Update frequency	53	33	33	15	33	8	18	30
Detection range	50	25; 33	33	48	6	8	5	33
Interoperability		30	6; 30	30	6; 28	30	30	30
Automation level	48	28	33	46	33	33	18	18
Versatility		33	33	10	18	26	18	33
Hardware size			33	10	18	26	18	5
Hardware weight			33	10	18	26	18	5
Weaknesess (-)								
Technology requirements								
Training data		17		12 ;15				
Targets carry a device		25	6	55	6	8; 26	8	8
Line of sight		25; 51	33	46	28	8	8; 36	16
Implementation Cost	48	17; 28; 33	33	18	12; 28; 18	8; 33; 35	18	23
Hardware	48	17	33	50	18	8	5	8; 33
Quantity		28	6	55	18	8	8	8
Requires batteries		30	30	30		26	5	16
Installation difficulty		28	18	12	18	26	18	
User training requirement		17	18	10	12; 18	33	18	
External Factors								
Opportunities (+)								
Indoor feasibility		17; 28; 25	6; 33		28 ;6	23	8	33
Outdoor feasibility		25; 51	6; 33	15	6	8; 26	33	33
Market leaders		25	6	10	19	26		
Technology acceptance		13	13	13; 55	13	8; 13	8; 13	8; 13
Current usage	48	3	3	3	3	23	18	3
Threats (-)								
Site Hindrance						8	8	8
Weather		51	33	20		8	33	33

Table 4 SWOT analysis sources as numbered on the list of literature. Elaborated by the author.

The comparative SWOT analysis is presented in table 3, followed by the sources on table 4. The information, presented explicitly in a condensed manner and by using the traffic light metaphor, facilitates the identification of patterns and relations.

The current practices have the inherent advantage of being common and well known around the world, these can capture all types of relevant data from the construction site, however, their accuracy and low update frequency indicate outdated and unreliable data. This contributes to uncertainty and risks which need to be managed and can cause delays, quality defects, and cost overruns.

The technological requirements of the current practices refer to computers, smartphones, and tables which are generally not actively used to retrieve monitoring information but to register and communicate the monitoring assessment of the inspectors.

The implementation costs are relatively high and related to the need to hire professionally educated staff for inspections, to the site area and layout, the number of laborers, and to the desired range of the inspection. This is because a larger area of the site and a higher number of laborers on site will require more inspection personnel to be successfully monitored.

Range cameras, photogrammetry, and computer vision use cameras as hardware, which explains the relatively high similarity between the three technologies. All of them are passive sensors which require line of sight and one camera is enough to provide acceptable monitoring results, this camera can be mounted on temporary site structures, workers, robots, or drones to travel around the site.

However, there are also contrasting factors inherent to the three camera based technologies: The detection range of range cameras is limited by the capacity of their range sensor to 5 meters, photogrammetry analyses photos therefore data which require the analysis of the time variable are not covered by the existing literature, and computer vision is restricted by the amount of data it needs for training.

These limitations can also become invitations for further research, in pursuit of alternatives and possible improvements to the range sensor of RGB-D, the transition from photogrammetry to videogrammetry, and collaborative data bases among AEC industry stakeholders could bring significant breakthroughs and changes to the profiles of these technologies.

The following technologies can be grouped as sensors which use the time of arrival of a specific signal to calculate distances and presented in order according to their accuracy. Among them, laser scanning stands out for its more complete set of data which it can retrieve, and its high accuracy (2-5mm), it is also the only technology using a passive sensor, allowing it to reduce the number of sensors required, however, these sensors are bulky and difficult to use indoor during construction, also laser scanning demands post processing, professionally trained users, and high implementation costs.

GPS can reach accuracies of 70cm, however, this is achieved only on rural areas without buildings and other signals affecting the results; generally, GPS can prove useful when analyzing earthworks by installing a device on the excavators and dump trucks, the load-dump cycles can be detected and counted, then cut and fill volumes can be estimated with the estimated load size on the dump trucks and the properties of the soil. GPS can also be used to track the progress of large linear projects.

Radio frequency identification and its sub-type, ultra-wideband are then presented as two separate technologies, differentiated by the increased range, accuracy, and costs of ultra-wideband. These location technologies do not require line of sight between tags and receivers, this is the main difference and advantage over the rest of technologies and even current practices presented on this SWOT analysis; they are also weather resistant, the combination of this features make them ideal for indoor and outdoor use.

Focusing on a feature perspective and scanning the table horizontally according to certain characteristics allows practical comparisons and decision making. Looking at types of project data which can be assessed it becomes evident that current practice, range cameras, and computer vision are wholistic alternatives, each one of them able to evaluate the monitoring data independently while other technologies mainly retrieve location data. Nevertheless, these wholistic alternatives have limitations, current practices providing inaccurate and outdated data, range cameras' short range, computer vision's need for training data, and the consistent requirement for line-of-sight inherent to all three of them.

From the perspective of value of data ultra-wideband stands out as the only technology with a green set of values, however, this technology is limited to location data capture. Current practices stand out as well due to an almost completely red set of values, yet it can retrieve all types of data, and despite its flaws it is the functional alternative the AEC has adopted, or rather adapted to it (see table 5).

SWOT		**Current Practice**	**UWB**
Internal Factors			
Strengths (+)			
Value of data			
	Accuracy	Low	30cm
	Update frequency	Monthly	Real Time
	Detection range	Limited by personel	up to 1000m
	Interoperability	N/A	BIM
	Automation level	Manual	Automated

Table 5 Value of data of current practices and Ultra-wideband. Elaborated by the author, source: Table 2.

Versatility is an essential aspect for any device to be used on a construction site, and most of the studied technologies meet this criterion according to the existing literature, the exception being laser scanners, which are too bulky and heavy to be used comfortably on construction sites, especially indoors. However, in accordance with Moore's law, laser scanners are expected to experience a reduction in size and weight, today the market already offers seemingly handheld laser scanners (Leica, 2019), however, there is still no research exploring their performance.

