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Preface

The Master Construction & Robotics was founded in 2020 as an interdisciplinary programme bridging four different faculties: Architecture, Structural & Mechanical Engineering & Computer Science. The summer semester 2021 was once again a special semester. As the corona restrictions limited the physical interaction, the students, tutors and lecturers were faced with additional effort in communication and collaboration. During the semester the students were distributed worldwide and they took part to digital formats from different time zones and local conditions. Therefore, online-contents were extended to ensure the teaching and communication with the students. Especially competences in digital collaboration became more important and cloud-based tools for research, citation and writing took a greater role in the curriculum.

A result in sharing these efforts and results is the first volume of Research Driven Project Book. It shows first scientific papers of different groups of the Research Driven Project as a collection of various research papers on different topics. The students had to develop the state of the art in construction processes, robot systems and software application and came up with a variety of research questions to the transfer of robotic systems into construction environment. For example, students faced the challenges of the integration of COBOTs on construction sites, the difficulties in crane automation for assembling or demands for computer vision approaches in tunnelling environments. Based on these questions they've dealt intensively with methods of research in various disciplines such as mechanics, material science, robotics and programming. The basic principles and technologies were collected and analysed due to chances and threats for construction purposes. These results are the basis for a successful transfer of digital technologies into the field of construction and indicate potential projects that will be further researched and developed in the following semester.

We thank all the students who contributed to this book through their work. The book creates a fundamental knowledge about state of the art in interdisciplinary fields of technology and supports students in their research and development.

Aachen, 21 March 2022

PROF. DR. SIGRID BRELL-COKCAN
INITIATOR OF CR-MASTER PROGRAM

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LECTURER OF RESEARCH DRIVEN PROJECT

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Research Paper

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Potential improvement of on-site construction processes by integrating human-robot collaboration

ABSTRACT

The application of industrial robots is widespread in industry shows potential for application in construction.

Due to the highly dynamic nature of construction sites, there are still challenges for such implementation in the construction industry especially in the aspect of human-robot collaboration (HRC).

In this paper, the aim is to draw out the possible construction processes to implement Cobot on sites. Firstly, the potential and challenges of implementing an industrial robotic arm are documented in chapter 2. Secondly, the term HRC is explained in chapter 2.1. Then, the Cobot technologies with its' comparison among different Cobot on market is recorded in chapter 2.2. Lastly, a SWOT analysis is carried out and the potential construction processes is discussed based on the on-site requirements to identify the potential to integrate Cobot systems on sites.

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1. Introduction

1.1 Motivation

The evolution of the industrial industry had brought many digitization and automation processes, which leads to the development of construction industry in the last decade. In this regard, the construction industry benefits highly from the implementation of robotic systems in recent years due to the automation trend. The capability of varying in settings, handling heavy material, safety monitoring while in action and execution of complex navigation in a given environment while manipulating a tool for a specific action makes the automation of robotic arms attractive in industrial production, manufacturing, and assembly sectors. The development of automation technology and robotics can contribute to the future of the construction industry.

The construction industry is still in the early stages of automation with robotics, and mostly benefits from them on prefabrication phase, nevertheless, in the future, robotics will likely play a crucial role in all steps of architectural design and processes. Challenges, such as the establishment of full automation, human-robot interaction, building in uninhabitable environments and planets, or the creation of reactive living buildings will be possible to overcome with the help of each small step of the development of robotics. This development can contribute to low error and high efficiency in entire construction processes.

Applications and design of robotics for automation on construction sites will be highly dependent on information from multiple construction stages, through the implementation of a continuing process. Efficient information exchange enhances accuracy and real-time decision-making, along with reductions of delivery times [BAT21]. The information flow between the whole network of robots and interpretation or transfer of the locally gathered sensorial data will make the collaboration of robots, as well as human-robot interaction, seamless and possible.

However, due to specification of construction sites, such as harsh and dynamic environment implementing robotics systems stays still as a challenge, and most construction processes are still carried out manually. The manual works might lead to injuries easily as stated by the occupational safety and health administration (OSHA), there is one out of ten construction workers injured every year [Kel]. The robotics system has the potential to replace dangerous works, such as works at high attitudes and heavy loads. Moreover, the collaboration between humans and robots has the potential to improve the productivity and efficiency of construction processes.

1.2 Goal of research

One challenge is to find a way to fill the gap between current widespread manual labor and the future of full automation on sites. In that case, human-robot collaboration systems can be considered for the transition. Collaborative robots are designed to be able to learn, adapt and execute the given action or input simultaneously, which can be used to overcome the stated challenge. Thus, the research question of ”How can a Cobot be integrated for handling tasks on construction site” arises.

2. State of the art

A typical industrial robot arm has a set of joints connecting the sections, articulations, and manipulators that operate together to closely resemble the motion and functionality of a human arm for precise positioning of the end-effector. The common applications of industrial robotic arms are welding, additive manufacturing, milling, cutting, picking, and placing [BGN+20]. The application of industrial robotic arm brings various advantages as following according to Stevens, Mark [Ste19] which are ensuring production quality and consistency of reliable processes, improvement of productivity, safeguarding the employees for repetitive and dangerous tasks, and reduction of direct labor cost.

The current usage of robotics are focusing on operation cost reduction by removing human operation or improvement of efficiency by robotization [SBG16]. According to [SBG16], the solution on construction phase problem is categorized into the teleoperated system by remote-control machine with the human operation, software-programmable construction machine with sensors under a human operation, and intelligent system with remote-control robots. This shows us that there is a lack of research going on human-robot collaboration (HRC).

Apart from that, the construction industry is suffering from the adoption of robotics and auto- mated systems industry-specific. This is because the sites are often structure-less, chaotic, overcrowded. Furthermore, the operation of robots generally highly depends on construction tasks where oftentimes different operating tasks required different robotic systems and may lead to the high initial investment. According to [DOA+19], the major limitation of adopting robotics system in construction based on reliability analysis are as following:

- High capital investment at the beginning
- Lack of motive to improve productivity
- Low research and development budgets in the construction industry
- Work Cultural (Human-robot interaction)
- Unskilled workforce
- Lack of evidence on technology
- Accessible to labor easily
- Low return on investment
- Insufficient government incentives
- Reduced of public infrastructure funding
- Fragmentation nature of construction industry

The application of industrial robot arm in the construction industry are often only in prefabrication and rarely on sites which is due to the harsh environment, outdoor weather situation, robotics power system and safety measures. Thus, the robots are often programmed in a specific zone. Besides, there are also gaps existed for collaboration between humans and robots where collaborative robots (Cobot) are scarcely implemented on sites. Due to the limitation of adapting industrial robotic arms and the harsh situation of construction sites, it is crucial to realize the optimum use-case scenarios of human-robot collaboration before implementing Cobot in the construction industry.

2.1 Collaborative robots (Cobot)

A Cobot is usually referring as an interactive robot where there is direct physical interaction between humans and robots. In addition, a Cobot is often a relatively lightweight and small robot as compared with traditional industrial robots. According to [SBBC19], it is critical to implement diversified interfaces especially on configuration and setup of new robotic working stations for HRC. The interfaces that are crucial in allowing HRC to teach pendant, teleoperation, machine to machine interfaces, human motion tracking, and hand-guiding control [SBBC19].

A touchpad with a six degree of freedom (DoF) mouse, the so-called “teach pendant” is utilized to act as a keyboard for typing and control the position in the Cartesian coordinate system. With such a control pendant, the robot is able to manipulate in several different modes such as manual control with safety speed limit (T1), manual control with automatic speed (T2), and automatic program mode (Automatic) [SBBC19]. Moreover, the Cobot also acts as a teleoperation robot where the interactive robots considering the environment and being used to perform complex tasks autonomously or remotely.

In machine-to-machine interfaces, it can be used to transfer programs or data to a controller by offline programming or via the Internet of Things (IoT) communications or extract the configuration information to design PC [SBBC19]. On the other hand, a human-machine interface is generated on another supervision controller in order to select and start any programs.

A human motion can be inputted into a controller to give direct control or act as an abstract for the interfaces which are so-called “demonstration” in this case. The learned motion at the robot from the inserted human demonstration is used to extract the critical motion path. The generalization techniques played a key role here for the relationship of motion and objects as the motion trajectory from human motion can be segmented from the continuous flow.

In the interface of hand-guided control, the user can lead the robot by hand or even touch to a particular position with an integrated internal force-torque sensor [SBBC19]. Thus, the user can teach the robots directly by hand-guided control as it allows dynamic translation of parameters and robot space. HRC is currently at the stage of the combination of hand-guided control and semi-automatic control from teleoperation. In other words, the action of robots is triggered by haptic gestures, like handshakes to activate the performance automatically.

2.2 Comparison of Cobot technologies

There is numerous Cobot existing on the market. In this section, the existing Cobots, as well as the traditional industrial robot arm, are documented, compared, and listed in the figure 1 In this figure, the KPIs such as the payload, maximum range, weight, maximum size, number of axes, repeatability accuracy, vision and sensors, and programming languages of each Cobots are documented according to [KBK20, KUK03, KUK16, AGAL18, Ret17, ABB15].

	Traditional industrial Robot (KR6-2)	Cobot - lightweight robot (LBR iiwa 7, R800)	Baxter - collaborative Robot Rethink Robotics	YuMi - two-armed Robot ABB IRB 14000	UR - six-axis sigle armed Universal Robots R3-5-10
Payload	6 kg	7 kg	2,2 kg per arm	0,5 kg per arm	3 kg
Maximum range	1611 mm per arm	800 mm	1210 mm per arm	559 mm per arm	500 mm
Weight	235 kg	23,9kg	75 kg	38 kg	11.2 kg
Maximum size *(for streched robot arm)*	2026 mm	1306 mm	1900 mm	1202 mm	1900 mm
Number of axes	6	7	7	14	6
Repeatability accuracy	± 0,5 mm	± 0,1 mm	± 0,1 mm	± 0,2 mm	± 0,1 mm
Vision & Sensors	-	Sensitive joint torque sensors	Spring for physical compliance - collision sensing	Force feedback sensing, integrated Camera	Inertial sensors each arm overcurrent, collision detection
Programming	KRL - WorkVisual, PRC	Kuka Sunrise, PRC, Teaching by manual guidance	MoveIt - path planning, ROS, training by showing - Rethink	Wizard easy Programming - graphical interface	UR COM1LAPI library Polyscope GUI interface on pendant

Figure 1: Comparison of multiple Cobots [KBK20, KUK03, KUK16, AGAL18, Ret17, ABB15]

Figure 1 shows the comparison of traditional industrial robots, KR6-2, and multiple Cobots, namely LBR iiwa 7, Baxter Robot, ABB-YuMi, and Universal Robots - UR3. In contrast, Cobots come in various sizes, which are generally smaller than the traditional industrial robots. Avail- able Cobots on the market are designed to carry out more precise actions while collaborating with the human operator. They have a lower maximum range and speed of a single axis in 500 - 800 mm which means also inferior in the function of repeatability to a traditional industrial robot for safety reasons.

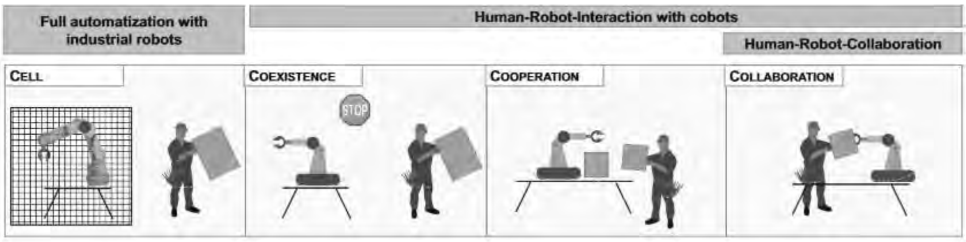
The number of axes of Cobots can vary based on the specific application, which proposes better flexibility for application due to the higher number of axes and lower weight. Cobots are built with integrated sensors and/or cameras to be able to sense their environments and execute pre-defined security measures as explained in previous subchapters 2.1. On the other hand, listed Cobots offers a wide variety of easy-to-learn operating and programming solutions. Interfaces such as ABB-Wizard easy programming, Kuka|prc, and UR-COM1LAPI [KUK16, Ret17, ABB15] introduces visual programming environments to make offline programming easily understandable for end-users. Companies also offer real-time programming solutions with LBR iiwa 7 and Baxter by moving robots at specific positions and recording them to be executed later when desired.

Human-robot collaboration

Another type of collaboration is the physical interaction between the human and robot in a particular way, that is defined by ISO standard 8373:2012 [ISO12] as Human-robot collaboration (HRC). According to [KBK20, KSK20], the human-robot interaction (HRI) can be categorized by its type and characteristics as in the figure 2. The HRI is classified into four different scenarios where cell, coexistence, cooperation, and collabo- ration.

In the case of cell scenarios, the robotic arm performs at fully automated and at maximum speed inside “cage” without human interaction. This is not feasible for construction processes, since “cage” setup time for each individual action requires significant amount of time. While in the case of coexistence scenarios, the robotic arm performs conventionally automated where does not share a common workspace with humans. A safety measure of stopping mechanism is implemented to avoid contact of human and robot as there is no physical separation. In the case of cooperation scenarios, humans and robots share the same collaboration area. The working tasks are performed sequentially between human and robot arms. In the case of collaboration scenarios, the work between humans and robots is carried out simultaneously on the same item in a common workspace.

As humans and robots are working in the same environment, safety measures for employees are crucial. To minimize injuries coming from direct physical interaction with robots, the minimal safety requirements DIN EN ISO 10218-1 give guidelines on the monitor of speed and separation, limit of power and force, and hand-guided control when implementing Cobots application [KBK20]. By detecting human presence using integrated sensors on Cobots, the speed and separation monitoring will be activated to maintain specified speed and distance from the hu- man operator when in close proximity. In terms of power and force limiting, the robot engine can be dimensioned automatically to restrict the



	Cell	Coexistence	Cooperation	Collaboration
Working steps	Sequential			Simultaneously
Working space	Separated working spaces		Shared collaboration space If synchronised: Timely separated	
Working tasks	Tasks are not linked		Linked tasks	Shared tasks
Physical contact	Impossible		Possible, not necessary	Possible, often desired
Minimal safety requirements according to DIN EN ISO 10218-1	Automatic operation with safeguards	Safety-rated monitored stop	Speed and separation monitoring Power and force limiting	 Hand-guided control
Robot speed	Maximum speed	Limited speed		

Figure 2: Type of collaboration with its characteristics [KBK20, KSK20]

forces when working with humans. Hand-guided control of Cobots brings flexibility to a variety of tasks with mobile design opportunities independent of the work location.

2.3 Methodology

In this paper, the methodology carried out to integrate Cobot for construction processes on sites is explained in the following. Firstly, the requirement for implementing Cobot on sites is identify. Then, the existing Cobot is research and compared within each other. Afterward, the potential for automation and collaboration of current construction processes on sites is listed and discussed with implementing Cobot under SWOT analysis, where strength, weaknesses, opportunities and threats of the technology will be compared, in the chapter 3. Lastly, a concept for Cobot on Construction Sites is proposed for existing projects..

3. Analysis of potential on construction sites

This chapter represents a general overview of construction processes to be able to identify potentials in HRC and automation as the current state of the construction industry. In the figure 3, a modular construction of a simple building is segmented into its main construction phases and analyzed based on automation and collaboration potentials for the construction sites of today. The structure of the figure presents the potential of

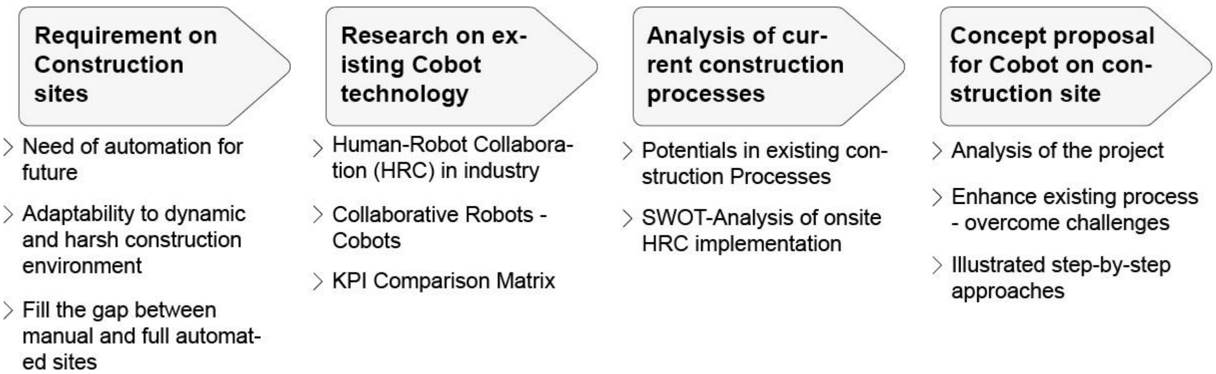


Figure 3: Methodology Diagram

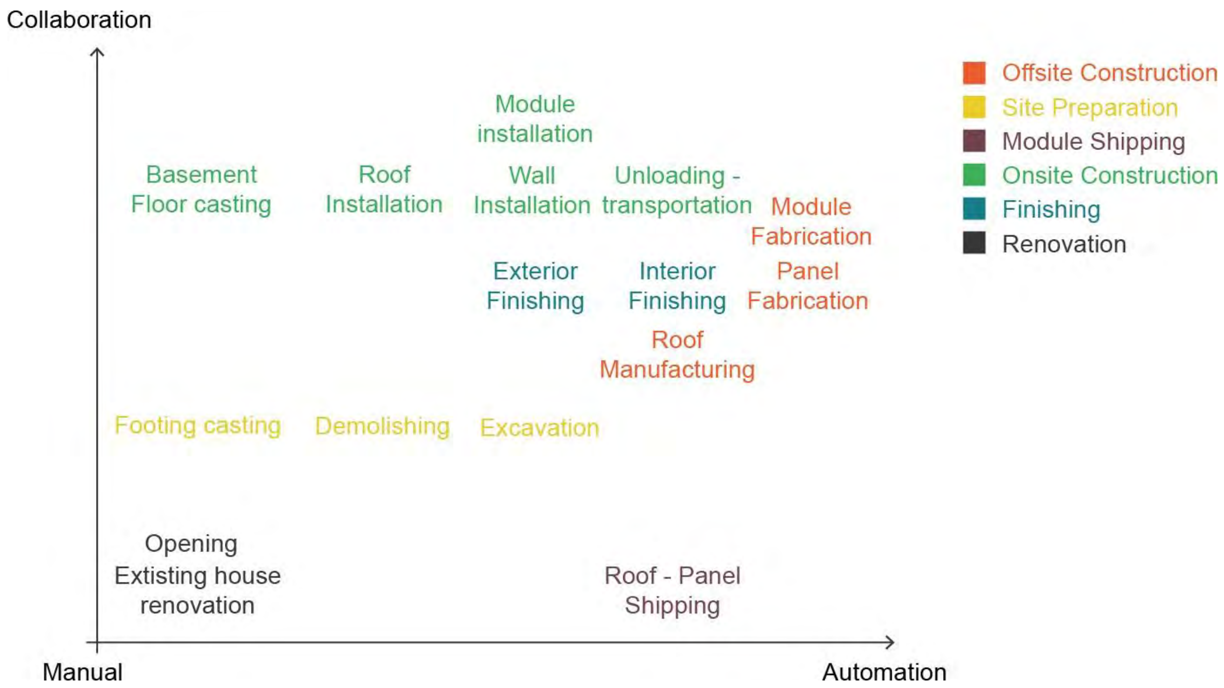


Figure 4: Potentials on automation and collaboration of current construction processes

automation in the process, increasing from left to right and for the potential of collaboration increasing from bottom to up.