Regarding technology requirements, the studied approaches can be divided into two groups according to their line-of-sight requirement, as mentioned in the previous chapter, previous studies have focused on integrating these technologies to overcome this limitation. Wearable technologies can also be identified as those relying on active sensors; significant challenges derive from this aspect due to the need to have workers carry the devices or to install these devices on materials or owned and/or rented equipment. Finally, training data is exposed as computer vision's exclusive constraint.

Cost related to the implementation of each system, assessed by researchers, is included in the table as it is a main factor to consider when deciding which technology to use, for example, photogrammetry is often used as a lower cost alternative to laser scanning; this is also the case between radio-frequency identification and Ultra-wideband; in both situations some data quality is compromised (e.g. accuracy, range) when the lower cost alternative is chosen.

Installation difficulties and user training requirements are preliminary measures which demand time and cost, and mustn't be ignored, in this regard GPS and range cameras excel for their simple and intuitive operation, while laser scanning presents the most challenging setup among the studied technologies.

Radio frequency identification along with ultra-wide band can handle either indoor and outdoor construction site environments with ease due to their small size, interference resistance, and lack of line-of-sight requirement, the rest of the technologies are affected by a range of challenges, among them, GPS appears to be the most influenced by these requirements since line-of-sight must be maintained between the GPS devices and at least four satellites, and even outdoors with clear line-of-sight, readings are vulnerable to the interaction with surrounding elements.

The implementation of technologies is significantly influenced by their presence in the market, leading technologies determine the visibility of innovations, and the access to user support, maintenance, and spare parts. Microsoft and

Google stand out as industry giants behind the development of range cameras (Kinect) and computer vision (Google lens), the latter presenting a positive prognosis in regards of their technology acceptance.

The threats section consists of two aspects, site hindrance and weather, current practices excel due to existing tools and equipment which enable construction activities on a wide range of environments, the studied technologies generally lack development on these characteristics, further research and development could have a significant impact on their potential.

7. Monitoring data management systems

Information gathered through monitoring needs to be managed; different stakeholders have different information requirements and can provide specific information. Therefore, a data management system can be conveniently used to efficiently gather and share data among stakeholders.

(Ma, et al., 2018) developed a system that integrates Indoor Positioning technologies and BIM into a construction sites inspection system. This system generates interactive inspection checklists according to standards, the checklists are used on mobile devices during the inspection, afterwards the results are summarized and shared with the relevant stakeholders (Ma, et al., 2018).

(Ma, et al., 2018) gathered feedback from engineers who used their system, this feedback indicated an increase in the reliability of standards enforcement in the construction process, a significant reduction of time (50%) for inspection activities, as well as a positive response towards preserving and easily consult inspection data (Ma, et al., 2018).

Based on the ‘Power to the Edge’ management technique, (Garcia-Lopez & Fischer, 2014) developed their ‘Work Tracking System’ (WTS), which takes advantage of mobile devices and cloud data technologies to facilitate information sharing between project stakeholders, to improve coordination and decision making (Garcia-Lopez & Fischer, 2014). “Power to the Edge states that in a highly uncertain and dynamic environment, traditional methods of command and control break down” (Garcia-Lopez & Fischer, 2014).

An important focus is given to communication latency, which must be addressed to avoid rework (Garcia-Lopez & Fischer, 2014).

To assess the progress of an activity, the system needs to have access to essential data such as planned and actual starting date, planned and actual finishing date, issues encountered, and responsible Individuals/organization.

Data should be distributed in a "publish and subscribe" manner, so information can be supplied by a wide range of participants, and specific stakeholders can have access to the information that is relevant to them (Garcia-Lopez & Fischer, 2014).

(Garcia-Lopez & Fischer, 2014) Investigated which information is useful for each stakeholder and which of them can supply this data (Garcia-Lopez & Fischer, 2014). Their results are described in the figure below.

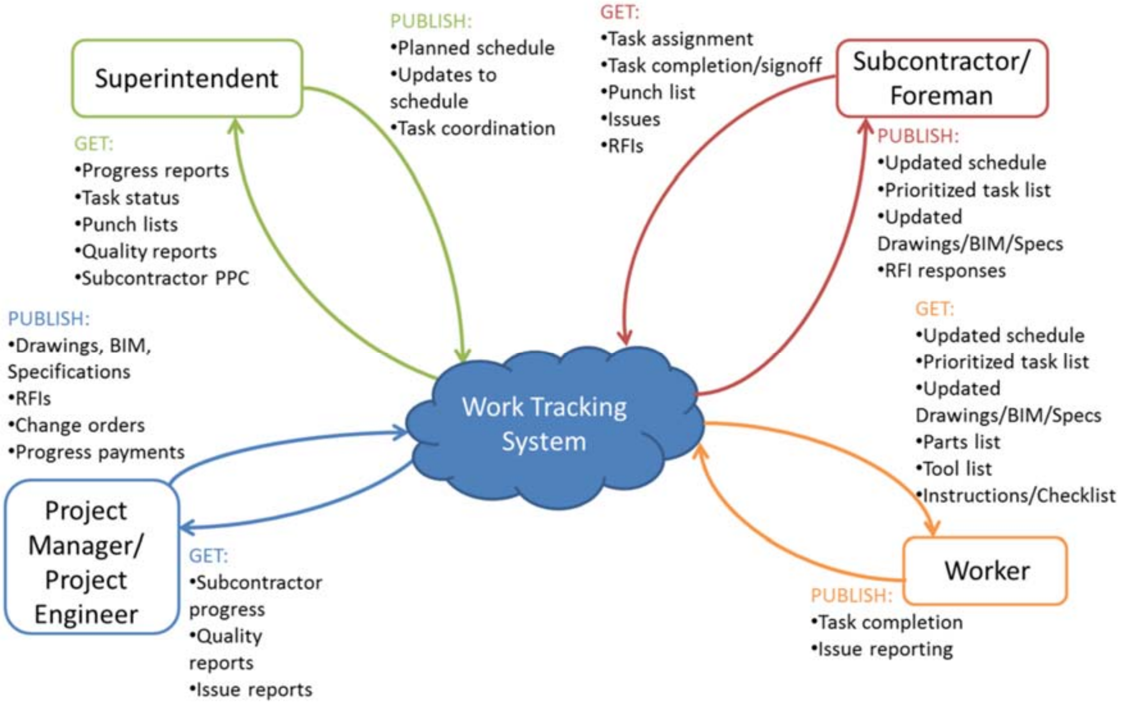


Figure 14 Project stakeholders information requirements and sources (Garcia-Lopez & Fischer, 2014)

According to these results, (Garcia-Lopez & Fischer, 2014) designed the WTS structure, including the use of BIM, cloud computing, and mobile devices depicted on the following figure.

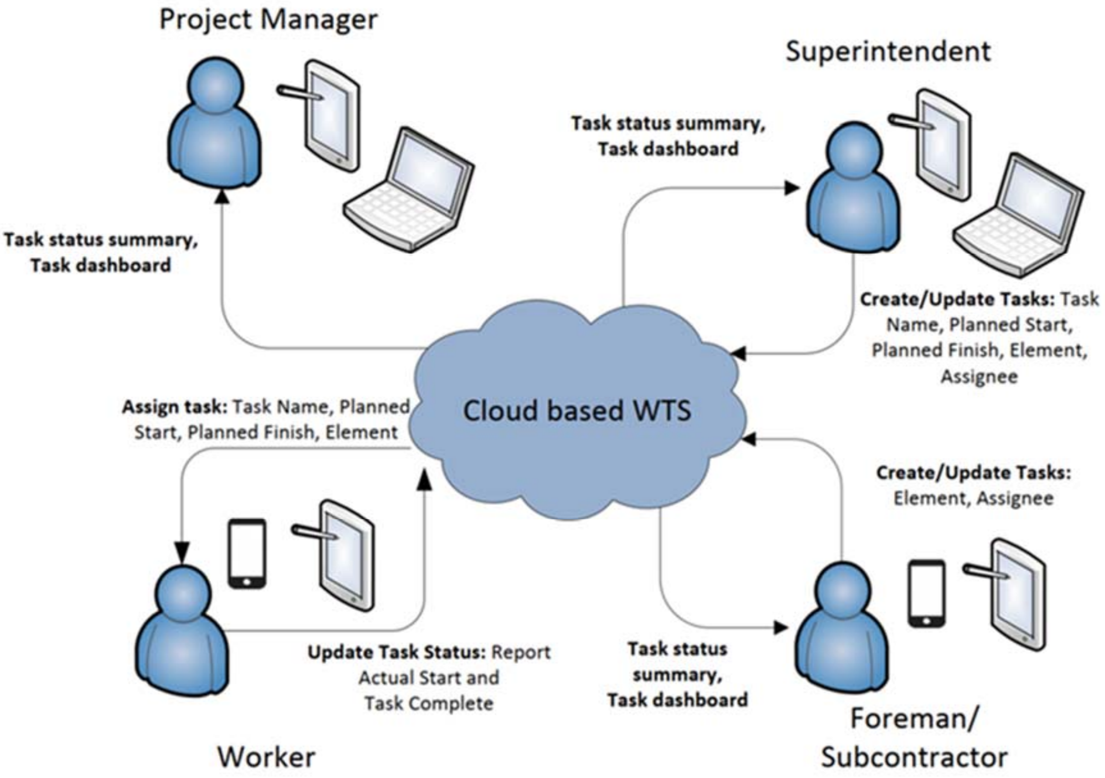
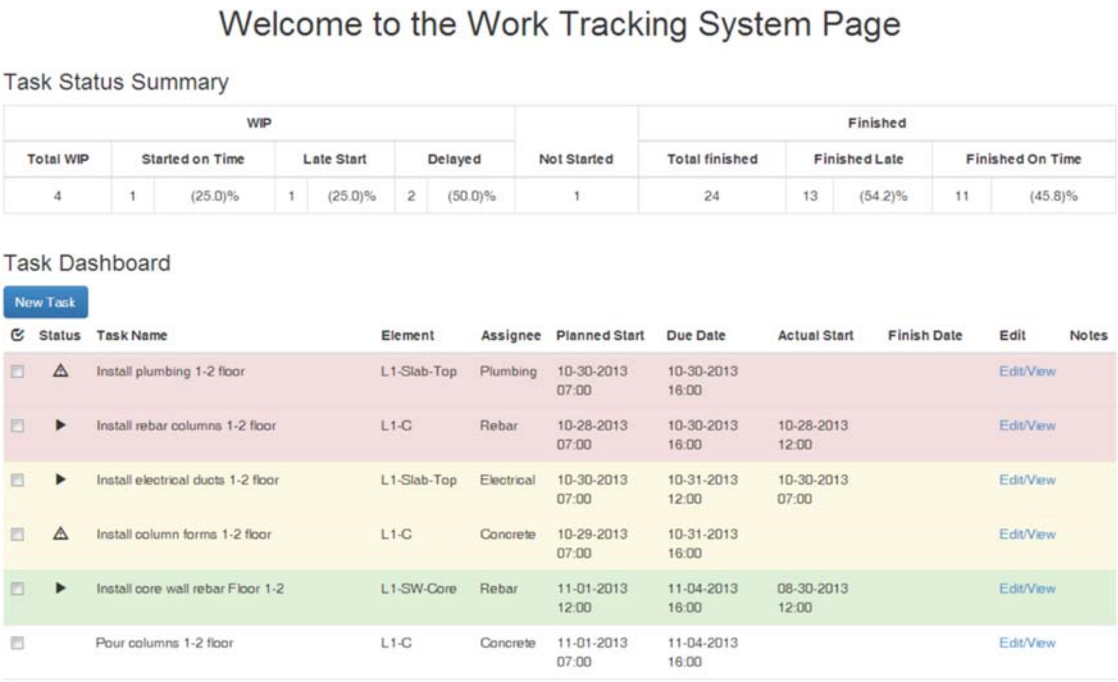