As the first stage of construction, offsite production of elements offers high potential in automation and HRC, since the manufacturing can take place in factories and workshops, where robots are already used widely. As mentioned in [CBP20], the manufacturing stream can be automated by means of CNC, alternative shapes of components, can be fabricated following customized designs. This process does not require flexibility as the modular designs have predefined properties.

Furthermore, site preparation is highly dependent on environmental conditions and yet a huge challenge to overcome with robot applications instead of heavy machinery. Casting, demolition, and excavation steps are arranged based on the tolerances and probability of inconsistencies during the operation and remains as manual labor operations. As part of transportation, components of a prefabricated structure are mostly produced in manufacturing factories and delivered to the construction site by rail, ship, or road transportation. Today, automatic train operation (ATO) has already been incorporated in the railway systems of many countries [CBP20].

However, on-site construction steps present high potential in collaborative workflows. Most of the of handling and joining processes consists of simple actions, such as drilling, bolting welding, screwing etc. but requires planned execution. In that case collaboration provides efficient workspaces, where commanding and monitoring can be done by workers, and heavy, partially repeatable, simultaneous actions are done by collaborative robots. The implementation requirements can be listed as;

- Large and specific working space [WWW16]
- Self-localization for better contextual awareness [LC17]

- Constant power supply for full functionality
- On-site Weather protection [LC17]
- Safety measures of Cobot in collaborative space [KBK20]

Material handling, load carrying, precise positioning, and partial assembly of elements in modular construction can benefit from collaborative robots. Most of the current practices in robotic construction require the development of various robots to specifically suit complex tasks in construction or structural assembly [CBP20]. Nevertheless, highly flexible systems, such as Cobots, can be integrated into complex applications and operate with workers while learning from them to execute an action. Cobots are designed to be applied as seamlessly as possible with less preparation, installation, and programming times, which makes them highly suitable for onsite construction phases.

3.1 Result

This chapter discusses Cobot implementation potentials based on the statements of construction processes in previous chapters. A SWOT-Analysis, which is a strategic planning approach, has been carried out as it pinpoint the strengths, weaknesses, opportunities, and threats for implementing Cobot in the onsite construction process which includes relatively high collaborated tasks in the figure 4.

A pairwise comparison shows that on-site construction processes can benefit from the internal advantages of a Cobot. Integrated sensors on Cobots help to realize the collaborative workspace between humans and robots. A Cobot can get information from simultaneous actions in the environment and adapt to its surroundings. This way of collaboration can reduce the amount of manual labor during on-site tasks, such as physical workload (S3) and repetition (2S) and can enhance the workflows in regard to high precision and working in high-risk, manually unreachable areas. Cobot utilization allows to increases the repeatability and quality of production, allows to obtain stable production parameters, high accuracy, and thus allows the production of quality products and in addition, the increase in productivity [PGBU21]. Furthermore, the capability of easy programming offers new ways of on-site task execution to be able to overcome new challenges and innovative construction processes, which comes with industry 4.0.

As the strength of Cobot on-site integration, it consists of integrated sensors, hand-guided control for teaching, high precision, and flexibility which is suitable for eliminating repetitive and autonomous tasks, and reducing physical workload [KBK20, KSK20]. Furthermore, these lead to the coexistence of humans and robots in the same working environment and flexibility to the position which is not reachable by humans. Moreover, this also creates jobs opportunities as implementation, and research on such new technology in the construction industry are necessary.

However, there is still a lack of proof of on-site implementation and inexperience in the Cobot system which caused a lack of funding from stakeholders [DOA+19] as return on investment is unknown. Besides, the Cobot is highly sensitive equipment and has to limit functionality due to safety reasons [KBK20, KSK20]. Due to the

Positive	Negative
S1. Enviromental awareness with integrated sensor	W1. Lack of proof of on-site implementations
S2. Elimination of repetitive and monotonous tasks	W2. Lack of work experience in the cobot systems
S3. Reducing physical workload	W3. Highly sensitive equipments
S4. Hand-guided control for teaching/programming	W4. Limiting robot functionality
S5. High precision and flexibility	
O1. Coexistence in the same work environment	T1. Insufficient initial funding
O2. Ability to operate on unreachable areas for humans	T2. Require setup, configuration, and adaptation setting for construction sites
O3. Creation of new jobs	T3. Low productivity at the beginning
O4. Responding to the challenges of Industry 4.0	T4. Lower robot efficiency than full automation
	T5. Reduction of job vacancy

Strengths Weaknesses Opportunities Threats

Figure 5: SWOT-Analysis on HRC implementation for construction sites

dynamic and harsh environment on construction sites, a certain amount of setup, configuration, and adaptation have to be implemented as in [SBBC19]. Last but not least, there might here might be even reduction of the job vacancy as some of the human works can be replaced by Cobot.

3.2 Discussion

Research and analysis show that Cobot integration can be utilized in on-site construction phases. This chapter focuses on proposing a concept of Cobot on the construction site based on an existing process with the consideration of opportunities and threats, such as harsh environmental effects, stated in figure 4. The selected project is NEST-HiLo which presenting research on lightweight construction and adaptive energy systems. The proposal of the project is based on the innovative construction process of the lightweight, sandwich, thin shell roof structure, integrating both structure and building systems. This is because module installation, like falsework installation, is a high collaborated construction process and there is a room for automation as in chapter 3.1.

The proposal is based on the cable-net installation of the documented construction process. The theoretical workflow requires a set of individually manufactured cables to be connected using steel node components for the creation of the prestressed mesh falsework to show potential of Cobot integration in any on-site construction process. This process has been done by manual work by labeling each cable element and connecting them based on the planned sequence. The current workflow, as well as two proposed approaches (naive and advanced approaches), are compared in figure 8. The mentioned advanced and naive approach could be ideal in this case to achieved by LBR iiwa 7, R800 as it's a one-armed Cobot with high repeatability accuracy and sensitive joint torque sensors as figure 1 [KUK16]. On the first row current approach, the Nest-Hilo project consists of prefabrication of mesh cables, labeling and grouping, setup of boom lift for installation, and manual connection of nodes are listed in the figure 8.

The proposed naive approach has similar steps to the current one and utilizes robot integration based on the existing assembly and construction systems. This process starts with prefabrication and continues with QR-barcode labeling, which is used for scanning node elements during the collaborative assembly. The setup of the boom lift is similar to the current approach but for this case, the system will be configured for a human worker and robot collaboration. As the assembly process starts, the robot assists the assembly process by minimizing downtime of cable element selection according to the planned progression.

According to [OSS08], it is also important to consider the capabilities, limitations, actions, goals, the status of the team member to reach a seamless HRC mode. Moreover, the success factors of initiating an HRC effectively is established by systematic literature reviews and online survey of enterprise representatives. The critical factors implementing a successful HRC are employees feeling of being informed (fear of job loss), reliability of Cobot, gripper of the industrial robotic arm, IT security, occupational safety, and appropriate allocation of tasks according to [KBK20]. As stated in [Nik11] in robotics, sensors are used for both internal feedback control and external interaction with the outside environment. Especially in the documented application, the robot must act and execute movements based on the completion of the worker's task.

Even so, one of the main challenges would be the localization of the robot in the dynamic environment. The nature of the high dynamicity of construction sites is unpredictable for robots. Nevertheless, on already-built elements visual or physical markers can be placed, which can be detected through a set of sensors. For example, QR/barcode or infrared tags can be detected visually and the robot can locate itself based on the camera recordings and image segmentation 9. This helps the robot to know which command it has to execute, depending on its location.

Lastly, a more advanced approach based on on-site fabrication is proposed. The boom manlift with one worker and a Cobot is set up and Cobot localization is done by scanning as in figure 3.6. Then, the node can be defined and tensioning the cable automatically. When the Cobot completed its task, a haptic sequence is generated to alert the human for the manual node connection. This approach eliminates full prefabrication of the net cables, thus saves a huge amount of production time, and uses a specially designed end-effector for on-site tensioning of the cable and cutting for node assembly. The node can be connected by the worker as the robot places it in the planned position. Cobot is required to decide and act in case of a complication of the task, conflict with a worker or asset, and interruption of the process or workspace under minimal safety requirements according to DIN EN ISO 10218-1.

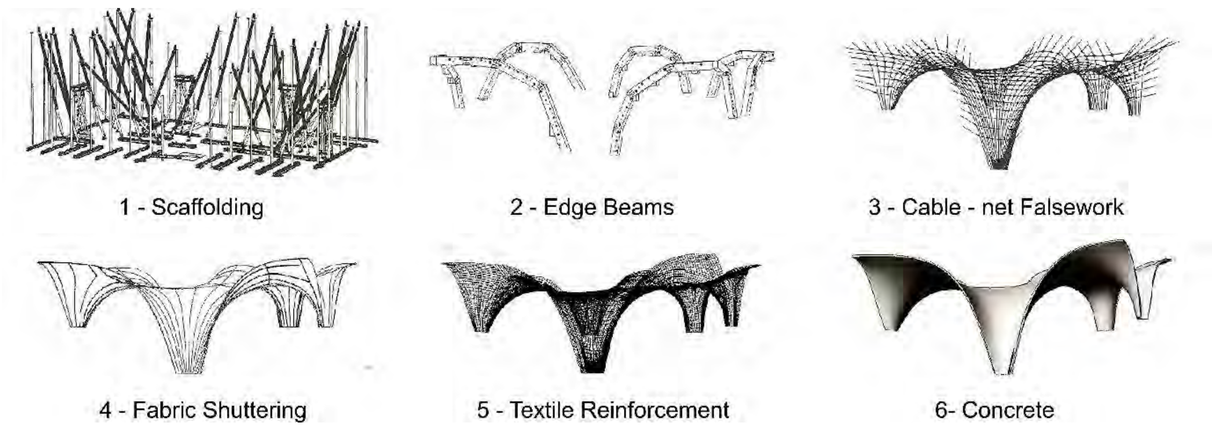


Figure 6: Construction steps of the NEST - HiLo Project [PAJ+17]


Figure 7: Cable-Net falsework installation - HiLo Project [BRG]

Blue: Cobot + Worker on boom manlift

Yellow: Localization in construction space based on barcode readings on installed elements

Red: Current progress of wire connecting

Figure 8: Localization of Cobot in work environment [PAJ+17]

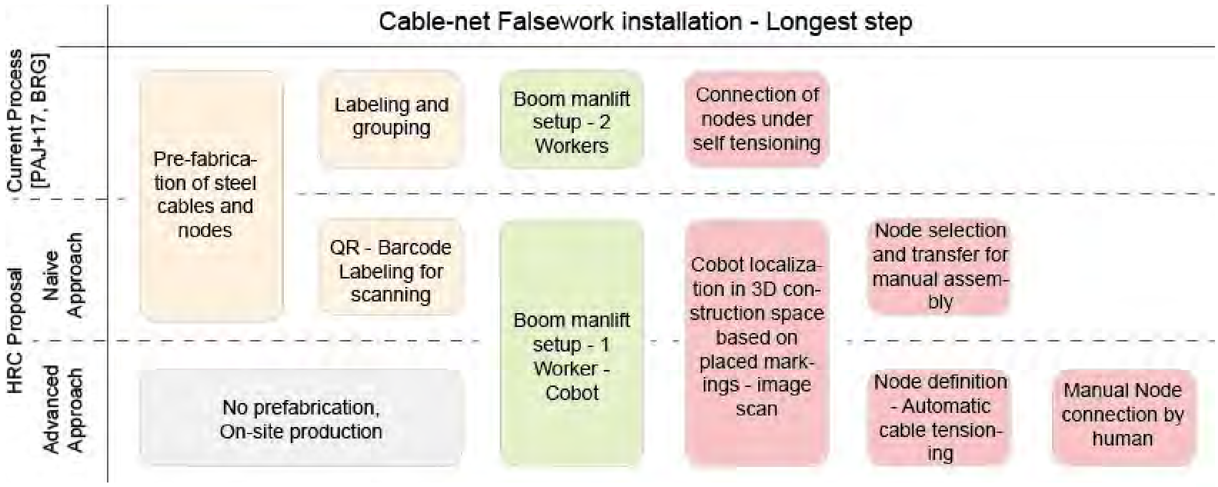


Figure 9: Current and proposed approaches on cable net installation

According to [OSS08], it is also important to consider the capabilities, limitations, actions, goals, the status of the team member to reach a seamless HRC m

4. Summary and Outlook

In summary, the potential and challenges of implementing an industrial robotics arm in the construction industry are documented by referencing to existed literature. Then, the term HRC and Cobot is explained and the comparison of Cobot technologies is under a comparison table. Subsequently, the requirement of Cobot implementation on-site is considered and the potential for automation and collaboration of current construction processes listed in a figure. After that, a SWOT analysis is utilized to identify the strengths, weaknesses, opportunities, and threats for implementing Cobot for on-site construction processes. With the consideration of SWOT analysis and analysis of potential on construction sites, a concept for Cobot onsite is proposed based on an existing project (NEST-Hilo) [PAJ+17].

The suggested proposals aim to improve the efficiency of assembly workflow between humans and robots on sites. With integrated sensors, such as QR-barcode scanning systems, force- torque sensors, external awareness of the Cobots is achieved and collaboration environment has been made safer. In addition, the suggested advanced approach has the capability of eliminating the full fabrication of preproduction time where overall construction duration is minimized. With the implementation of Cobot, hand-guided control improves the workflow time within humans and robots and standard minimal safety requirement ensure worker safety in the same working environment. Moreover, haptic sequence from Cobot may lead to improvement of workflow for humans and Cobots. The major challenges of the proposed approaches are the localization of robot which required several different considerations, especially in regards of sensors and safety measures.

As for future works, the suggested approach can be evaluated by implementing a camera sensor into Cobot and testing on a simplified workflow before going to a complex workflow of the construction process. Next, the designed prototyping can be validated in form of simulation where the design is simulated with real construction data and iterated with industry feedback as in Stanford Robotics Lab [BGK+20]. Then, the research can go further for other on-site construction processes such as basement floor casting, roof installation, wall installation, and unloading in transportation.

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Toward a Framework for On-site Welding Robot Implementation

Abstract

Construction is one of the most delayed fields in the implementation of automated processes. This is due to the fact that construction presents unique contexts in each case, with unconstructed environments and daily changes on site. The implementation of robotics on site requires systematic methods for challenges. Specifically, welding automation on-site is seldom addressed because its use is necessary only for specific jobs. Since steelwork is generally focused on the prefabrication of parts, this hider potential implementation on site. In this paper we research the different options for robotic welding technologies that when potentially used together can support the implementation of on-site welding robots. The goal is to propose a framework composed of three decision matrices for consideration during the design of an onsite automated process. For welding robots, the great variety of 6DOF welding robots already available in the market was investigated. In the state-of-the-art of this paper, the first section the robots are grouped in 4 categories: light, medium, heavy weight, and long-range types. Second section explores robot pose estimation, the research on this topic was classified between camera-based, sensor-based, and camera and sensor-based, as well as the location of these receivers between stationary, on-robot and on-worker (augmented reality devices). Third section examines seam detection applied to automated welding. These technologies were grouped according to type: manual location, touch sensing and laser detection. After categorizing these three technologies, an outline composed of three decision matrices is proposed in the framework section to allow the interested party using this proposal to select, according to their specific site requirements, which technologies to implement in the on-site welding robots. In the discussion section, this paper finally presents advantages and potential improvements of this framework facing the daily challenges of the construction site and allows to identify future developments and improvements.

1. Introduction

Industrial robots and automation have become indispensable for industrial welding over half a century. Although a large variety of automated welding systems have been widely adopted in the industrial manufacturing and fabrication process, the construction industry is still behind the average in automation and digital intensity and remains manual labor dominant compared to other industries, with a low intensity qualification of 41-43 over 100 in the ISIC indicator [OEC18]. As the demand for accuracy and productivity boosted, the traditional construction industry has reached its plateau and beset with inefficiency and qualified welder shortage estimated in 375.000 by 2023 [ARC21].

Construction site faces challenges for its automation processes due to lack of repetition, complexity, long-life cycle, dispersion of the projects and diversity of dimensions and materiality [BOC15], as well as weight, size, and mobility limitations of the robot systems [GRI13]. On-site welding is focused on three groups, structural elements such as columns and beams, non-structural elements including balustrades, fences, doors, windows and other façade elements, and installations such as pipes for drinking water and special gases. In addition, it is mostly executed to connect these elements previously pre-welded in the workshop, which is why on-site welding automation states challenges for its implementation due to its specific, complex, and diverse characteristics.

Unlike automated welding in factories, on-site welding has three main unresolved challenges for its implementation: the first is the transportability, reach and payload of the 6DOF robots that perform this task, the second is their adaptability to the unstructured or construction environment, where pose estimation is essential to avoid collisions, generate a safe environment for workers and create adaptability in the various workspaces, and the third is the detection and tracking of seams, since it cannot be preprogrammed through a digital path, the robot must be able to identify the location of the weld, in addition to options that meet your requirements for accuracy and tolerance as well as restrictions by contaminated environments, dirty, or weather exposed.

In this paper we aim to research on the state-of-the-art mentioned, consolidate them in a single document and serve as a practical guide to understand the technologies applicable in on-site welding automation, comparing them to identify similarities and differences.

The objective of this paper is to propose a framework that supports the stakeholders and decision-makers who want to implement and innovate in the field of on-site automated welding throughout easy-to-use multi-option matrixes to select the ideal combination of technologies to implement the on-site welding robots, according to their specific needs, improving and fostering then the widespread implementation.

2. Methodology

The research method in this paper includes qualitative and quantitative data, with a literature review of secondary data sources from reviewed research papers and books, as well as technical information on products available in the industry to identify the trends in the field.

The methodology of this paper is

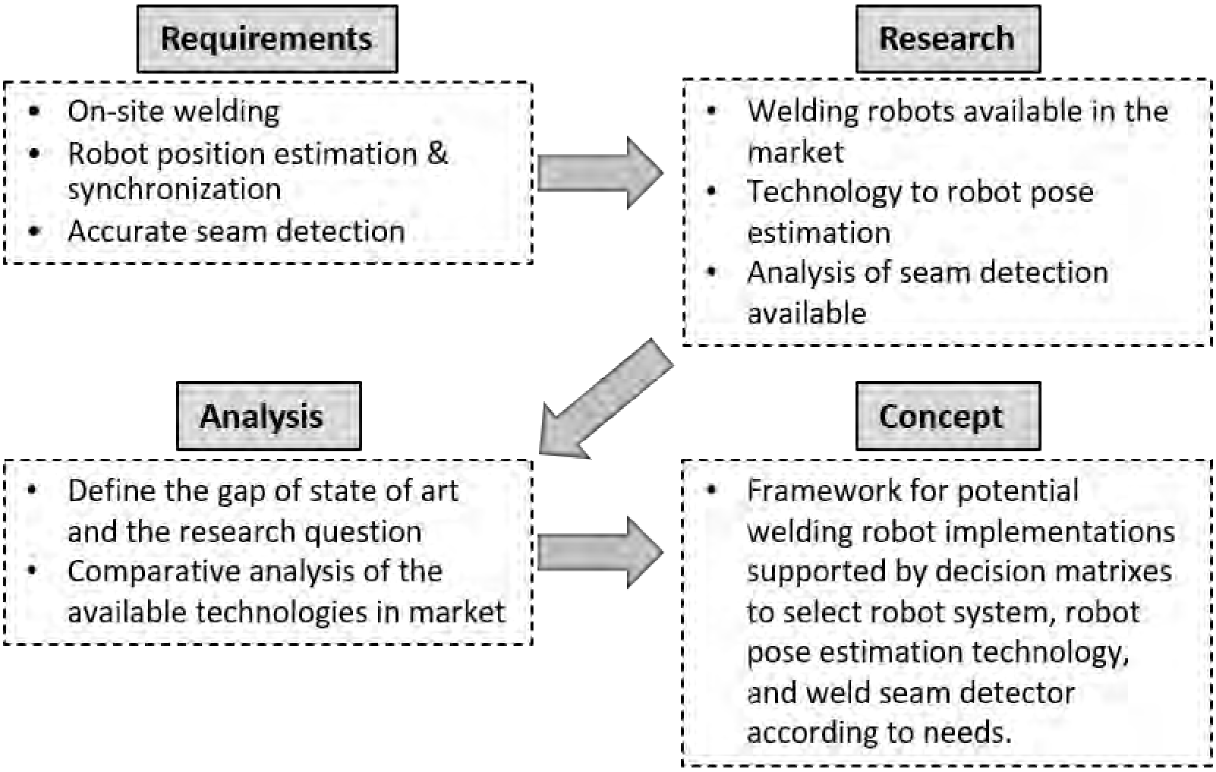

Figure 1: Structure of the paper methodology.

structured as follow (Figure 1): First, the subject is presented from an introduction of the general overview of the topic where the requirements and difficulties of this research are formulated. Then, state-of-the-art technologies will be conducted to explain the robotic system, after this, the technical data of different manufacturers will be presented, which will be the basis for the comparative analysis of the available products on the market. Next, a framework of application is presented, where the topics reviewed in the state of the art are related and categorized according of the possible needs in the implementation, followed by a discussion of the potentials and challenges faced by the proposal to be applied and finally conclusions and an overview that condenses the main ideas proposed in the paper with an outlook for future developments.

3. State of the art

3.1 Welding robots

Welding robots allow automation of this task that can be repetitive, difficult to execute depending on location and potentially dangerous for workers. For these activities there are currently different types of specialized robots categorized according to the phase of the project, the type of element to be welded or the location of the weld. Among the robots for pre-assembly there are: gantry cranes with one or multiple 6DOF manipulators, on-rail 6DOF manipulators, stand-alone 6DOF manipulators and other variations (Figure 2) [KUK17]; [ZEM21]; for on-site single-purpose welding robots there are beam robots and column robots; and for on-site multi-purpose welding there are a variety of options such as mobile platform with 6DOF manipulator [BOC16], and 6DOF manipulators on adaptable rail (Figure 3)

[INR21]. Currently, there are a wide variety of devices available for specific uses and payloads, as well as combinations of systems - gantry cranes for structural welding, rail lines for pipe welding and mobile platforms with 6DOF manipulators for non-structural elements - that enrich the adaptability according to the requirements and the specific context of the welding task.

This paper is focus on the 6DOF welding robots which are the more widespread and

Figure 2: Stand-alone 6DOF manipulator [KUK17]

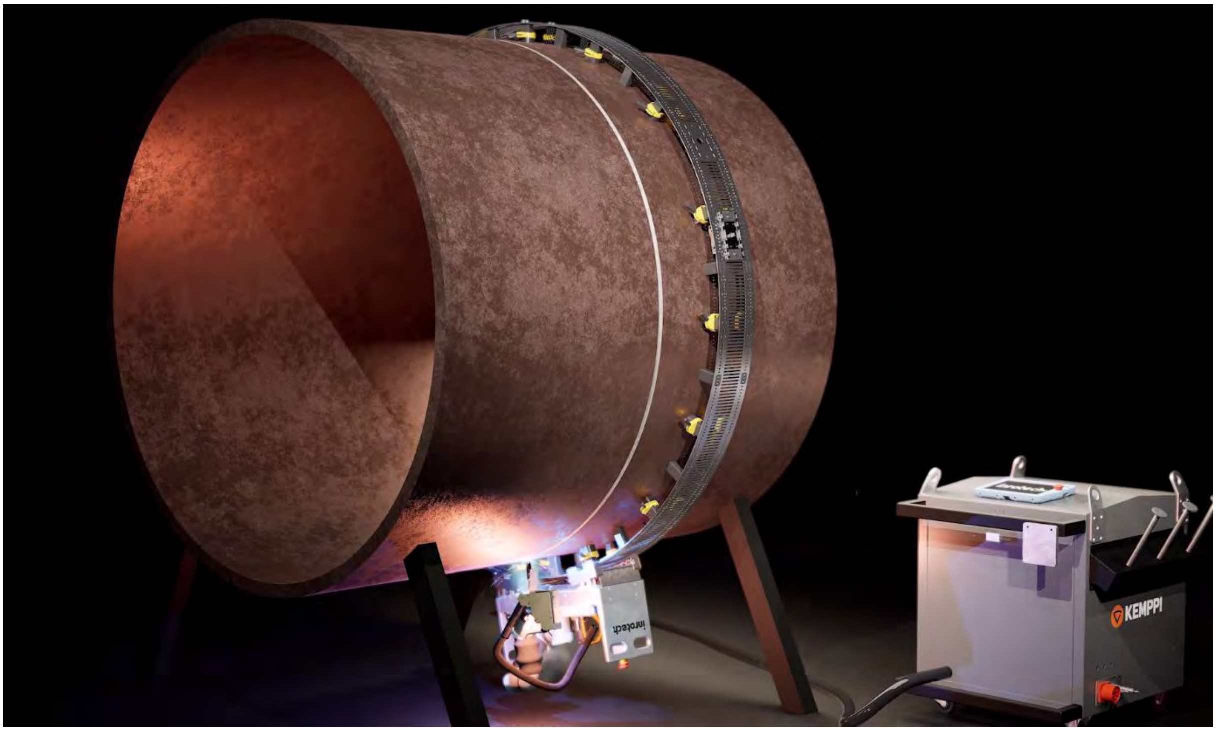

Figure 3: Welding robot on adaptable rail. [INR21]

available on the market due to their ability to adapt to different positions and lengths, parameters required for on-site welding. From the current market, more than 100 types of 6DOF welding robots from 10 well-known brands in the industry were analyzed in a comparison matrix (Figure 4), and the devices were compared with the parameters that can be crucial for their application on site, such as robot weight, maximum reach and pose repeatability. The weight of the robot was taken as a factor of analysis since this paper, being focused on on-site work, it is important to analyze its portability; the measure of maximum reach was taken as the distance from the robot base axis to the maximum distance in the horizontal plane, a parameter also standardized in the data sheets of the robots presented and that applied to on-site work is remarkable for its usefulness in reaching work areas that for a worker can be dangerous or difficult to access; Finally, the robots were categorized according to their precision with the parameter of pose repeatability according to ISO 9283 of Manipulating industrial robots - Performance criteria and related test methods [ISO98]. This accuracy factor was grouped into three categories for easy selection and visualization. The welding robot brands reviewed are: Kawasaki [KAW21], Hyundai [HYU21], Cloos [CLO21b], Yaskawa [YAS21], Fanuc [FAN21], Comau [COM21], Panasonic [PAN21], OTC Daihen [OTC21], ABB [ABB21], and KUKA [KUK20].

When analyzing the matrix presented, the following findings are evident: first, the concentration of products between the ranges of 700 mm - 1000 mm in max. reach, weight less than 100 kg and high precision with a repeatability index of less

Figure 4: Comparison matrix of welding robots on the market.

FANUC.
Ref. ARC Mate 50*i*D/7L.
Max. Reach: 911mm.
Weight: 27kg

PANASONIC.
Ref:TS-950.
Max. Reach: 971mm.
Weight: 56kg

Figure 5: Light robots with high repeatability pose.

than 0.06mm, which can be useful for welds of easy access but very high precision (Figure 5); second, the other concentration of products between 1400 mm - 2200 mm max. reach and weight between 130 - 300 kg with no marked tendency between the analyzed precision ranges, which can be applicable for a great diversity of welds with a medium reach and viable portability (Figure 6); third, above 400 kg there is a scattered group of robots that perform up to a maximum reach of 3300mm, however their implementation on site can be difficult due to their weight, although there are some products above 3000mm max. reach that have high precision and can be useful for more specific tasks that require these features, also due to their design for higher payloads, they can perform multiple task besides welding (Figure 7); and finally it is worth mentioning robots with a max. reach over 3000mm and under 550 kg., that can be use specially for height and long distance welding works (Figure 8).

HYUNDAI.
Ref. HA006B.
Max. Reach: 1425mm.
Weight: 145kg

ABB.
Ref. IRB 2600ID-8/2.00.
Max. Reach: 2000mm.
Weight: 276kg

Figure 6: Medium size robots and medium max. reach.

KUKA.
Ref. KR 20 R3100
Max. Reach: 3101mm.
Weight: 549kg

ABB.
Ref. IRB 6640-185/2.8Max.
Reach: 2800mm.
Weight: 1405kg

Figure 7: Heavy Multipurpose robots.

CLOOS.
Ref. QRH-390-E
Max. Reach: 3015mm.
Weight: 350kg

PANASONIC.
Ref. GIII-HH020L
Max. Reach: 3281mm.
Weight: 535kg

Figure 8: Long-range robots.

Robot Pose Estimation

Besides the physical features of the 6DOF welding robots, the robot pose is crucial for a proper execution of the task, unlike robots in factories where they are precisely calibrated, on-site robots must adapt to the environment, that is why the robot pose estimation is a key factor for a success welding in situ. The robot pose estimation is the automated calculation of

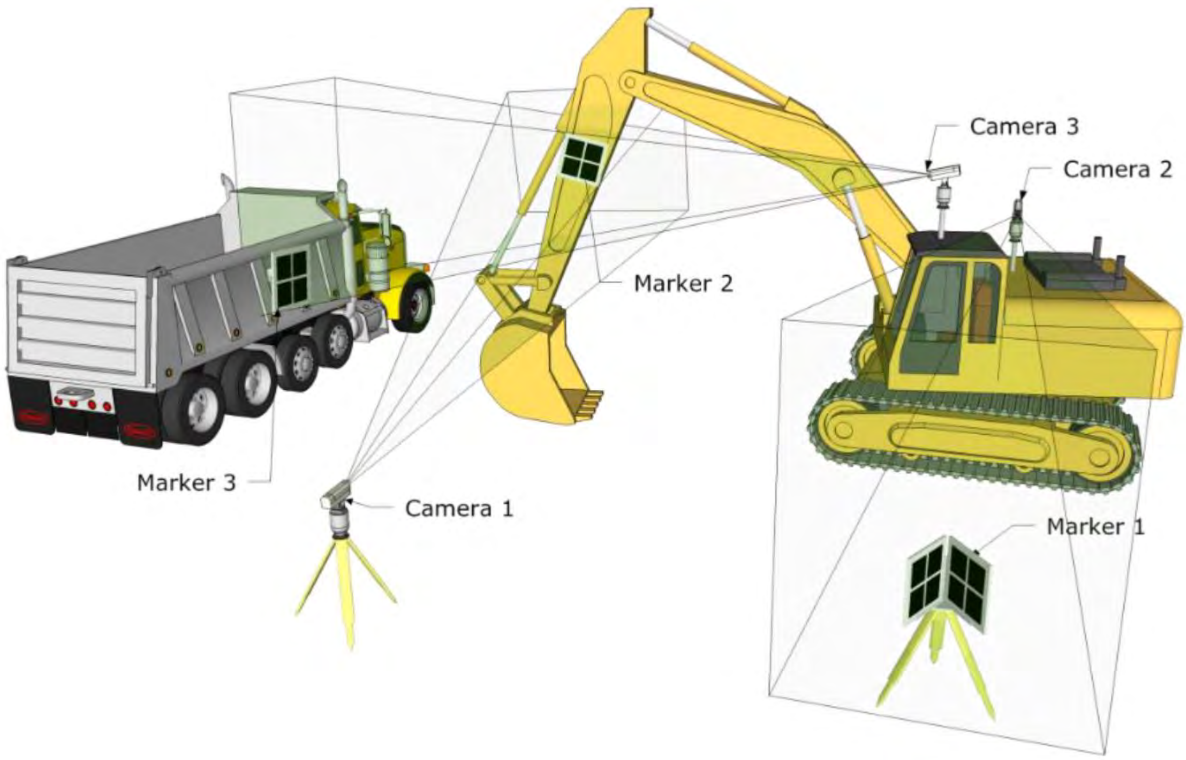

Figure 9: Camera marker networks applied on articulated machines on construction sites. [FEN18]

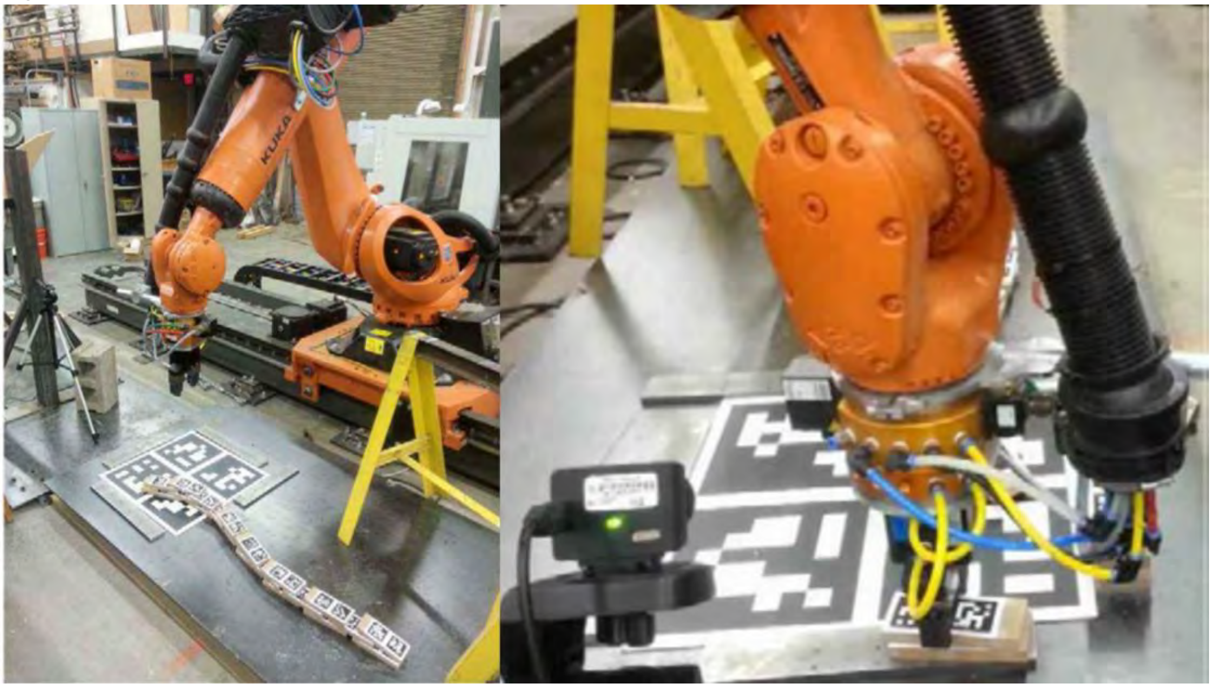

Figure 10: Robot pose estimation through on-robot camera and marker-based context. [FEN15]