Figure 15 Type of users, Information flows and IT Platforms (Garcia-Lopez & Fischer, 2014)

Data management permissions are assigned to each type of project participant according to this scheme and integrated with Revit, Navisworks, and Asana (Garcia-Lopez & Fischer, 2014). Revit enables BIM implementation, linking BIM elements with tasks, and then exporting this information to Navisworks, which allows visualization in 4D (Garcia-Lopez & Fischer, 2014). Asana enables project stakeholders to define and assign tasks to the respective participants and allows them to share information related to tasks in the form of comments and files (Garcia-Lopez & Fischer, 2014).

A beta version of the WTS can be accessed in: http://worktrackingsystem.appspot.com

Figure 16 shows a snapshot of this system.



Welcome to the Work Tracking System Page

Task Status Summary

WIP							Not Started	Finished				
Total WIP	Started on Time		Late Start		Delayed			Total finished	Finished Late		Finished On Time	
4	1	(25.0)%	1	(25.0)%	2	(50.0)%	1	24	13	(54.2)%	11	(45.8)%

Task Dashboard

☑	Status	Task Name	Element	Assignee	Planned Start	Due Date	Actual Start	Finish Date	Edit	Notes
☐	⚠	Install plumbing 1-2 floor	L1-Slab-Top	Plumbing	10-30-2013 07:00	10-30-2013 16:00			Edit/View	
☐	▶	Install rebar columns 1-2 floor	L1-C	Rebar	10-28-2013 07:00	10-30-2013 16:00	10-28-2013 12:00		Edit/View	
☐	▶	Install electrical ducts 1-2 floor	L1-Slab-Top	Electrical	10-30-2013 07:00	10-31-2013 12:00	10-30-2013 07:00		Edit/View	
☐	⚠	Install column forms 1-2 floor	L1-C	Concrete	10-29-2013 07:00	10-31-2013 16:00			Edit/View	
☐	▶	Install core wall rebar Floor 1-2	L1-SW-Core	Rebar	11-01-2013 12:00	11-04-2013 16:00	08-30-2013 12:00		Edit/View	
☐		Pour columns 1-2 floor	L1-C	Concrete	11-01-2013 07:00	11-04-2013 16:00			Edit/View	

Figure 16 Snapshot of the Work Tracking System Dashboard (Garcia-Lopez & Fischer, 2014)

The current version of the prototype was designed and built while receiving constant feedback from the project manager, superintendent, foreman, and workers in a mid-rise residential building (Garcia-Lopez & Fischer, 2014)

Stakeholder	Advantages	Limitations
Project Manager	• The Task Status Summary to understand the overall status of the project. • Choosing the namespace for the project was an interesting exercise. It would help as a planning exercise at the beginning of the project. • Visualizing the work in the BIM was very interesting, since one could see where the time slippage had happened.	• Would like to filter by subcontractors and see their individual performance. • Integration with progress payments would be beneficial. • Summary report for task status using the WBS or PBS to calculate earned value. • The integration between the BIM, WTS, and Navisworks could be smoother. Not all of our subcontractors/workers have data plans on their phones. Would need to consider a cost-benefit analysis.
Superintendent	• Provides an intuitive interface to log in weekly commitments and track them. • Color coding is useful to see which tasks are falling behind and require attention. • The 4D visualization showing the difference between planned and actual	• Automatic synchronization with Microsoft Project would be very useful to notice changes in downstream tasks. • Aggregation of tasks by WBS hierarchy would help understand what percentage of the project is complete and whether we will hit a milestone or not.

	dates allows me to "replay" the work and explore improvements. • If the 4D visualization could be done in real time, I would save time walking around the site.	• Choosing the namespace was not intuitive. Element grouping depends on the task and is constantly evolving as the project progresses (different grouping for pouring columns than placing the rebar).
Foreman	• Linking a task to element(s) helps visualize where the work is being performed and loose less time searching for the worker to give him instructions. • Icons help prioritize my attention to the tasks that need help or clarifications, and not waste time checking up tasks that are doing well.	• Filtering by "area" would be good so I can check all the tasks in my proximity and not walk around the project. • Showing the status by subcontractor or worker would be useful to know who to motivate. • Would need to motivate workers to want to report task completion.
Worker	• Good to have clarity on what tasks are assigned to me. • The comment section is useful to inform of problems.	• Would like to be able to access the drawings from my phone.

Table 6 Summary of advantages and limitations of the WTS described by the different stakeholders (Garcia-Lopez & Fischer, 2014)

The main benefits of the implementation of WTS were the summary reports, useful for the project manager, and the individual tasks progress for the foreman and workers (Garcia-Lopez & Fischer, 2014). The main limitations were in the integration with BIM, which was inconvenient and prone to errors. Also, the participants noted the need to link the WTS to the scheduling system to improve the assessment of work progress via earned value (Garcia-Lopez & Fischer, 2014).

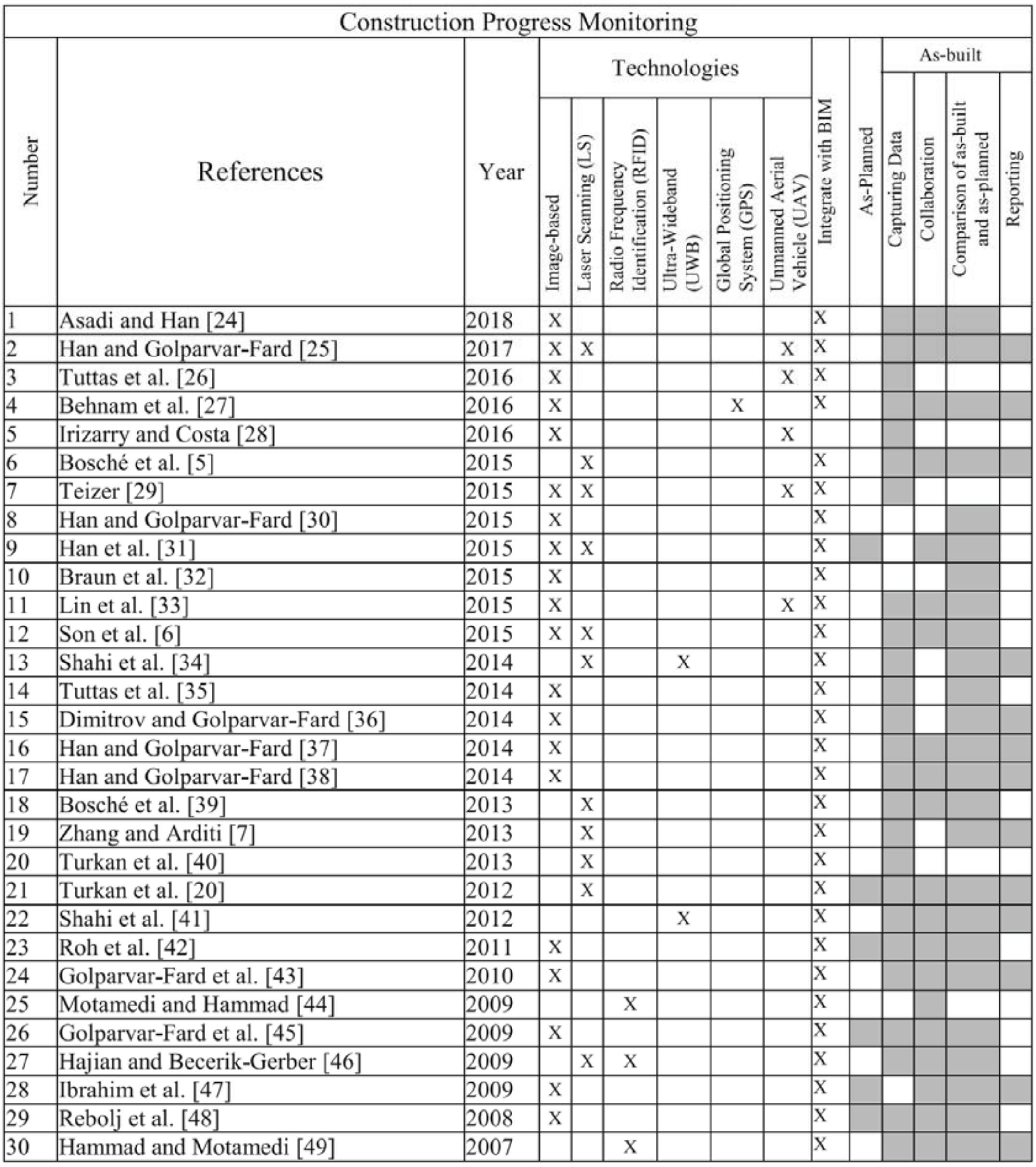
The project information needs to be filtered according to the target stakeholder to avoid information overload and to successfully deliver the needed information (Garcia-Lopez & Fischer, 2014).

7.1 BIM in monitoring technologies

Building Information Modeling (BIM) is a comprehensive model and documentation database that facilitates construction stakeholders' collaboration (Alizadehsalehi & Yitmen, 2019).

Linking the information gathered using available and developing technologies with BIM would enhance monitoring and control automation (Alizadehsalehi & Yitmen, 2019).

(Alizadehsalehi & Yitmen, 2019) developed a table describing the research on construction site data gathering technologies (see table), many of which are used as a reference for this thesis. The table evidences that all monitoring technologies studied integrate with BIM. Another fact that can be seen is the popularity of research on image-based technologies, which include range cameras, photogrammetry, and computer vision (Alizadehsalehi & Yitmen, 2019).



Construction Progress Monitoring														
Number	References	Year	Technologies						Integrate with BIM	As-Planned	As-built			
			Image-based	Laser Scanning (LS)	Radio Frequency Identification (RFID)	Ultra-Wideband (UWB)	Global Positioning System (GPS)	Unmanned Aerial Vehicle (UAV)			Capturing Data	Collaboration	Comparison of as-built and as-planned	Reporting
1	Asadi and Han [24]	2018	X						X		▨	▨	▨	
2	Han and Golparvar-Fard [25]	2017	X	X				X	X		▨	▨	▨	▨
3	Tuttas et al. [26]	2016	X					X	X		▨			
4	Behnam et al. [27]	2016	X				X		X		▨	▨	▨	▨
5	Irizarry and Costa [28]	2016	X					X			▨			
6	Bosché et al. [5]	2015		X					X		▨	▨	▨	▨
7	Teizer [29]	2015	X	X				X	X		▨			
8	Han and Golparvar-Fard [30]	2015	X						X				▨	
9	Han et al. [31]	2015	X	X					X	▨		▨	▨	
10	Braun et al. [32]	2015	X						X				▨	
11	Lin et al. [33]	2015	X					X	X		▨	▨	▨	
12	Son et al. [6]	2015	X	X					X		▨	▨	▨	
13	Shahi et al. [34]	2014		X		X			X		▨		▨	▨
14	Tuttas et al. [35]	2014	X						X		▨		▨	
15	Dimitrov and Golparvar-Fard [36]	2014	X						X		▨		▨	▨
16	Han and Golparvar-Fard [37]	2014	X						X		▨	▨	▨	▨
17	Han and Golparvar-Fard [38]	2014	X						X		▨	▨	▨	▨
18	Bosché et al. [39]	2013		X					X		▨	▨	▨	
19	Zhang and Arditi [7]	2013		X					X		▨		▨	▨
20	Turkan et al. [40]	2013		X					X		▨			
21	Turkan et al. [20]	2012		X					X	▨	▨	▨	▨	▨
22	Shahi et al. [41]	2012				X			X		▨	▨	▨	▨
23	Roh et al. [42]	2011	X						X	▨	▨	▨	▨	
24	Golparvar-Fard et al. [43]	2010	X						X		▨	▨	▨	▨
25	Motamedi and Hammad [44]	2009			X				X			▨		
26	Golparvar-Fard et al. [45]	2009	X						X	▨	▨	▨	▨	
27	Hajian and Becerik-Gerber [46]	2009		X	X				X		▨	▨	▨	
28	Ibrahim et al. [47]	2009	X						X	▨		▨	▨	▨
29	Rebolj et al. [48]	2008	X						X	▨	▨	▨	▨	
30	Hammad and Motamedi [49]	2007			X				X		▨	▨	▨	▨