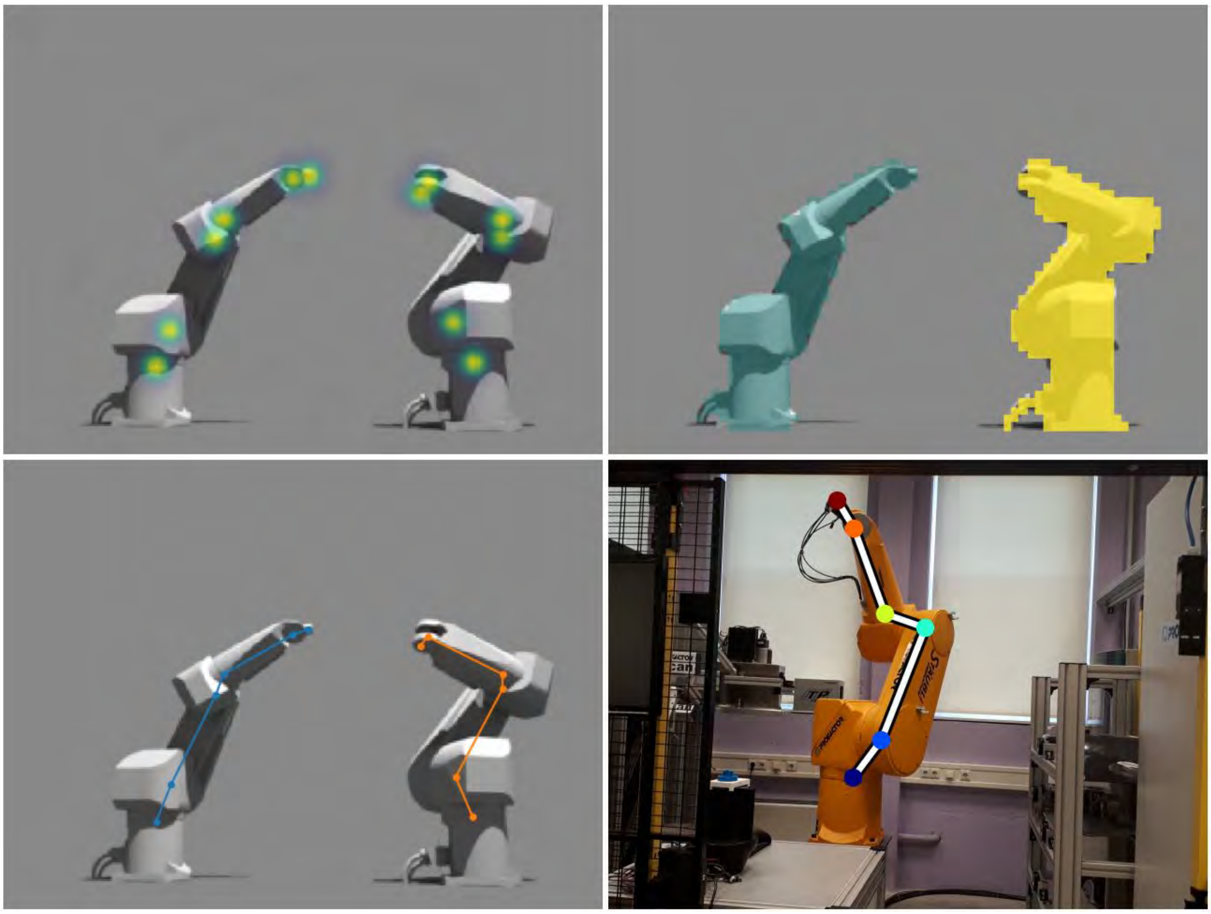

Figure 11: . 3D robot pose estimation from single shot [HEI19]

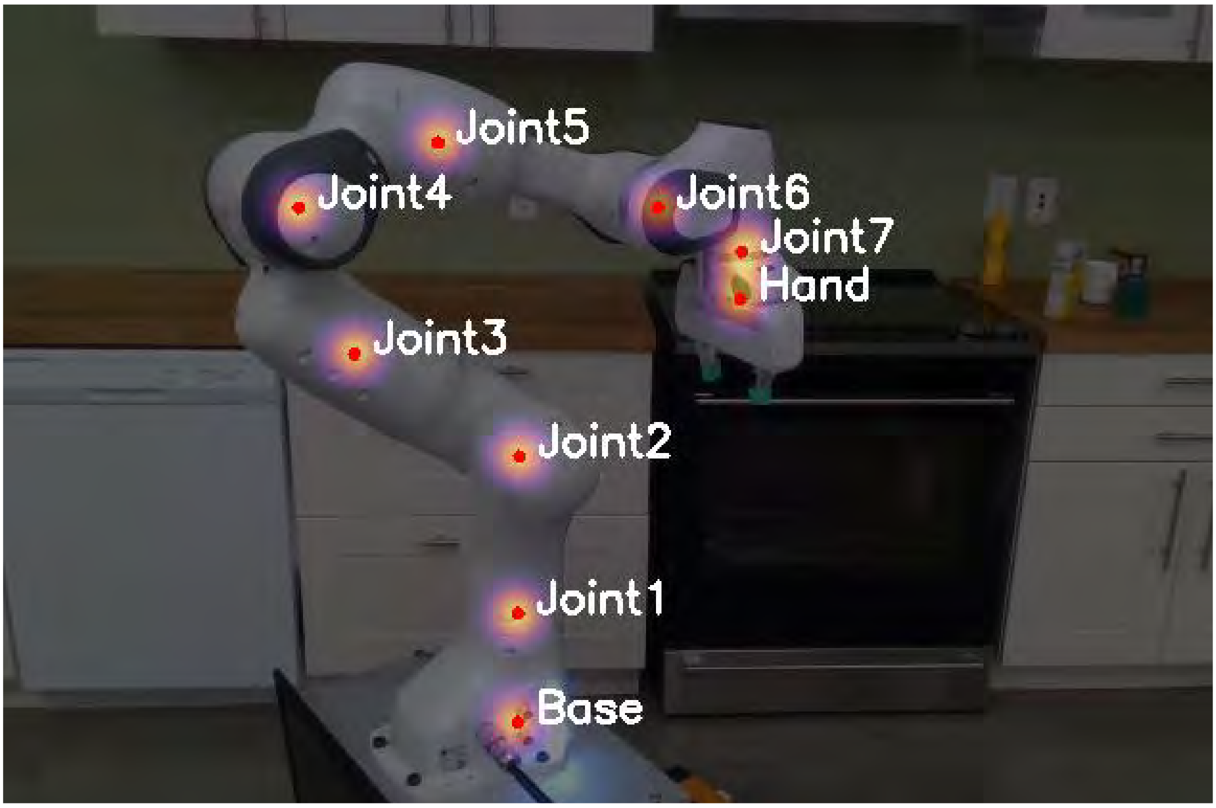

Figure 12: DNN technology applied on robot pose estimation [LEE19]

robot key points or nodes coordinates from an initial point to a goal point including its path, this with the objective of commanding the robot movements, executing the most efficient drive as well as avoiding potential collisions with elements of the environment. The robot pose estimation for unstructured environments can be done through different approaches such as capturing the context with cameras, sensors, or a combination of both. In addition to the location of these and possible use of refence markers.

For camera-based robot pose estimation with reference markers there are different research approaches. A first method to the pose estimation robot is given through marker networks and live capture of the environment with a stationary camera and using algorithms the pose estimation is modeled giving a range of accuracy at centimeter level for distances between the marker and the camera of up to 15 meters. [FEN18] (Figure 9). A second approach is pose estimation based on algorithms that use a single robot-mounted live-camera and visual marker-based metrology to quickly establish local reference frames and can also detect building elements by generating point clouds and building BIM models, the accuracy of this procedure is in the sub-centimeter range, thus effectively addressing challenges of the unstructured environment without requiring stationary devices. [FEN15] (Figure 10).

Moreover, in the research field of robot pose estimation there are several camera-based marker-less approaches. One of them is 3d robot pose estimation from 2d images, where a single shot of the environment is taken with a stationary camera, this approach is based on a trained data model that can estimate the location and segmentation of robot instances from the 2d image taken. It even identifies the location of the joints including the depth, however these models have shown that the error in the depth coordinate is in the range of 50mm. [HEI19](Figure 11). Additionally, a complementary research develops an added technology of a stacked hourglass network that is trained with databases collected from multiple poses in the laboratory improving accuracy to a precision level of around 40mm [LIA19]. Another approach is based on the same principles of a single shot of the stationary camera and no reference markers but additionally implements deep neural networks to calibrate the camera-to-robot pose instead of a hand-eye calibration and

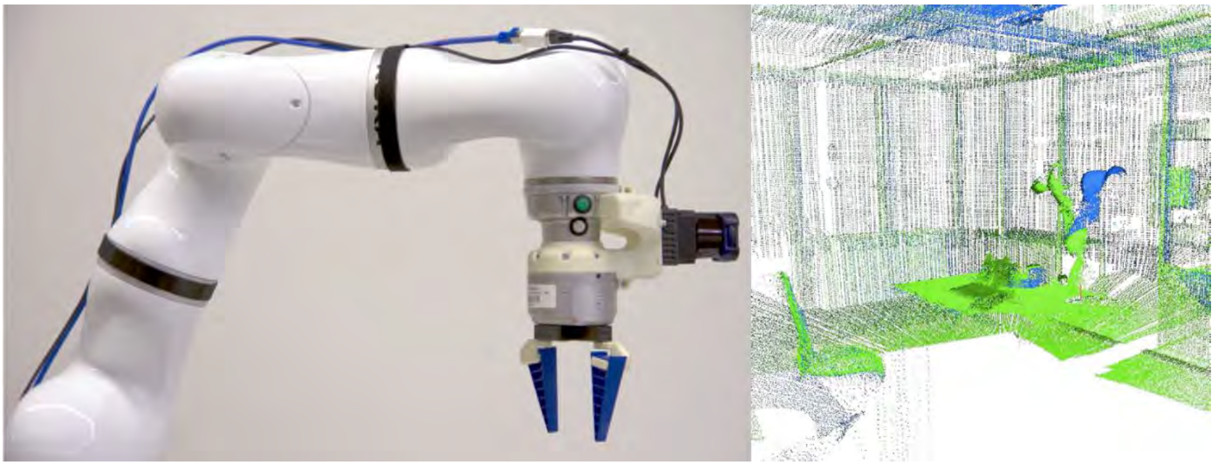

Figure 13: Robot pose-estimation based on a mounted LiDAR-sensor (left); cloud point created (right) [PET20]

according to the analyzed research has an average margin of error of 27.4mm, which can be further improved with multiple image shots [LEE19](Figure 12).

Besides to camera-based robot pose estimation, there are also proposals through the unique use of LiDAR sensors, the objective of this sensor-based system is to constantly recalibrate in situ the area where the robot is moving without requiring any other calibration device or external reference, this can be achieved by mounting the sensor at the end of the robot and it scans in unbuilt environment and adjusts its movement path. With this methodology the robot has an average accuracy range of 10.6mm. Additional features of this implementation include the ability to identify objects and grasp planning [PET20] (Figure 13).

There are also mixed camera and sensor-based solutions, one such approach is through the capture of key points with IMU sensors pre-installed on the robot joints to recognize locations, poses and movements and additionally using stationary or surveillance cameras to record pose history. By collecting historical data this technology improves the pose processes of both potential position calculation and danger zone detection through on-site training using recurrent neural network (RNN) algorithms with an accuracy of average percentage of correct key points (PCK) of 90.22%. [LUO21](Figure 14). Another approach to the combined use of camera and sensor to estimate the pose of the robot is based on the use of a stationary monochromatic camera and a LiDAR sensor, the camera has the function of identifying in its field of view the objects in the robot's environment, and the LiDAR sensor improves the calibration in the estimation of the coordinates of these elements necessary for the coordination of the final position and the path of the robot. The combination of these two techniques results in a type of real-time 3-D sensing of the environment, however it is susceptible to errors due to occlusion of either receiver. Pilot tests of this approach had results of between 90% and 100% accuracy comparing the reference model and the real-time execution. [MEH20]

There are specific cases where the worker needs to interact with the operation performed by the robot, this is intended to be achieved using virtual reality, unlike the approaches presented previously, the sensors and camera are located where the

Figure 14: Application of surveillance camera and IMU sensors for the pose estimation of articulated machines [LUO21]

Figure 15: VR application in the robot pose-estimation. User highlights possible collision (left). Robot finds new path (right)

worker is, also the worker interacts with the robot through VR glasses or hand-held devices, allowing greater flexibility for whoever supervises the task. The calibration of the instruments is automated thanks to the use of algorithms based on CNN methods, and does not require any manual adjustment for its operation; it uses as a form of intercommunication between the robot, the AR device and the data stored in cloud 5G communication networks, which allows high fidelity and speed of information transmission required for the robot pose estimation in real time. The accuracy tolerance given in controlled environment has been in the range of millimeters [LAM21] (Figure 15).

The comparison matrix (Figure 16) summarizes the different papers presented by the various robot pose estimation approaches. The technologies analyzed are grouped according to 3 types of parameters: the first is the type of environment receiver, which can be camera-based, sensor-based or combined, in addition to the subgroup of reference requirement: marker-based or marker-less; the second parameter is the location of these receivers, whether they are stationary, on-robot or on-worker; and the last parameter is the accuracy margin,

COMPARABLE MATRIX FOR ROBOT POSE ESTIMATION RESEARCH PAPERS			
RECEPTION DEVICE TYPE	PAPER	RECEPTION DEVICE LOCATION	ACCURACY (Error range)[1]
CAMERA	Camera marker networks for articulated machine pose estimation [FEN18]	Marker-based statinary camera	Centimeters
	3D Robot Pose Estimation from 2D Images [HEI19]	Marker-less stationary camera	50 mm
	Camera-to-Robot Pose Estimation from a Single Image [LEE19]		27,4mm
	A vision-based marker-less pose estimation system for articulated construction robots [LIA19]		40 mm
	Vision guided autonomous robotic assembly and as-built scanning on unstructured construction sites [FEN15]	Marker-based on-robot camera	Sub-centimeters
CAMERA AND SENSOR	Construction machine pose prediction considering historical motions and activity attributes using gated recurrent unit (GRU) [LUO21]	Marker-less stationary camera and marker-less on-robot sensor	90,22%
	Location and Vision Techniques to Control a KUKA KR6 R900 Six Robot Arm [MEH20]	Marker-less stationary camera and sensor	90% - 100%
	Towards commissioning, resilience and added value of Augmented Reality in robotics: Overcoming technical obstacles to industrial applicability [LAM21]	AR device (on-worker)	Milimeters
SENSOR	Extrinsic Calibration of an Eye-In-Hand 2D LiDAR Sensor in Unstructured Environments Using ICP [PET20]	Marker-less on-robot sensor	10,6mm

1. Some tolerances are not comparable due to scope or unit used to evaluate the approach.

Figure 16: Comparison matrix of robot pose estimation technologies.

however it is not entirely comparable due to the different emphases of each research. Although they are not analogous, they are sufficient for the robot positioning since the welding precision is given by the technologies of detection and tracking of the seams.

3.2 Detection and tracking of the welding seam

The welding process in most automotive factories as well as some other industries has been robotized, where the conventional "teaching and playback" mode is still playing the dominant role in the robot programming since the configuration and implementation of the robot is relatively simple using a few internal sensors to control the end effector [HON09], this method is reliable in mass production. However, this type of industrial robots lacks flexibility and cannot adapt the variation during the pre-programmed digital path. So, in order to implement more complicated welding tasks and make the welding robots more robust against the changes of the conditions for the automated process, the tracking seam is needed. Compared to the in-factory welding process, the on-site welding is more challenging because of the dynamic nature of the environment on the construction site and the unfeasible presetting path for the welding, so the detection and tracking of the seams are fundamental technology in the process success on-site.

During the automatic welding process, the welding quality can be ensured by precisely tracking the weld seam and

Figure 17: Manually place the weld wire into the joint(left) and teach the robot start from the proper position(right) [HUB21]

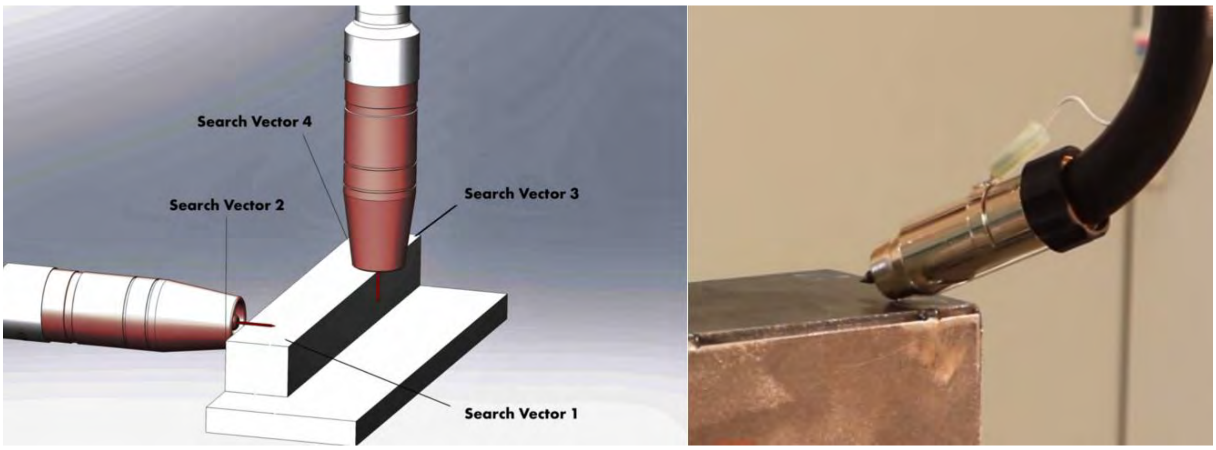

Figure 18: Wire touch sensing (left) and tactile nozzle touch sensing method (right) [HUB21]

adjusting the motion path of the welding torch in real time to align with the center of joint accordingly [XUE19]. Seam tracking has been a challenge in the welding industry for more than 30 years, it is still the subject of intense research in the field of automated and intelligent welding, this process requires two steps, the first one is to detect the starting point of the seam, and the second step is to guide the torch to track the seam while welding. For detecting the weld joint some of the solutions are the manual positioning, the touching sensing, and the laser vision sensing [ABI21].