Table 7 Literature on field data collection technologies 2007-2018 . Source: (Alizadehsalehi & Yitmen, 2019)

7.2 Visualization

It is essential for the monitoring data retrieved to be presented to the users in an efficient manner (Kopsida, Brilakis, & Vela, 2015).

According to (Guo, Yu, & Skitmore, 2016) previous research regarding visualization leverage for worksite safety has focused on five categories: job hazard area (JHA) identification, worker behavior monitoring, construction environment monitoring, and early warning on site.

Visualization can be used on safety training to achieve the benefits of on-site training without interfering with ongoing construction activities, providing interactive learning opportunities for workers off-site (Guo, Yu, & Skitmore, 2016). In this regard, it has been suggested to include information regarding temporary facilities, equipment, site configurations on building models to provide training tailored to each project's conditions (Guo, Yu, & Skitmore, 2016).

Based on the metaphor of traffic lights, data can be represented as a dashboard, indicating deviations from schedule and supporting decision making for control responses (Yang, Park, Vela, & Goldparvar-Fard, 2015). Figures 17 and 18 present examples of traffic lights metaphor on visualization.

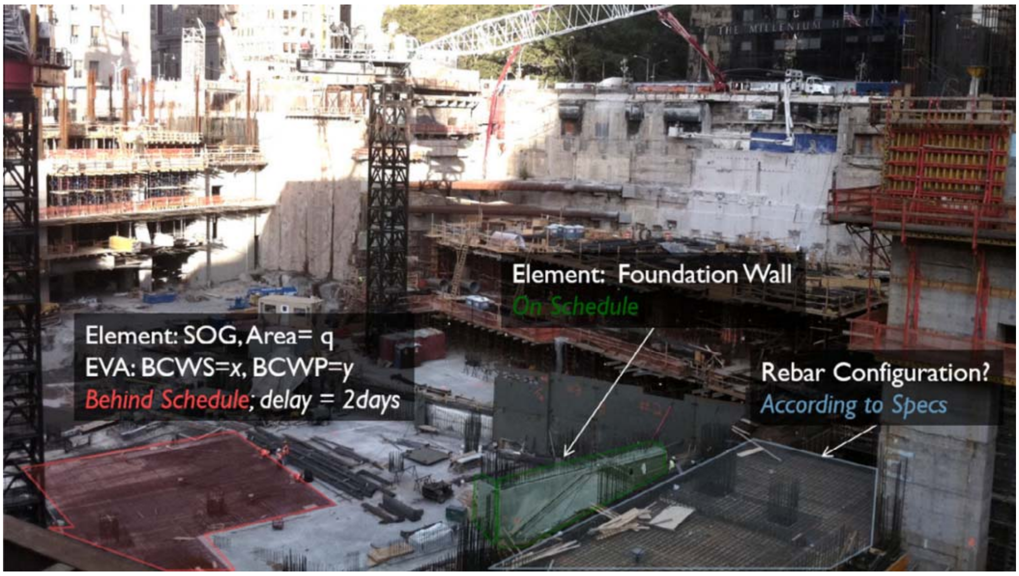
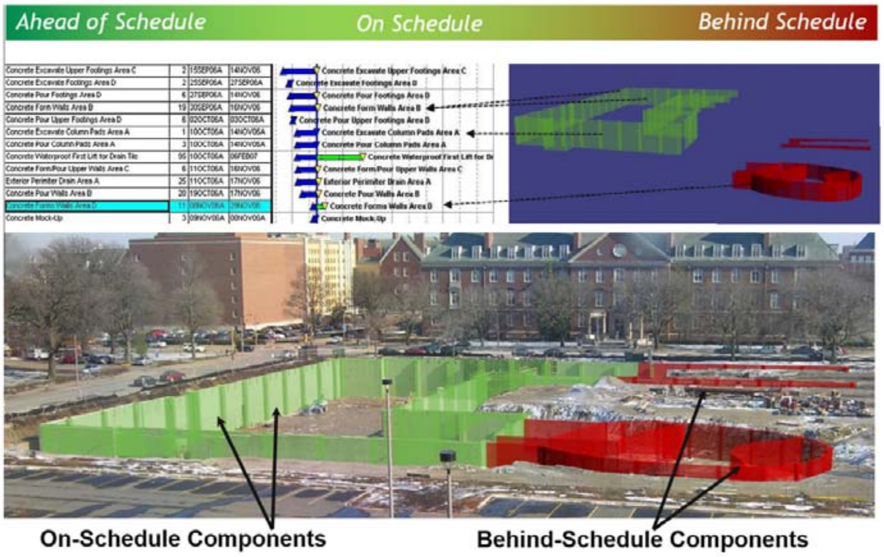