For manual positioning, the operator needs to manually place the weld wire into the joint - this can be done by programming - to start from the proper position every time, which means the adaptability is not ideal when the welding parts or other working conditions change, as well as a consistent weld is required; one of the perks for this approach is that this method ignores the dirty surface obstacles (Figure 17). Touch sensing solution can be divided as nozzle touch sensing and wire touch sensing, the first one uses the gas nozzle and second uses the welding wire for joint detection, the principle behind these two methods is applying small amount of voltage to the gas nozzle or welding wire,

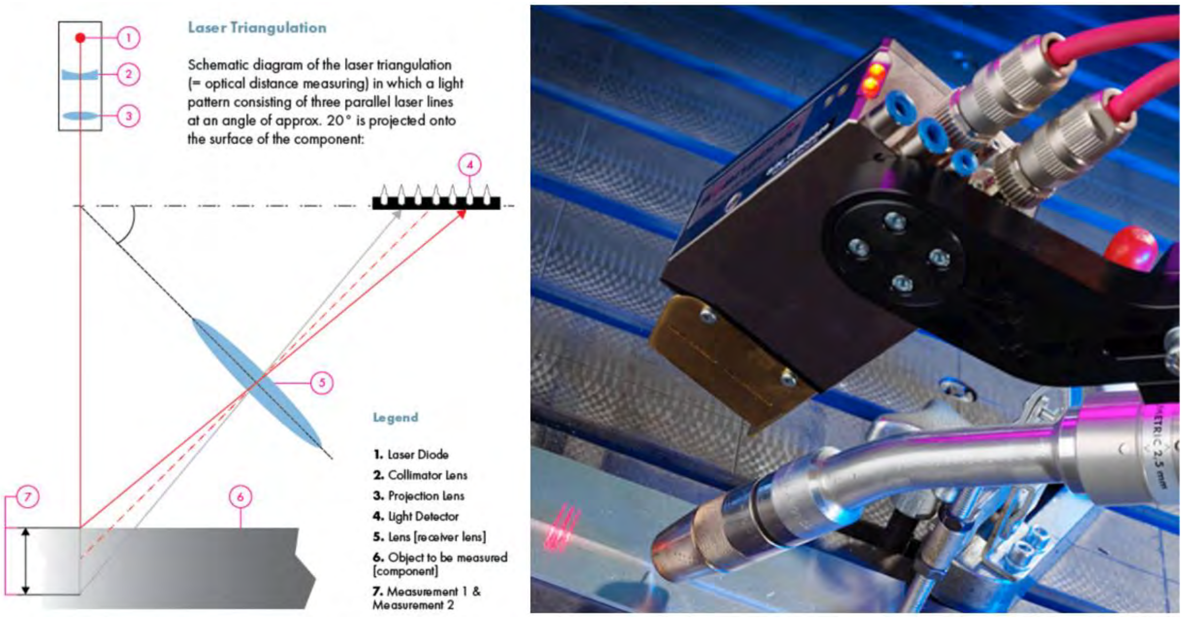

Figure 19: Laser sensing principle diagram (left) and optical seam tracking sensors (right) [HUB21]

FEATURES	Manual positioning	Touch sensing	Laser vision sensing
Adaptability to environment changes	No adaptability	Medium	Very good
Process speed(mm/min)	Slow	200~250	200~300
Ability to handle dirty material	Yes	No	Yes
Accuracy (mean error)	N.A.	±0.25mm	±0.24mm
Maintenance level required	None	Low	Medium
Weld joint applicable	Butt, lap, filet, V-groove	Lap, filet, V-groove	Butt, lap, filet, V-groove
Additional hardware required	No	Optional	Yes

Figure 20: Comparison chart for different joint finding methods [HUB21]

so when the nozzle or wire comes in contact with a welding part, a signal is sent to the robot and its position will be recorded to the data register (Figure 18). The laser sensing method use optical seam tracking sensors which consists of three parts: laser diode, CCD camera, and filter. During the welding process, the laser beam emitted from the diode is projected into the welding object, and the laser light will be diffusely reflected and captured by the CCD camera, the individual pixels are then filtered by the filter and the laser data will be processed by seam tracking controller to output information such as positions in X, Y, and Z directions, gap, mismatch, and angles, those information can be used to indicate what adjustments of robot motion path need to be made to accommodate the variation and errors (Figure 19), laser vision sensing method has the advantage of rich information acquisition and strong anti-interference ability, so it is one of the suitable automatic solutions for real time weld tracking robotic system.

Also, a comparison according to the criteria such as process speed and applicable weld joint types has been made (Figure 20). The data sources are ART-ST Seam Tracking Systems manual [ART19], A visual seam tracking system for robotic arc welding [XU08] and CLOOS manufacturer data sheet [CLO21a].

For tracking the joint three approaches are presented [ABI21]: the Tactile Probe with Automated Slides (TPAS), the Through the Arc Seam Tracking (TAST) and the 3D Laser Triangulation Seam Tracking with Robotics (3D-LTST). The working principle of TPAS method is using a probe that has been place d in the start point of the welding joint, during the welding process th e weld head will be led by the probe to move along the welding seam, the slide is semi-automated process and the joint normally need to be found by manual positioning by the operators (Figure 21). TAST method utilizes voltage variation or current changes induced from arc length change during the weaving of the torch and to indicate the torch to adjust its trajectory to keep it moving along the seam (Figure 22). The 3D-LTST seam tracking technology is based on the laser vision sensing technics, three laser beams are projected on the welding part and the reflected laser light will be captured by CMOS or CCD camera, then the pixels are then sorted by a filter and the laser data will be processed by seam tracking controller to output information about the seam tracking trajectory (Figure 23).

The table (Figure 24) compares the three seam tracking methods with respect to the accuracy, repeatability, process speed and ability to handle dirty material, the data source are ART-ST Seam Tracking Systems manual [ART19] and How Seam Tracking Solutions Compare [ABI21] as well as the experimental data from A visual seam tracking system for robotic arc welding [XU08] and CLOOS manufacturer data sheet [CLO21a].

According to the requirements of ISO 5817 the allowable tolerance and deviation for welds on steel and alloys are +/- 0.5 mm [ISO21], and investigations on the welding tolerance of stationary robots have given results between 0.387 - 0.429mm [ZHA21] and 0.28mm [ROU21] with different seam detection methods. Therefore, theoretically the deviation and tolerance of proposed framework will fulfill the acceptance level during the on-site fabrication process.

However, for on-site welding the seam tracking methods need to be more robust against noise due to the complicated

Figure 21: Tactile probe with automated slides [HUB21]

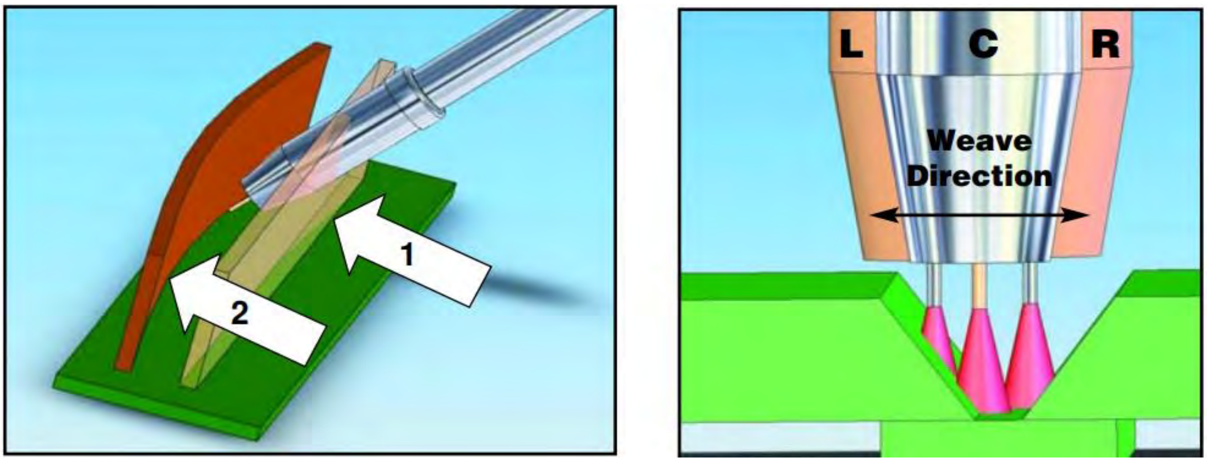

Figure 22: Through the arc seam tracking method [HUB21]

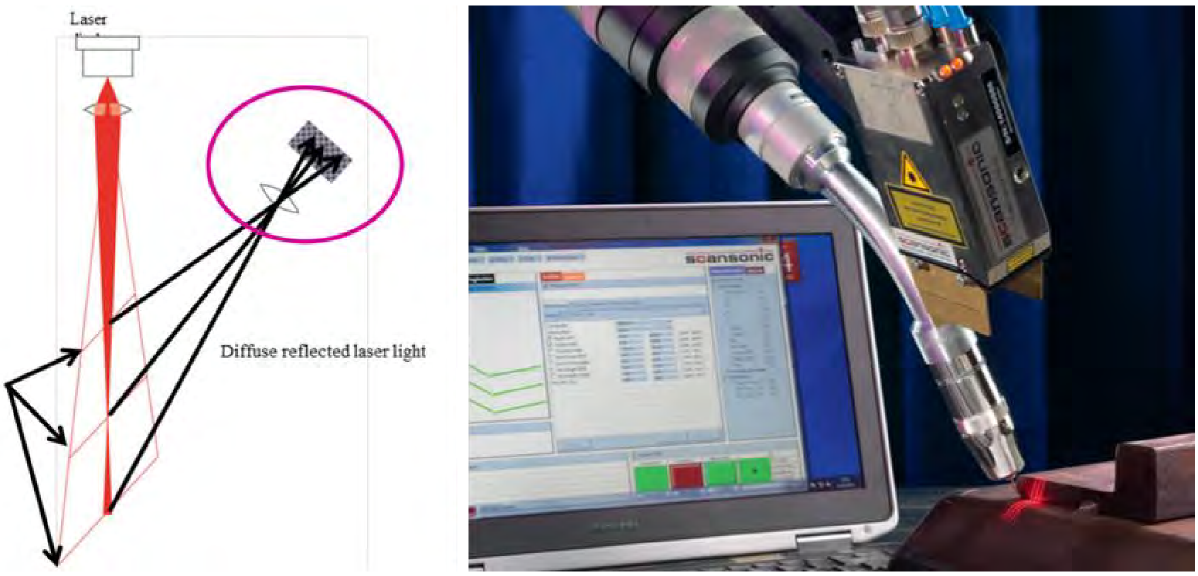

Figure 23: Through the arc seam tracking method [HUB21]

working environment, hence the Through the Arc Seam Tracking (TAST) and the 3D Laser Triangulation Seam Tracking (3D-LTST) are more suitable for on-site application.

For tracking the joint three approaches are presented [ABI21]: the Tactile Probe with Automated Slides (TPAS), the Through the Arc Seam Tracking (TAST) and the 3D Laser Triangulation Seam Tracking with Robotics (3D-LTST). The

FEATURES	TPAS	TAST	3D-LTST
Real time sensing	No	Yes	Yes
Ability to handle dirty material	No	No	Yes
Repeatability	Low	Medium	High
Process speed (mm/min)	200~250	890 ~1270	200~300

Figure 24: Seam tracking method comparison.

working principle of TPAS method is using a probe that has been placed in the start point of the welding joint, during the welding process the weld head will be led by the probe to move along the welding seam, the slide is semi-automated process and the joint normally need to be found by manual positioning by the operators (Figure 21). TAST method utilizes voltage variation or current changes induced from arc length change during the weaving of the torch and to indicate the torch to adjust its trajectory to keep it moving along the seam (Figure 22). The 3D-LTST seam tracking technology is based on the laser vision sensing technics, three laser beams are projected on the welding part and the reflected laser light will be captured by CMOS or CCD camera, then the pixels are then sorted by a filter and the laser data will be processed by seam tracking controller to output information about the seam tracking trajectory (Figure 23).

The table (Figure 24) compares the three seam tracking methods with respect to the accuracy, repeatability, process speed and ability to handle dirty material, the data source are ART-ST Seam Tracking Systems manual [ART19] and How Seam Tracking Solutions Compare [ABI21] as well as the experimental data from A visual seam tracking system for robotic arc welding [XU08] and CLOOS manufacturer data sheet [CLO21b].

According to the requirements of ISO 5817 the allowable tolerance and deviation for welds on steel and alloys are +/- 0.5 mm [ISO21], and investigations on the welding tolerance of stationary robots have given results between 0.387 - 0.429mm [ZHA21] and 0.28mm [ROU21] with different seam detection methods. Therefore, theoretically the deviation and tolerance of proposed framework will fulfill the acceptance level during the on-site fabrication process.

However, for on-site welding the seam tracking methods need to be more robust against noise due to the complicated working environment, hence the Through the Arc Seam Tracking (TAST) and the 3D Laser Triangulation Seam Tracking (3D-LTST) are more suitable for on-site application.

4. Framework

The framework presented aims to guide interested parties and decision-makers to select the right combination of technologies for an efficient implementation of automated welding on-site through the ideal selection of welding robots, robot pose estimation technology, and weld seam tracking sensors.

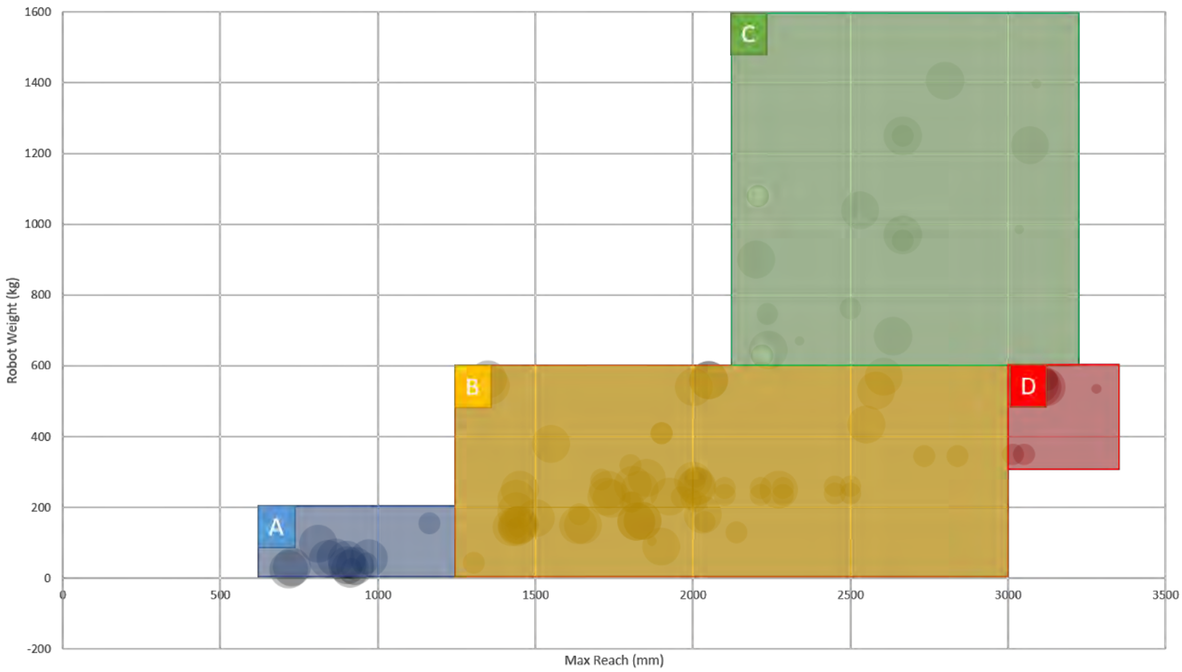

Figure 25: Categorization matrix of welding robots for decision support.

For the first part of the framework, a matrix of four welding robot categories is presented to supp ort the decision based on the features of the robot required (Figure 25). The first category is light weight robots (A) under 200kg, short range of reachability under the 1.20m and high precision with a repeatability pose of under 0.06mm. This group is focused on welding robots for precise tasks in small areas with short range. The second group is medium size robots (B) with a maximum of 600kg weight, a max reach length between the 1.20m to 3m, in this group the precision can vary among products and brands, but all are under 0.15mm in the repeatability pose measure. This group has the largest grouping of robots available in the market and serves for activities where the reach is medium with a permissible weight for transport. The third group corresponds to Heavy robots (C) over 600kg, long reachability from 2.20m up to 3.20m, and several precision variations all under 0.15mm. This group has limitations for its implementation on site due to its weight, however it can be feasible in some cases due to their high payload -variable not established in the scope of this paper- which allows them to be used for multiple tasks in addition to welding. The fourth group corresponds to long reachability robots (D), with a medium size between 300 - 600 Kg, maximum reach length of up to 3.30m with a repeatability pose under 0.15mm. This group is specialized for work at heights and long lengths in the horizontal plane with an admissible weight for transport within the construction site.

For the second part of the framework another decision matrix is presented where 7 categories are established that group the types of technology for the robot pose estimation (Figure 26). The first category (I) is based on marker-based stationary camera, its use can be implemented with reference markers in the capture area of the camera for the spatial positioning of the robot, this requires sufficient area for the location of the camera as well as access to the work surface for the location of the markers. The second category (II) is based on marker-less stationary camera where sufficient area is also required for camera placement but does not require access to the work surface for reference marker placement. The third category (III) is posing estimation based on a camera mounted on the robot and with reference markers, this approach can be implemented for spaces of reduced area but with accessible welding surfaces for the worker to locate the markers.

The fourth category (IV) corresponds to the use of a stationary or surveillance camera and the placement of IMU sensors on the robot joints to increase the accuracy of the robot location in 3 dimensions, this application requires a sufficient afferent working area for the stationary camera, however it is not required that the worker has access to the surface to be welded since there is no need to install reference markers. The fifth category (V) is based on the combined use of marker-less camera and LiDAR sensor in a stationary position, especially for applications where safety distance between the receivers and the robot is required.

The sixth category (VI) is based on the unique use of LiDAR sensor for the generation of point clouds that support the robot pose estimation algorithm, recreating the 3D space and thus identifying potential collisions and the best path between start and goal position; this technology is ideal for reduced working areas and without safe access to the surface to be welded, however it requires a higher computational power. The seventh and last category (VII) is based on the use of augmented reality through head-mounted or hand-held devices controlled by the worker, who supervises and warns the robot of possible collisions, this approach differs from the previous ones since the VR device has integrated both camera and LiDAR sensor but does not require the worker to be in a single position, so it can move at convenience to optimize the recognition of the unstructured environment, the

		SENSOR AND/OR CAMERA LOCATION				
		STATIONARY		ON-ROBOT		ON-WORKER (AR)
Requires large work area?		YES		NO		YES
		Marker-based	Marker-less	Marker-based	Marker-less	Marker-less
Requires worker access to the surface to be welded?		YES	NO	YES	NO	NO
TYPE OF RECEPTOR	CAMERA	I	II	III		
	CAMERA AND SENSOR		IV	IV		VII
			V			
	SENSOR				VI	

Figure 26: Decision matrix of robot pose estimation.

STEPS			Seam tracking technology	Short delivery time	High surface quality required	High precision required	Dynamic environment
1	Start and end point detection	a	Manual positioning	No	Yes	Yes	No
		b	Touch sensing	No	No	No	No
		c	Laser vision sensing	Yes	Yes	Yes	Yes
2	Joint tracking in real time	x	TPAS	Yes	No	No	No
		y	TAST	Yes	No	Yes	No
		z	3D-LTST	Yes	Yes	Yes	Yes

Figure 27: Decision matrix of weld seam detection and tracking.

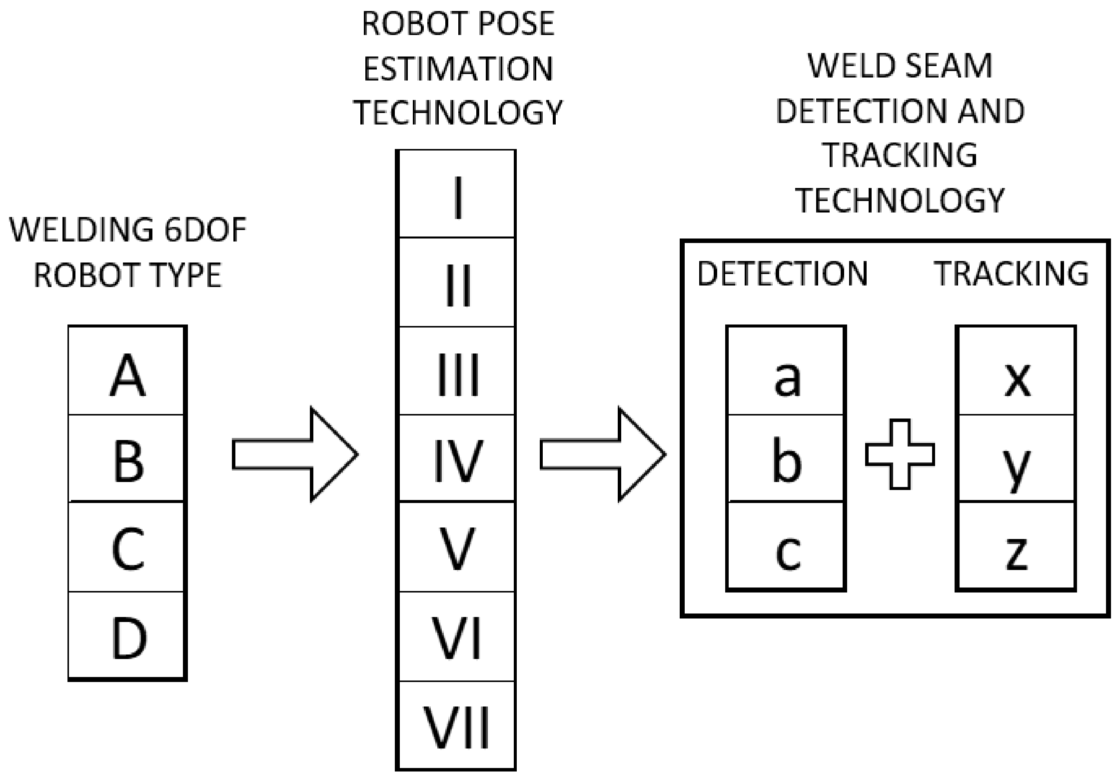

Figure 28: Framework summary flowchart.

challenge of its application in the requirement of high-speed networks such as 5G for data transmission.

The third part of the framework corresponds to the selection of seam tracking technologies (Figure 27), one for the starting and ending position detection and other for the seam tracking to guide the robotic motion in real time. As presented in the state-of-the-art, for the joint detection there are 3 commonly used methods: manual positioning of the welding wire into the joint, using wire or touch nozzle for touch sensing and laser vision sensing. Since this framework is used for construction on-site welding application, meaning that the joint detection and seam tracking technology must satisfying some criteria such as the adaptability to dynamic and changing working environment and maintain a good surface quality during the welding process, as well as the productivity and the accuracy of the seam detection and tracking in real-time.

As summary, the framework covers 3 aspects for the selection of technologies to implement an on-site welding robot (Figure 28). These aspects are the welding robot type, the robot pose estimation and the weld seam detection and tracking technologies.

5. Discussion

Upon completion of this whole literature research, the cutting-edge solutions in automatic welding technology have been delved into, the relevant data has been analyzed and the result has been presented along with an automatic welding framework which can be used in the on-site construction work application. Since the data and references presented in this research paper are mainly from recent experimental, as well as some datasheet or user manual of the newest products from well-known international manufacturing companies, the use of the complied data is reliable and time effective.

Based on the research and data analysis results, a first approach framework has been presented. The framework is addressing the most critical question in this research paper, which is how to compare and evaluate the selections of the different systems and technologies, namely the welding robots, robot pose estimation technology, and weld seam tracking sensors, based on the research we have done. The objective of this framework is to support the final decision of stakeholder about the feasibility of implement on-site welding robots as well as the right combination of technologies to realize it based on the theoretical research and data analysis results.

According to our framework, the on-site construction welding robotic system in this research is feasible and the optimal technologies combination can be chosen by the decision makers based on their specific applications or needs, this research can be used as a reference for the selection of techniques and welding systems. However, there are some considerations when challenging the framework:

1) When the different robotic systems and seam tracking technologies area compared, the compatibility between specific products is not considered, it means that some combination of punctual features may not be practically applicable.

2) The selected criteria for comparing different technologies are probably not able to fully support the final decision of the stakeholder due to the defined scope of this paper. In this research there are topics not covered that involves the robot application such as: the robot transportation method, complementary devices, the computer power requirements, and data processing technology.

3) The data used in the decision matrix of the framework are collected from different sources of research and company datasheets, so the difference in the research methodologies may cause the deviation of the data comparison results.

One of the possible applications of this proposed robotic welding framework can be exemplified as follows: steel panels on high-rise building façade are going to be installed, so a long-range robot (D) is mounted on a crane to execute the task. Since there is not enough area on the crane for a worker, a marker-less sensor mounted on the robot is needed for the pose estimation (VI). Once the welding robot reach the proper initial state, due to de heights a seam detecting and tracking system for dynamic environments is required (c+z). Afterwards, the sensor begins to detect the welding seam and sends instructions for the welding torch to execute the welding task. For most of the aerial and aloft construction work performed by human workers on site, the welding operation is extremely difficult since the lifting platform or lifting equipment is not always stable and provide sufficient working area, which creates additional hazards and operational limitations for the on-site welding works, the presented robotic welding system framework could be used as an alternative for such a construction process and make the on-site construction work more safe and efficient.

6. Conclusion and Outlook

This paper identified the lack of welding automation in unstructured contexts such as construction sites due to their changing and heterogeneous environments, so a framework was proposed to support the decision-making process of stakeholders who want to implement welding robots on-site. In order to propose this framework, first the state of the art of three related technologies was investigated, namely welding robots, robot pose estimation, and weld seam detection and tracking. These technologies were then categorized by groups according to advantages, disadvantages, and possible applications, thus giving the decision matrices that compose this framework. Subsequently, this approach was discussed according to its potential features as well as possible implementation challenges. This paper serves as a foundation towards more task-specific frameworks in the field of on-site welding robots, and even has the potential to be used as a basis for the specific construction of welding robots for unstructured environments.

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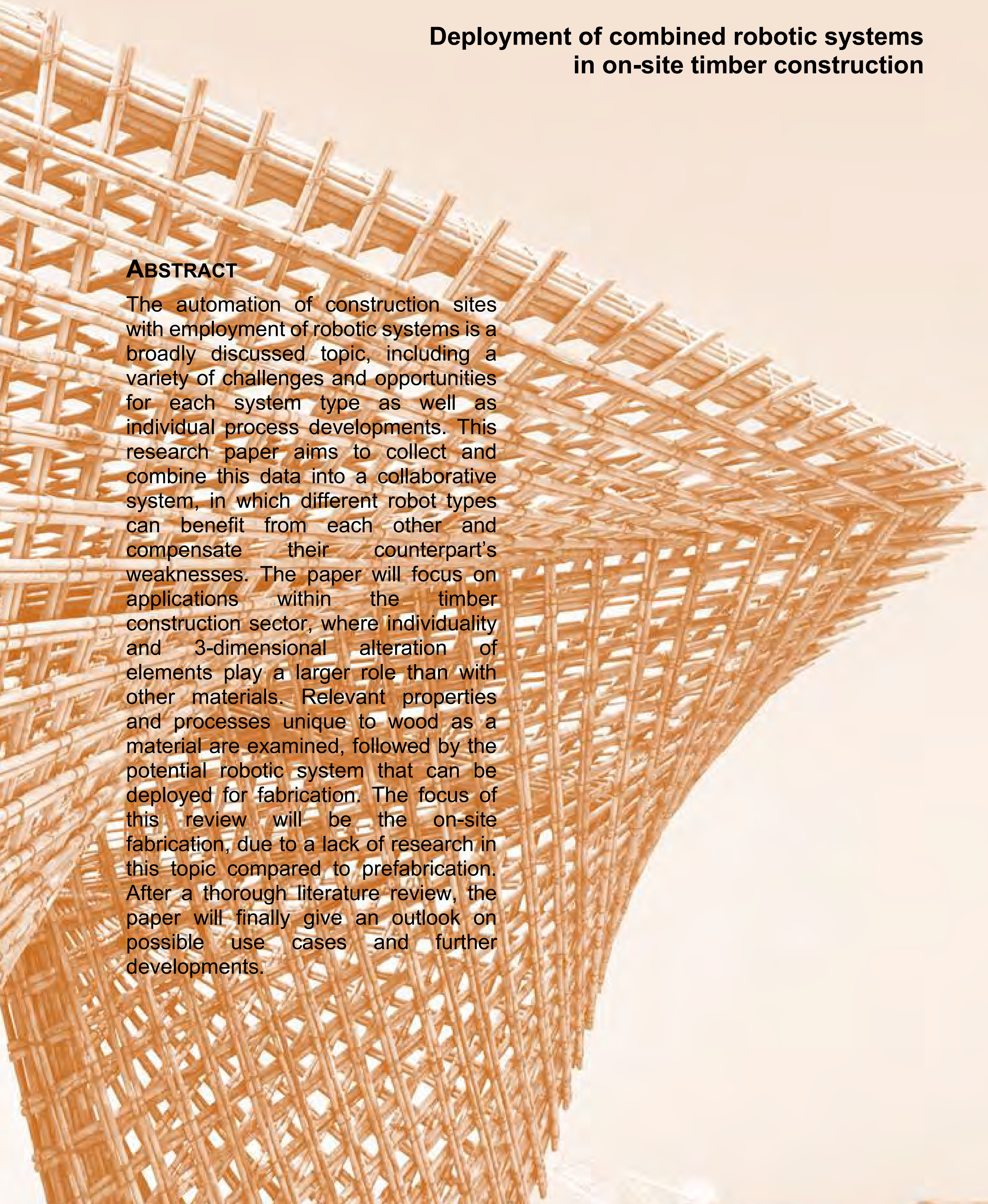
Deployment of combined robotic systems in on-site timber construction



Abstract

The automation of construction sites with employment of robotic systems is a broadly discussed topic, including a variety of challenges and opportunities for each system type as well as individual process developments. This research paper aims to collect and combine this data into a collaborative system, in which different robot types can benefit from each other and compensate their counterpart's weaknesses. The paper will focus on applications within the timber construction sector, where individuality and 3-dimensional alteration of elements play a larger role than with other materials. Relevant properties and processes unique to wood as a material are examined, followed by the potential robotic system that can be deployed for fabrication. The focus of this review will be the on-site fabrication, due to a lack of research in this topic compared to prefabrication. After a thorough literature review, the paper will finally give an outlook on possible use cases and further developments.

1. Introduction

In construction, shifts towards automation are getting more advanced with various processes being executed by different robotic systems, partly experimental but especially in pre-manufacturing already as the default system. In contrast to this, robot implementation is more complex to initiate and maintain on the construction site, as each system has limitations compared to human workers, that leave aspects like speed, precision, or mobility decreased, deflating the demand for change. While such disadvantages of robotic systems are generally known, reducing those negative impacts might not be focus point, as automation developments of construction sites are still at the beginning and implementation itself often is enough success for first projects.

In the following paper, collaboration techniques of different robotic systems are discussed and examined on their functionality in on-site timber construction. This will include the relationship between gantry and articulated robots, their individual and combined qualities, and the employment capabilities in the construction environment. Following, the developments in the sector of timber construction will be explored, including steps towards efficiency and on-site processes in modification and assembly. In summary, our research revolves around these questions:

- On which processes in timber construction can gantry and articulated robots work together?

- How can collaboration of different robotic systems work with and benefit from the unique structural properties

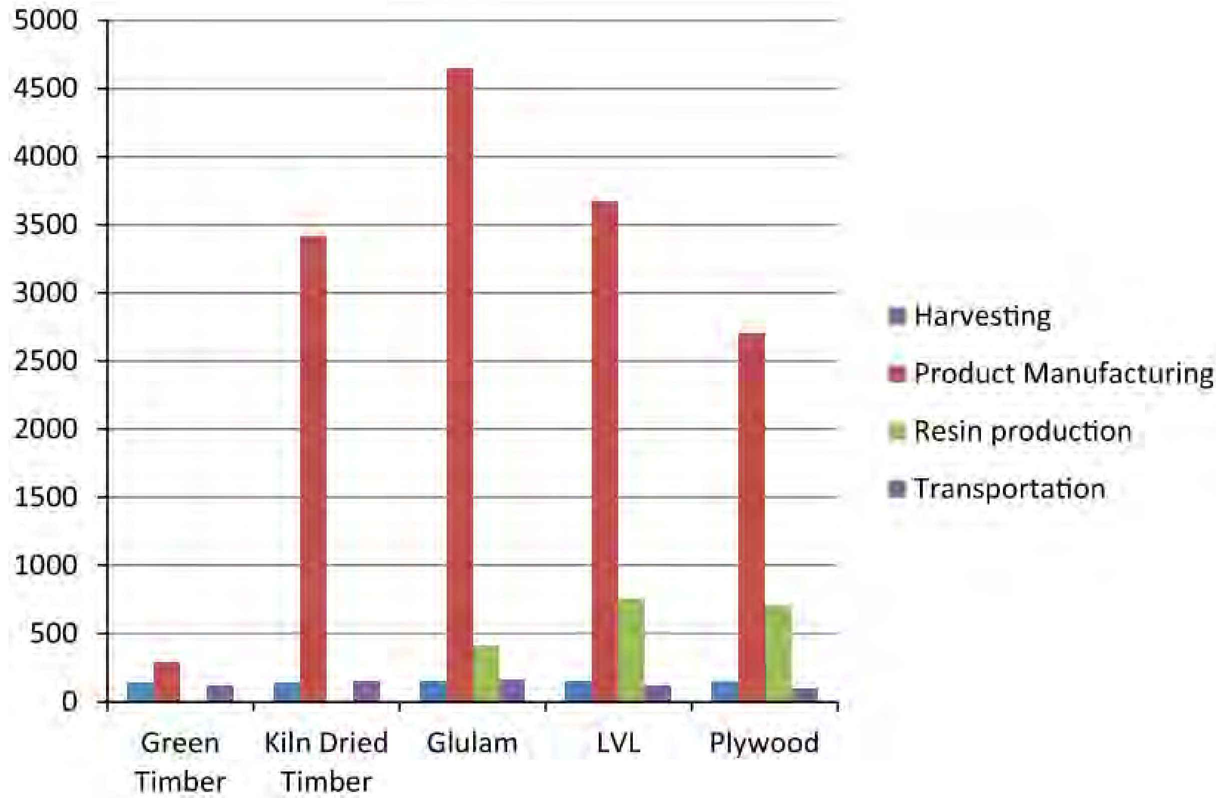


Figure 1: Typical embodied energy of construction timber products [RAM17]

of wood?