Figure 17 An overview of visual progress monitoring and quality assurance/quality control using still images (Yang, Park, Vela, & Goldparvar-Fard, 2015)



Concrete Excavate Upper Footings Area C	2	15SEP06A	14NOV06
Concrete Excavate Footings Area D	2	25SEP06A	27SEP06A
Concrete Pour Footings Area D	6	27SEP06A	14NOV06
Concrete Form Walls Area B	19	20SEP06A	16NOV06
Concrete Pour Upper Footings Area D	6	02OCT06A	03OCT06A
Concrete Excavate Column Pads Area A	1	10OCT06A	14NOV06A
Concrete Pour Column Pads Area A	3	10OCT06A	14NOV06A
Concrete Waterproof First Lift for Drain Tile	95	10OCT06A	06FEB07
Concrete Form/Pour Upper Walls Area C	6	11OCT06A	16NOV06
Exterior Perimeter Drain Area A	25	11OCT06A	17NOV06
Concrete Pour Walls Area B	20	19OCT06A	17NOV06
Concrete Forms Walls Area D	11	09NOV06A	29NOV06
Concrete Mock-Up	3	09NOV06A	09NOV06A

Figure 18 Superimposing 4D BIM on time-lapse images and color-coding progress deviations based on the metaphor of traffic lights colors (Yang, Park, Vela, & Goldparvar-Fard, 2015)

7.2.1 Augmented Reality

Augmented reality (AR) is defined as a live perception of a real-world environment, which elements are enriched with computer generated visuals (Tarek & Moncef, 2016).

Is a technology that shows promise as a mean to visualize monitoring data, allowing users to perceive real world image and computer generated data simultaneously, however, the current challenges include the correct synchronization between these two sources of information (Kopsida, Brilakis, & Vela, 2015).

The current application areas of AR include:

- Visualization
- Simulation
- Communication
- Collaboration
- Information modelling, access, and evaluation.
- Safety

Source: (Tarek & Moncef, 2016)

AR can be used to overlay the real construction site with the as designed model, allowing comparative analysis by personnel, to identify and evaluate defects, and support decision making (Tarek & Moncef, 2016).

(Guo, Yu, & Skitmore, 2016) argue that due to the dimensions of AR devices, they disturb construction operations. There are additional concerns regarding the power source limitations, resistance to harsh conditions, filtering of noise, and additional interactivity (Tarek & Moncef, 2016).

7.2.2 Mobile devices

Mobile devices have been recently introduced to construction sites, their main use is to retrieve project information (Awolusi, Marks, & Hallowell, 2018).

The popularity and development of mobile devices bring technology to the construction site (Garcia-Lopez & Fischer, 2014). Mobile phones include several built-in sensors, and can retrieve, compute, store, and display information (Akhavian & Behzadan, 2016).

Sensors commonly built-in smartphones include: accelerometer, gyroscope, GPS, magnetometer, barometer, temperature sensors, proximity sensors, light sensors, Bluetooth, Near Field Communication (NFC), and cameras (Akhavian & Behzadan, 2016).

There are smartphones designed for use in construction sites, with increased resistance to environmental conditions such as impacts, dust, and water (Akhavian & Behzadan, 2016).

Smartphones show promise regarding future implementation in construction site monitoring (Akhavian & Behzadan, 2016).

7.3 Technology acceptance

Technology acceptance involves the processes and variables which influence the approval and adoption of a new technology (Sepasgozaar, Shirowzhan, & Wang, 2017)

The construction industry has a strong technological inertia, preventing it from adapting the newest technologies into its processes. However, recently there have been increasing attempts to implement innovative technologies into AEC since there is a demand for real-time data supply and model updating systems (Sepasgozaar, Shirowzhan, & Wang, 2017).

The current situation demands the assessment of the technology adoption potential for different new technologies in the AEC, this would require several Technology Acceptance Models (TAM). These studies enable technology-specific stakeholders to make better decisions to adapt for the implementation of new technologies (Sepasgozaar, Shirowzhan, & Wang, 2017).

(Sepasgozaar, Shirowzhan, & Wang, 2017) present a Scanner Technology Acceptance Model (STAM), evaluating two main criteria: ‘ease of use’ and ‘usefulness’. Ease of use is a crucial factor in determining the adoption of innovations in the AEC industry since it consists mostly of low-skilled labor.

Factors that affect the adoption of a new technology:

- Physical characteristics of the hardware (size and weight)
- Skill, time, and costs required to buy, install, and operate technologies.
- External support: external organizations able to provide hardware, spare parts, maintenance, technical support.
- Value of the Output (Accuracy, interoperability, real-time demonstrability, automation, verification)

Source: (Sepasgozaar, Shirowzhan, & Wang, 2017)

One of the most effective models to predict acceptance of workplace technology is the Unified Theory of Acceptance and Use of Technology (UTAUT) (Jacobs, et al., 2019).

(Jacobs, et al., 2019) performed an online survey about technology acceptance of wearable devices. The survey involved 1273 employed adults (even part-time employed) from a broad range of industries across the United States of America.

(Jacobs, et al., 2019) claim that wearable technologies are especially sensitive to user acceptance and proper use (Jacobs, et al., 2019), on the other hand, (Yu, Guo, Ding, Li, & Skitmore, 2017) argue that wearable sensors impair workers' operations.

According to the results of the survey, technologies focused towards workplace safety are most likely to be accepted than productivity or quality-oriented technologies (Jacobs, et al., 2019). Also, performance expectancy is the main indicator of technology acceptance, technologies are more likely to be accepted if enough evidence of their effectivity and ease of use is presented to the prospective users (Jacobs, et al., 2019).