- How is the system combination calibrated when deployed on the construction site?
- How can deployment of combined robotic systems improve on-site timber construction?

After collecting and analysing information from both timber and various robotic systems, the benefits of those components on each other will then be analysed by a defined set of parameters. The results of the analysis will then be discussed and reviewed to formulate a proposal for possible use-cases.

With timber as a regenerative and in large quantities available construction material, it is of increased importance to the industry, both ecologically and economically [NAT02]. As building elements made from solid wood are limited in size and shape by the trees, a new robotic system is needed to cater for the unique properties of timber. To further evolve from the basic implementation of a single system, the opportunity to benefit from a collaboration seems promising in flaw elimination and productivity increases. The goal is to develop a concept and evaluate its capabilities in improving the overall system's reliability and precision in the challenges of changing on-site environment and tasks. The on-site fabrication becomes a focus point to reduce unnecessary transportation steps and thereby ecological footprints.

2. State of the Art

For a timber structure to be built, the wood must pass through several steps before it becomes part of a building. After harvesting it is first dried and transported to a sawmill to create planks and boards. These steps are relatively inefficient steps, as drying accounts for most of the energy consumption within the process chain, as seen in Figure 1, and the dimensional processing returns only around 50% of the round-wood as a viable building product, as seen in Figure 2 [RAM17]. While by-products can be further used, the material value decreases and energy recovery processes release carbon through burning.

The sawn pieces are then graded and optionally engineered to more developed timber products like Glulam. Modern timber is largely pre-manufactured to archive more precision in parts and a faster assembly process on site through reduced geometry deviations. The prefabricated timber products are then transported further to the construction site, where they can be assembled and if not done previously, protected against external influences.

Recent developments on more efficient process steps include the use of green round-wood as structural elements, eliminating the need for drying due to the round section, that can keep the wood from deforming during the use period [RAM17]. Possible automation steps for such elements are displayed in the Wood Chip Barn [DES16], where forked trusses are assembled in an optimized order to compose a load bearing arc, as seen in Figure 3. In wood grading, automation technologies like the use of ultrasound are being implemented for two decades already [RGP18] while timber engineering can be further improved through fiber reinforcement [TEI15] and joinery techniques are expanded to welding of

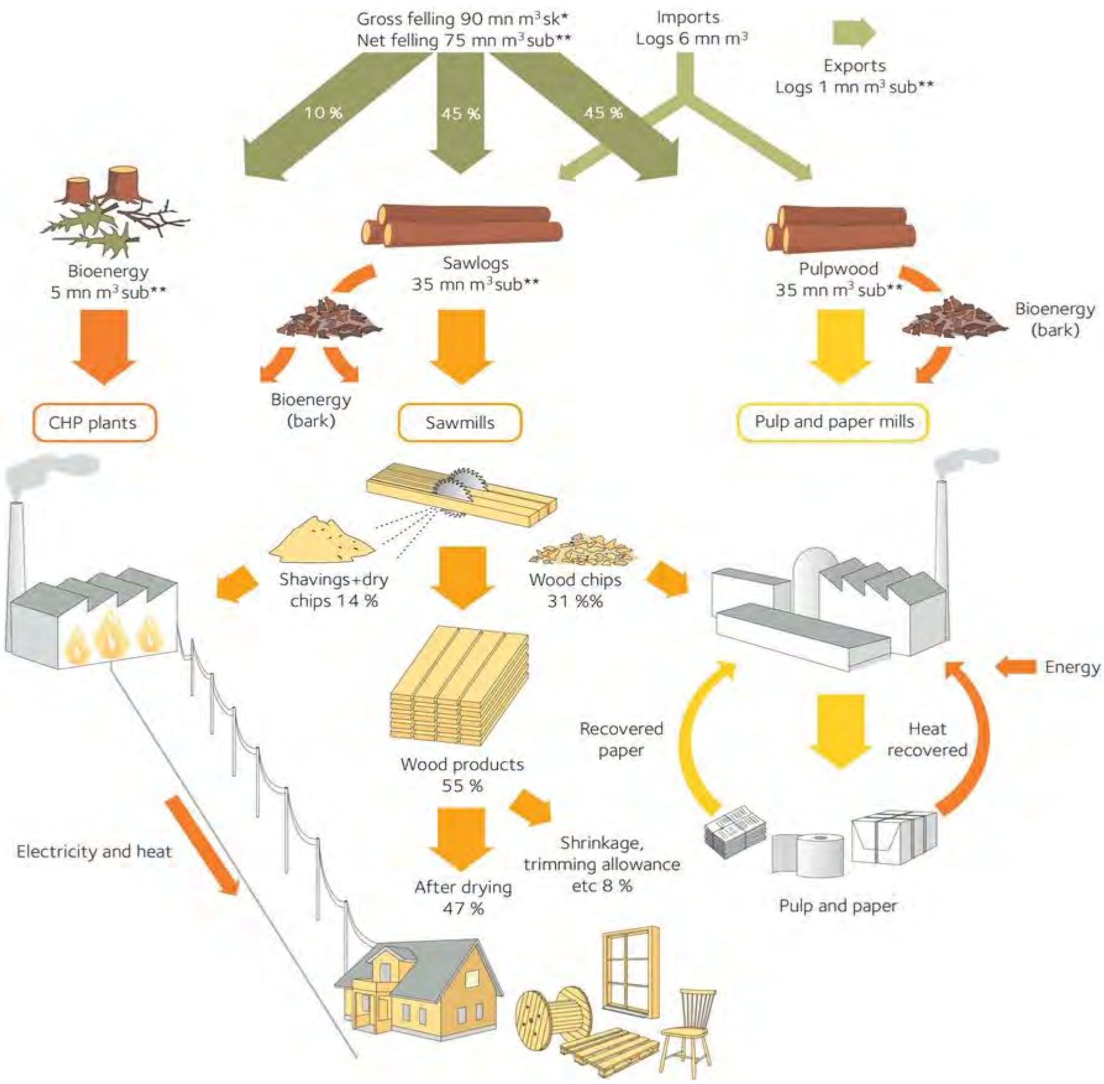


Figure 2: Wood utilisation 2018 [FRI21]

wood [HVS14]. Implementing robotics in construction has been at topic for some years. Various resources and techniques have been applied within construction to automate different on-site processes. For example, the BROKK robot has been utilized in demolition processes. Besides that, efforts have been put into research to increase the accuracy and the calibration ability of the robot [DZC20]. A gantry robot has also been deployed for reinforcement positioning [BOC07].

The general idea of having a robotics on-site wood construction can be found in the BUGA wood pavilion project [MK19]. The project uses two articulated robotic arms along with a turntable, all fastened onto a platform to counter uneven flooring issues, common to construction sites [WAK20]. Another research study negates the issue of uneven footing by introducing haptic feedback. The robot can calculate the deviation between the haptic fiducial and pre-calibrated position, which is then automatically updated to correct its position during the cutting process. This robot is also capable of assisting in assembling, enabling a semi-autonomous process [DSB19].

A prefabrication process of wooden

Figure 3: Wood Chip Barn [DES16]

doors utilized both articulated and gantry robot, along with the help of a conveyor belt [NIC18]. However, robotic system development that are designed to be deployed directly in the construction site is still rather uncommon due to the hectic environment of a construction site.

Articulated robots are mostly used in a more controlled environment, however, with the addition of a linear railway or mobile base, it is possible to increase its working range. To perform more complex tasks, it is not uncommon to have a collaboration of different robotic systems.

Figure 4: Flexible and transportable robotic timber construction platform [WAK20]

system	Transport-ability	movement volume	use	restriction
articulated	heavy, but one part	sphere	varying heavy duty tasks (welding, lifting etc.)	dedicated robot control system
humanoid	heavy, but one part	free up to certain height	individual, sensor reliant tasks, slow	slow
delta	fragile	contact lens	industrial/ factory use, pick and place	load restriction
SCARA	one part	donut	assembly and packaging	rigid z-axis
gantry	deconstruct	box	sealing, 3d printing, CNC	space requirements
wheel driven platform	one part	terrain surface	transportation	reliant on sensors
rope system	deconstruct	one to three dimensional	maintenance along narrow paths [windmill]	reliant on rope tension
drone	one part	free, but obstacle sensitive	hard to reach environments	precision

Figure 5: Overview of site applicable robotic systems based on [PLA21]

Figure 6: Adaptive Haptically Informed Assembly with Mobile Robots in Unstructured Environments [DSB19]

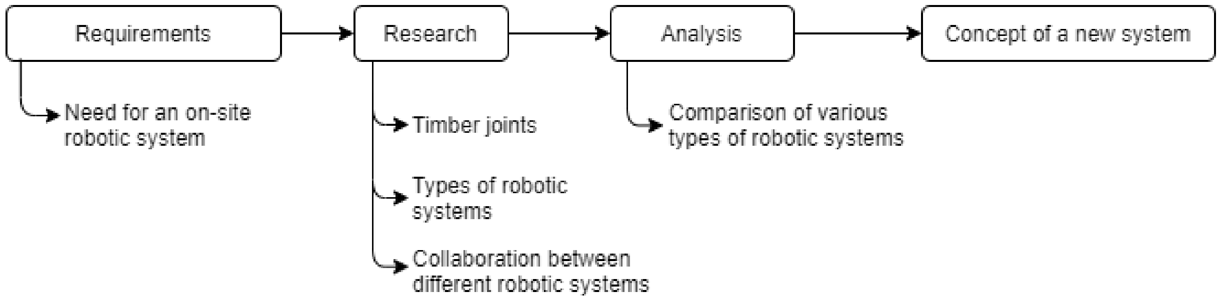


Figure 7: Methodology diagram

As of the time of this research paper is done, there is a lack of combined on-site timber construction robotic systems. The possibility and advantages of employing different robotic systems for timber construction is discussed in depth in this paper.

3. Methods of Analysis

To assess current developments and processes as objectively as possible, advantages and drawbacks of the existing processes of pre-manufacturing and manual labor are first laid out as a basis for the examination of literature on new developments. Here, reasons for current hesitations to move to automated on-site processes and challenges that might be solvable by robotic applications are given. Building on this, the paper will discuss the collected literature on general trends and interests, with examples and new processes being analysed on their applicability in common construction processes, economically sustainable projects, and general feasibility. Lastly, improvement opportunities and challenges of on-site automation in timber construction are discussed before drawing connections to our research goals.

4. Results

4.1 Requirements

To define necessary requirements on the realization of the system, task capabilities need to be set first. Our use-case proposal aims for a system, that could shape, prepare, and assemble the joinery of wood pieces in both round-wood and cut timber for individual or non-perpendicular structures. In execution, we plan for the articulated robots to carry individual timber elements, either together for added stability or one per arm to join pieces together. In this format, the gantry system would be responsible for a set of tools that must be interchangeable, with some common tools like a mill or drill but also devices to apply and remove glue, place screws and so on. The gantry system also needs an installation for tool changing. The robotic arm only has to be equipped with gripping devices large enough to hold elements stable and with.

This collaboration system proposal is suitable for automated wood joining. The endless possibilities of wood joinery technique are made possible with the high degree of freedom and accuracy of the articulated arms to hold the pieces in place, which is then fastened with any means such as glue or nail gun that is attached to the gantry robot.

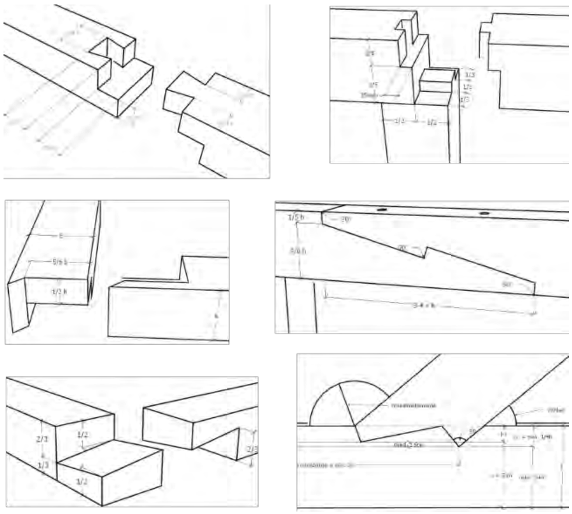


Figure 8: Basic Timber Joints [SCH21]

4.2 Research

Following the definition of required properties for tasks and environment, we propose a concept of robotic collaboration in timber construction automation. The system includes a gantry robot as the base, to which an articulated robot can be added to combine the flexibility and freedom of a robotic arm with the area of reach of a gantry system, that can additionally provide stability and orientation, as seen in Figure 9 to Figure 11.

In this exemplary use-case, a KUKA QUANTEC nano with a maximum payload of 180kg could be chosen due to its compactness and small weight, which benefits transportation procedures. It also has a digital motion mode that allows continuous path motion with higher accuracy and precision, which is especially useful for more complex geometries. It is designed to be used in foundry environment, which means is it highly water and heat resistant which again is favorable in a construction site due its subjectivity to weather.

As for the gantry system, high precision and weight determine the choice. Aluminium extrusions have an extremely high strength to weight ratio, depending on the profile. This profile structure also

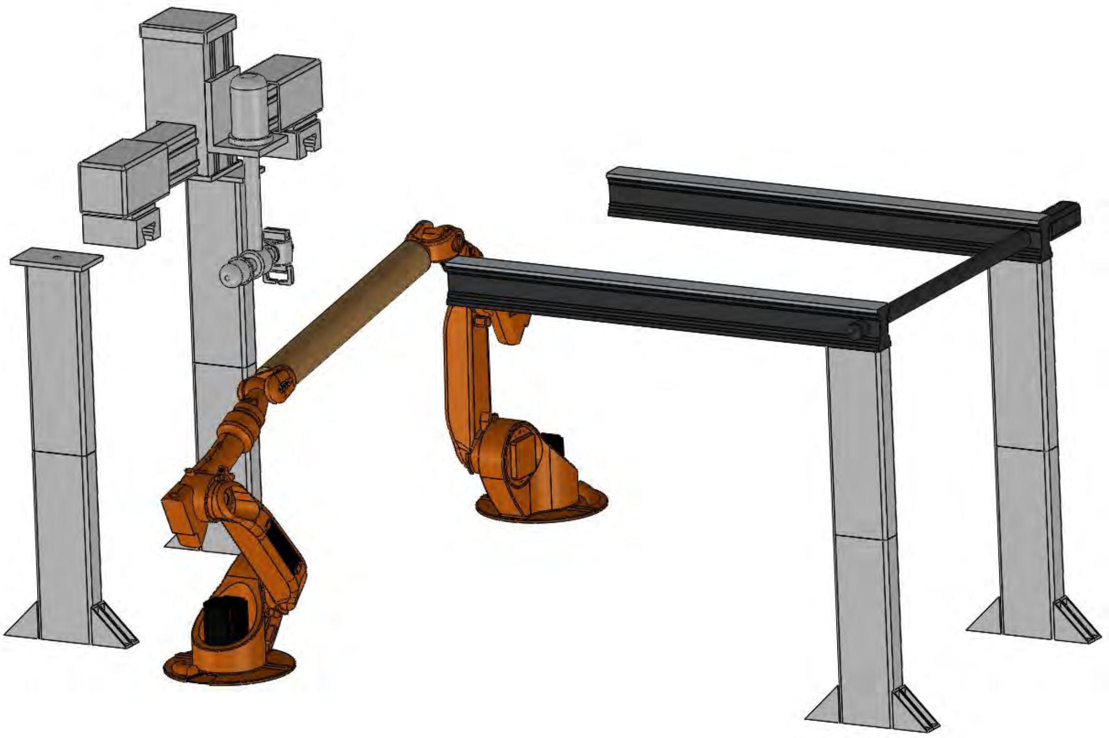


Figure 9: Collaboration visualization via CAD (SOLIDWORKS)

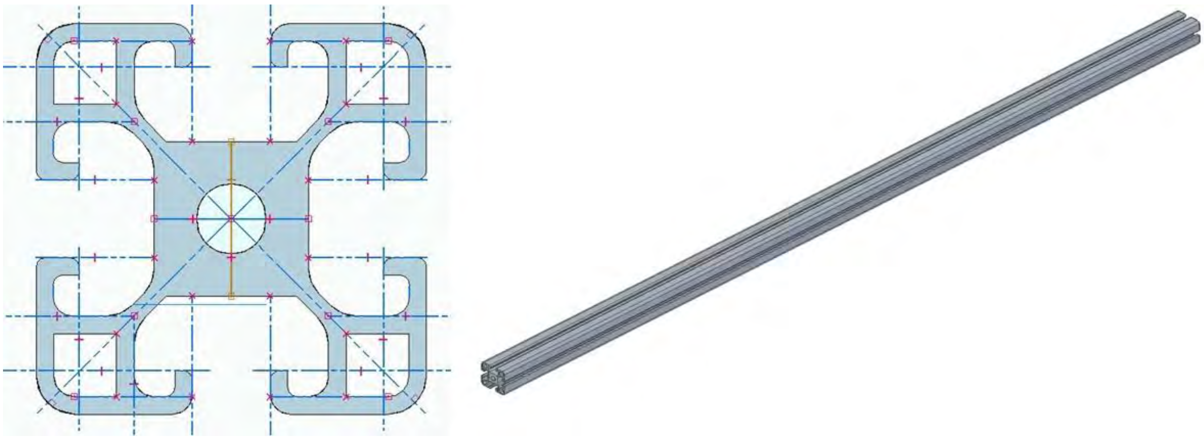


Figure 10: Cross sectional view and isometric view of an aluminium profile

Figure 11: Rendered deployment visualization

speeds up assembly and fabrication, supporting the suitability of this system for transportation and on-site use. Lastly, aluminium is corrosion resistant, perfect for exposure of the sun and weather.