(Jacobs, et al., 2019) also concluded that workers are more likely to accept the use of a technology when they are involved in the selection and implementation processes of said technology. They suggest employers to consider providing incentives to their employees to increase their willingness to use the technologies, even though this would effectively increase the total economic investment required to implement the technology, affecting its feasibility (Jacobs, et al., 2019).

7.3.1 Privacy concerns

(Li, et al., 2015) noted that construction workers show aversion towards the idea of being monitored due to privacy concerns.

In cases where the health of construction workers is being monitored, the privacy, security, and legal aspects concerning this information must be addressed; the information could be transmitted wirelessly and through the internet, therefore it should be encrypted, and security measures must be taken to prevent any leaks (Awolusi, Marks, & Hallowell, 2018).

(Zhu, et al., 2016) claim that unions could object against the tracking workers due to privacy and health concerns. (Li, et al., 2015) noted a concern regarding responsibility in cases where risks materialize while using the RTLS they researched.

8. Conclusions and Recommendations

This research explored current construction site monitoring practices through chapter 4, capitulating on their crucial role towards project safety, duration, cost, and quality; and found significant inefficiencies and unreliable procedures. Monitoring assessments are based on experts' opinions, and demand on-site visits by inspection personnel, paper-based reports, post-processing, and other time-consuming, error-prone, as well as expensive activities.

Chapter 5 explained the need of the construction industry to adopt more efficient monitoring techniques, as well as the general reluctance of this industry to do so. Computers, smartphones, tablets, and cameras are used to facilitate communication and security services, however, monitoring processes remain manual. This chapter describes how technology can retrieve information from the environment, materials, equipment, and employees; to later process it and provide it to the stakeholders, improving health and safety on the workplace, project quality, duration, and cost. The challenges of monitoring technologies are discussed as well, generally they must not disrupt on-site activities, they must be affordable, and provide valuable information tailored to different stakeholder groups.

Sub chapter 5.5 described the wide variety of technologies available and developing for automatic construction site monitoring, their operation, characteristics, potential, and limitations. Among them, the existing literature gives especial attention to range cameras, photogrammetry, computer vision, laser scanning, global positioning systems, radio frequency identification, and ultra-wideband. Technologies briefly mentioned in the 'additional mentions' title lack sufficient literature basis to be included in the grand analysis, however, these technologies present unique potentials which prove useful in the field, perhaps in combination with any of the main technologies previously listed. The shortage of literature covering these technologies could point towards a lack of interest from researchers and the industry, nevertheless, it could also hide valuable potential.

While developing chapter 5, the asymmetry of current research efforts was evident, most recent publications were focused on computer vision, revealing the interest of the research community into the development of computer vision, and neural network in general into data capturing technologies to obtain more refined outputs and reach higher levels of automation.

Chapter 6 presents a novel comparative SWOT table, which evaluates the information covered on chapter 4 and 5, facilitating the analysis of specific strategies in contrast to a given construction project, supporting decision making. The SWOT successfully becomes an intuitive, information-rich instrument; it also allows further elaboration, additional technologies can be added to this instrument, as well as specific devices. Moreover, present data could be refined, qualitative assessments from experts can be replaced by factual data (e.g. all accuracy fields containing error ranges), and aspects can be further subdivided into their components (e.g. implementation costs including hardware and software related costs).

None of the publications found applied the SWOT method to monitoring technologies, which in this research was adapted to allow for comparison of multiple approaches to construction site monitoring. The SWOT analysis presented on this research also evidences areas where important gaps of knowledge are currently present, which could be addressed by future research.

Chapter 7 evaluates the integration of monitoring systems data among the project stakeholders, presenting the inputs of experts on this matter, and the "Work Tracking System" developed by (Garcia-Lopez & Fischer, 2014) as a prime example of monitoring data management software. Investigating the integration of monitoring technologies and building information modeling revealed that the main technologies contained in the SWOT analysis support BIM interoperability.

Exploring data visualization alternatives remarked the convenience of the street light metaphor; and the opportunities related to the use of augmented reality and smartphones. Technology acceptance was also covered as it is critical for any technology to be implemented in any given industry, possibly of special importance in the construction industry which usually resists change. This section of the study revealed a set of variables which influence technology acceptance, such as device cost, simplicity of use, data relevancy, and contribution to work safety.

Regarding recommendations of improvements to this research and future research efforts, more data and a standardized project evaluation are required to allow for the comparison, identification, and assessment of favorable monitoring strategies. This remains a complex task due to the disparity among construction projects, however, despite the differences, catalogued building types and properties exist, perhaps a comparative scheme could be applied to simple projects to then evaluate the extrapolation of results to more complex projects.

The combination of the traffic light metaphor and the comparative SWOT analysis (section 6.2) facilitates the identification of present challenges of the analyzed strategies, pointing to possible areas of developments such as range cameras sensor range, the accuracy and user training requirements of photogrammetry, computer vision’s need for training data, high cost, size, and weigh related to laser scanning, GPS vulnerability to interference, RFID short range, and UWB high costs.

Additional factors and technologies could be included and evaluated inside the proposed SWOT analysis format, also the factors currently on the table could be broken down into more detailed components, for example, ‘implementation cost’ could present an exhaustive cost structure for each technology, including device related costs and software costs; similarly, a specific set of devices could be analyzed instead of a general technology. Alternatively, other analysis tools could be used, such as PESTLE analysis.

Legal regulations related to the use of monitoring technologies must also be defined and considered in the analysis.

9. Declaration of Authorship

I hereby declare that the attached Master’s thesis was completed independently and without the prohibited assistance of third parties, and that no sources or assistance were used other than those listed. All passages whose content or wording originates from another publication have been marked as such. Neither this thesis nor any variant of it has previously been submitted to an examination authority or published.

Date

Signature of the student

10. List of Literature

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