The workspace of our system is largely dependent on the gantry robot's size, for which limits apply with the free movement of timber elements on the minimal size requirements and the transport conditions on the other, for example the maximal profile length of 12 m following the 40 ft shipping container. Assuming those numbers as the largest possible system, and excluding the construction site in size limitations, the system could cover 144 m² in gantry movement. Active processing is additionally limited by the reach of articulated robots, with the radius of access on our chosen system being 1,8 m per arm. Subtracting the smaller area from that of the gantry system, we can add 122 m² to the reachable area of the robotic arms while keeping ground occupation on a nearly equal amount, as figured in Figure 12.

As to enable our system to be mobile and transportable, the gantry system should keep a balance between necessary profile strength for rigid precision and weight reducing measures for easy assembly, deconstruction, and movement. For this purpose, we differ from the known systems of carrying the robotic arm and instead shift (back) towards the tool movement. The robotic arms can although placed on the ground still work in a larger area of influence, as the gantry system can bring tools there and optionally carry

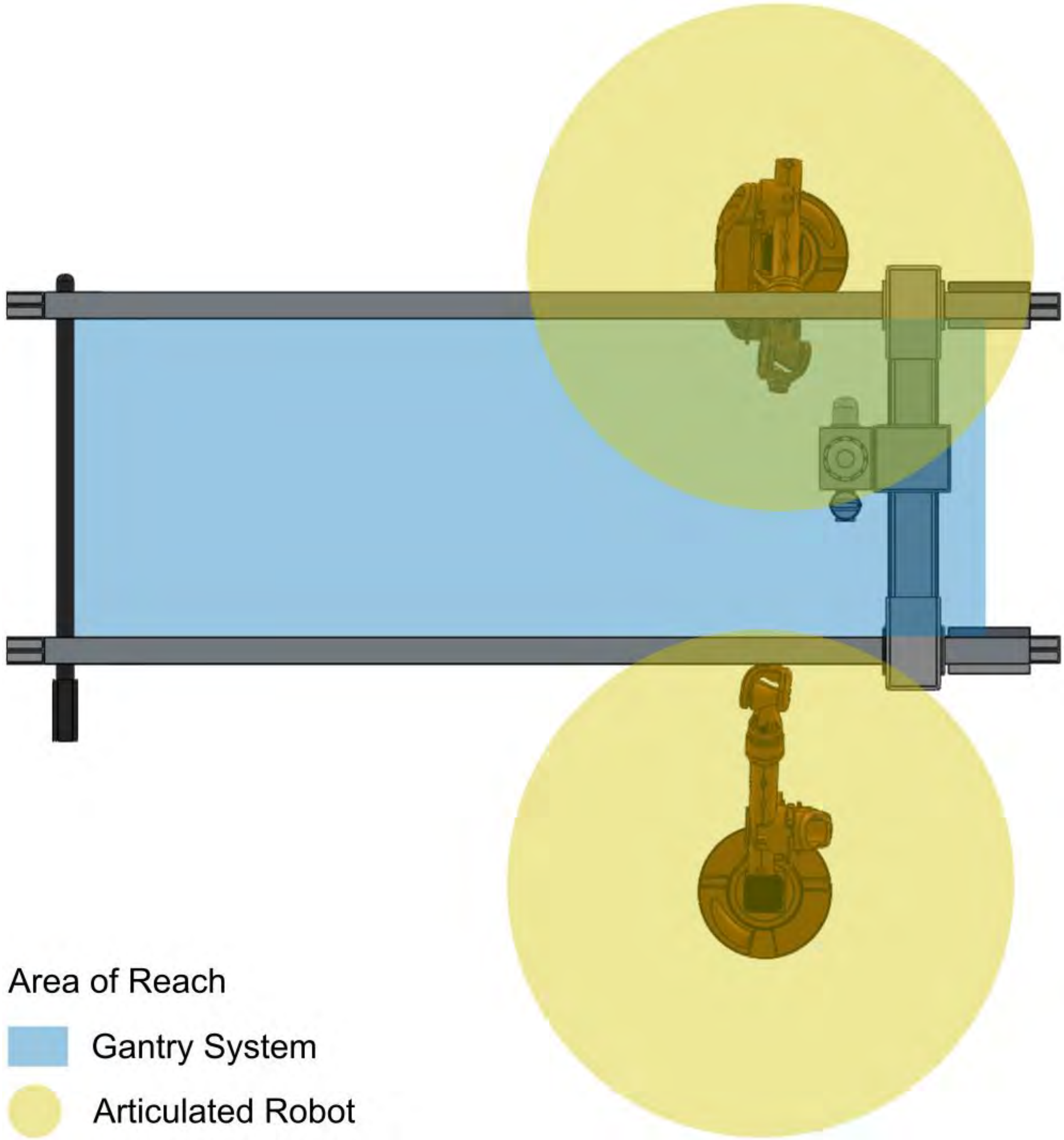


Figure 12: Overlapping and extension of reachable areas through a combination of systems

finished products elsewhere. As there is little difference in moving the tool or the element, the gantry system can solve XY-plane movements while the articulated part is responsible for rotations and angles.

5. Discussion

5.1 Trends in timber construction

Drying and cutting promise significant ecological and economical improvement potentials through energy and material recovery. While those steps usually do not fall into the sector of on-site processes, there might be some connections to be drawn. To avoid excessive drying, previous research has proposed green round-wood utilization, which could also be cost efficient to a certain degree, as the cutting and reshaping process is no longer needed. On the other hand, these shapes are not as adaptable to individual stresses as sawn wood is in its controllable geometry, nor does round-wood follow size related norms. The use of robots could answer the individualized needs of such naturally shaped timber elements, as the processes of joint preparation, structural optimization and precise placement of curved and twisted pieces demand 3-dimensional optimization, as shown in the Wood Chip Barn. While this example is not typical for general construction purposes, it is aesthetically pleasing and could cater to sculptural architecture or in smaller scale, like visible columns, also in more commercial buildings. An example here is the Fortbildungsakademie Mont-Centis in Herne, Germany, where roundwood columns are fitted with steel cords for primary structural parts [SBP21]. Against this speaks the need for norms in typical construction processes, where consistency ensures the execution of planned structures and even surfaces are needed for connections to other building elements.

In terms of material efficiency, recent trends work on improving a variety of engineered timber products and composite materials like fiber-reinforcement and friction welding of laminated timber [RAM17] as well as various composite materials [TEI15]. But while research focuses on improving the structural properties, there is little focus on shaping the structure according to the stresses it is exposed to. Modifying or engineering the material requires a manufacturing step that could be unnecessary if simpler pieces were combined in a more optimized shape. While assembly of elements in irregular and precise angles is a challenge for humans that could be solved through robotic precision, given a stable environment.

Timber, being a natural building resource, is subject to various natural and inconsistencies, which influence the load bearing capacity of the material, making the engineering and shielding of products necessary, processes which have an even larger need for protection against weather, making the controllable indoor fabrication the ideal strategy in terms of quality control. The large set of tools and machines also brings more freedom and precision in manufacturing, improved further by the familiar and reliable environment for carpenters. Compared to robot employment and automation, humans bring much more adaptability and decisiveness to the tasks at hand, showing suitable reactions to a changed or obstructed environment and occurring problems. While robots can work fast and with high precision in areas, where the surroundings are known, techniques that rely on sensors for orientation are still much slower than human workers in terms of mobility, interaction, and placement [ROB21].

5.2 Advantages of deploying an on-site fabrication robotic system

A study on the economics of on-site vs off-site fabrication of rebar shows arguments that are also applicable to timber construction [PAB06]. Among the arguments made for off-site fabrication are lower investment, labor, waste, and inventory cost as well as cycle time, but these assertions exist due to a lack of on-site robotic fabrication systems.

Labor costs can be significantly reduced, depending on the degree of automation. Besides the cost factor, reduced involvement of human interaction in fabrication also signifies the decrease of chances of injury of workers. Thirdly, the material waste of on-site fabrication can be potentially reduced with the deployment of on-site fabricator. This is shown in an accuracy test of multiple robots in a paper [YP00] and none of the robots exceed a deviation of 1.8mm error band, with the IRB 6400 model being the most accurate with the deviation of less than 1.5mm for all 3 axis. With these numbers being partially outdated as recent sources report KUKA robots to have a deviation margin of 0.05mm [RW21]. Finally, inventory costs are high, as according to some, [WCZ20] Just-In-Time (JIT) delivery of a prefabricated module component is not possible, so bulky prefabricated

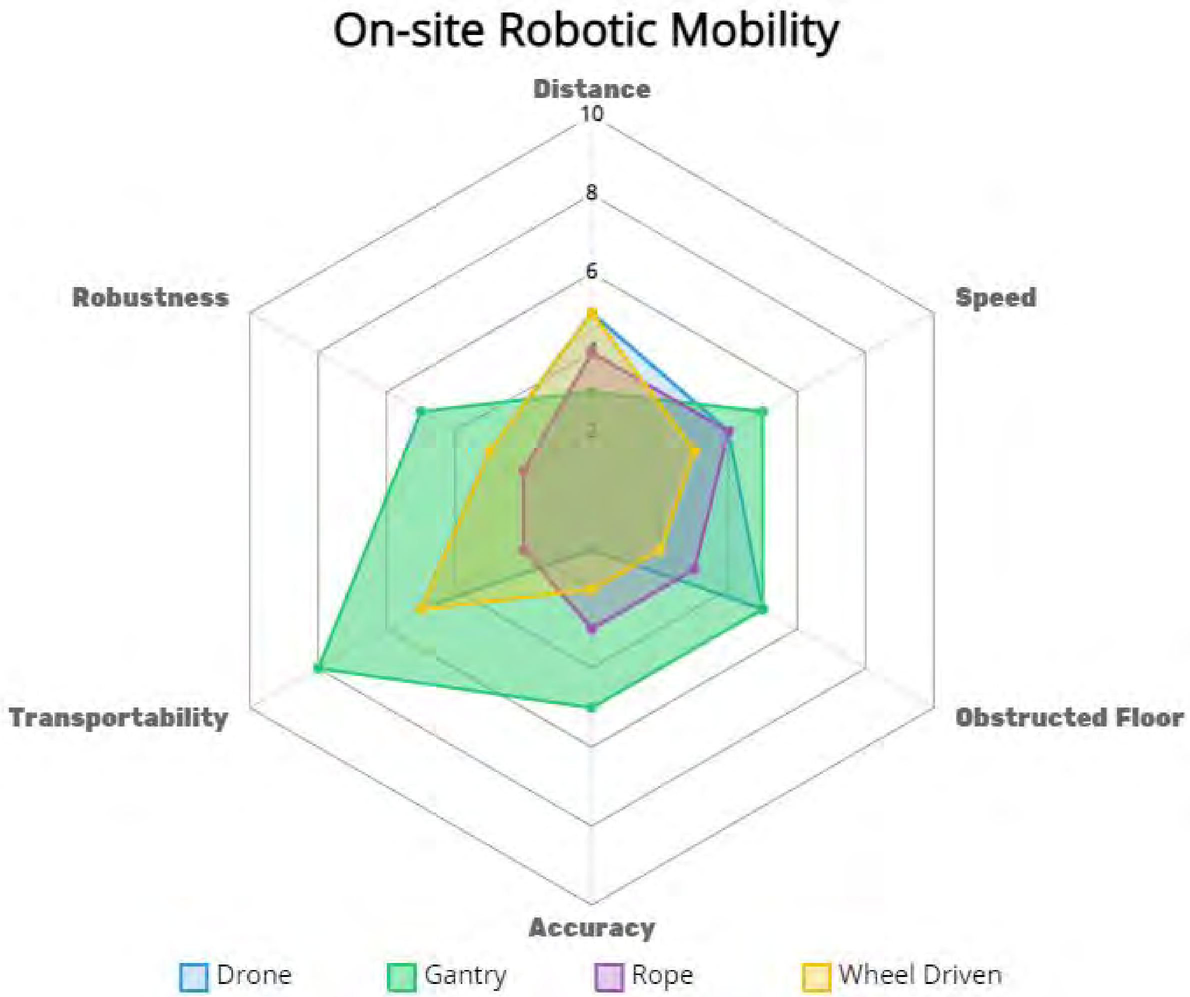


Figure 13: Assessment of the suitability for on-site system combination, mobility based on data from [PLA21]

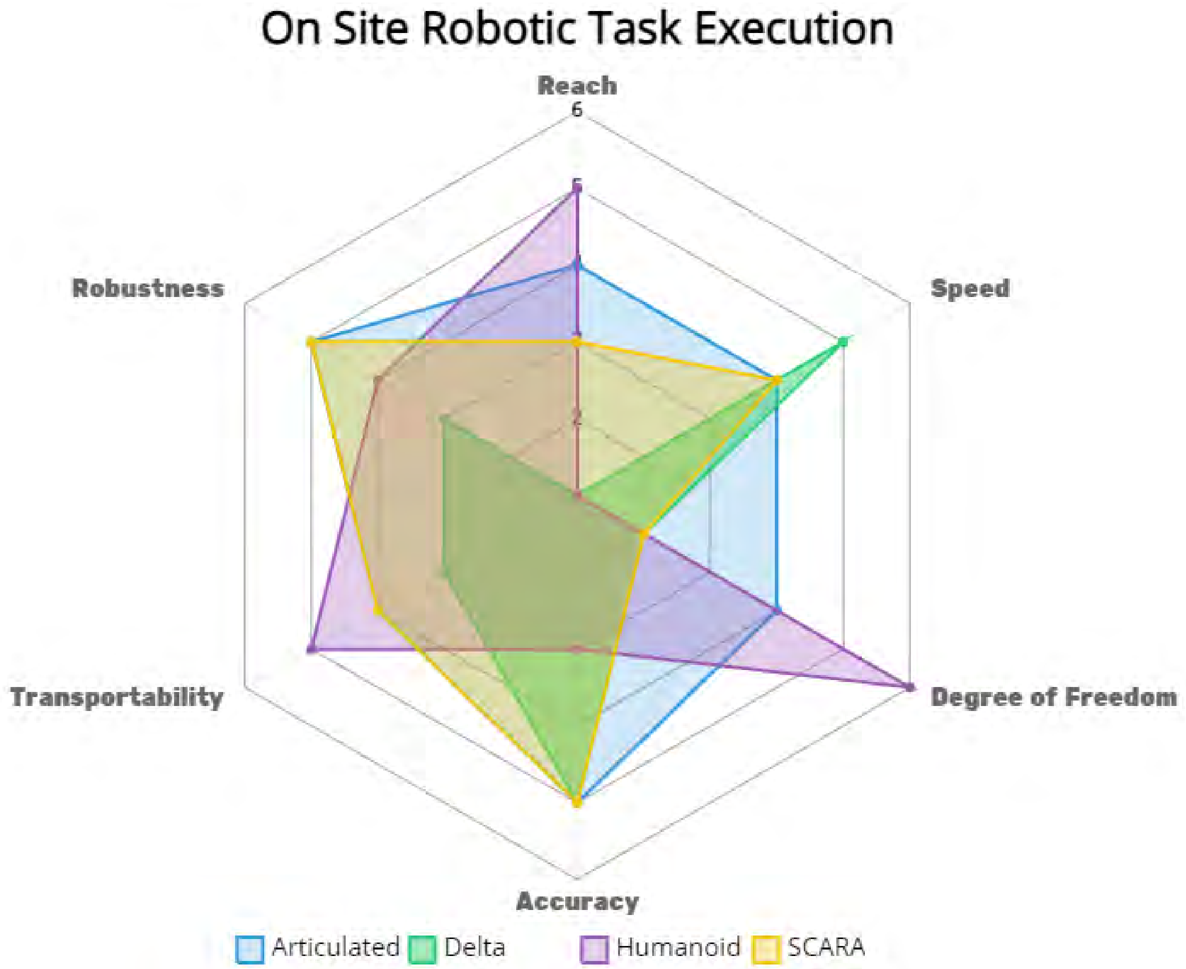


Figure 14: Assessment of the suitability for on-site system combination, task execution based on data from [PLA21]

components are usually stored in construction consolidation centre (CCC). This drives the storage expenses up, while also costing time and labour to retrieve and transport the prefabricated components. This can however be solved with an on-site fabrication robotic system that allows the material to be ordered in small batches and fabricated to the construction's need and pace. In summary, the need to implement robotic systems on-site must be acknowledged, despite difficulties like a chaotic environment and always changing construction site and processes Additionally, uneven footing and exposure to weather complicate requirements.

Depending on the designed piece of the component, a prefabricated systems might limit the architecture's design as the size of the component's module is limited by the transportation means, which in an urban area is estimated to be around 3x3x12m according to a paper [MDR14]. In addition, on-site fabrication also offers the flexibility of alteration after construction. In case of unaccounted deviation in the actual construction process, engineers and architects can amend their design and measurements after the start of construction. This is not possible with pre-fabrication as the component modules are pre-ordered much earlier to ensure an arrival when needed.

Some of the problems are solved or improved by deploying another gantry robotic system into them. Gantry systems have a reputation of high accuracy and customizability. For the TIM system, a gantry system could be attached with a vacuum saw dust extraction system which removes any saw dust left from the milling process and the fabricated wood piece could be stacked or arranged together at a designated area depending on the geometry, further reducing human involvement. Also, by collaborating a gantry robotic system with an adaptive haptically informed mobile articulated robot, processes such as cutting, milling, fastening, assembly, and positioning are theoretically possible.

While there are some existing systems even for the combination of articulated and gantry robots, those cases are solely employed within a factory environment. For example, the Robotic fabrication laboratory (RFL) of the ETH Zürich [SST19] is composed of a large gantry system that stretches over the hall's full length with four robot arms suspended from the gantry by telescope lie arms to adjust the height. The system allows for robot-to-robot and robot-to-human collaboration while keeping the floor unobstructed, but to realize such a suspension, the full weight of several robots must be carried and moved by the gantry system, leading to large dimensions of the parts. In examination of factory based examples, benefits of such combinations seem capable of improvements in efficiency and accuracy on site as well.

The TIM system has a robotic system, that employs two articulated robotic arms and a turntable, along with automatically

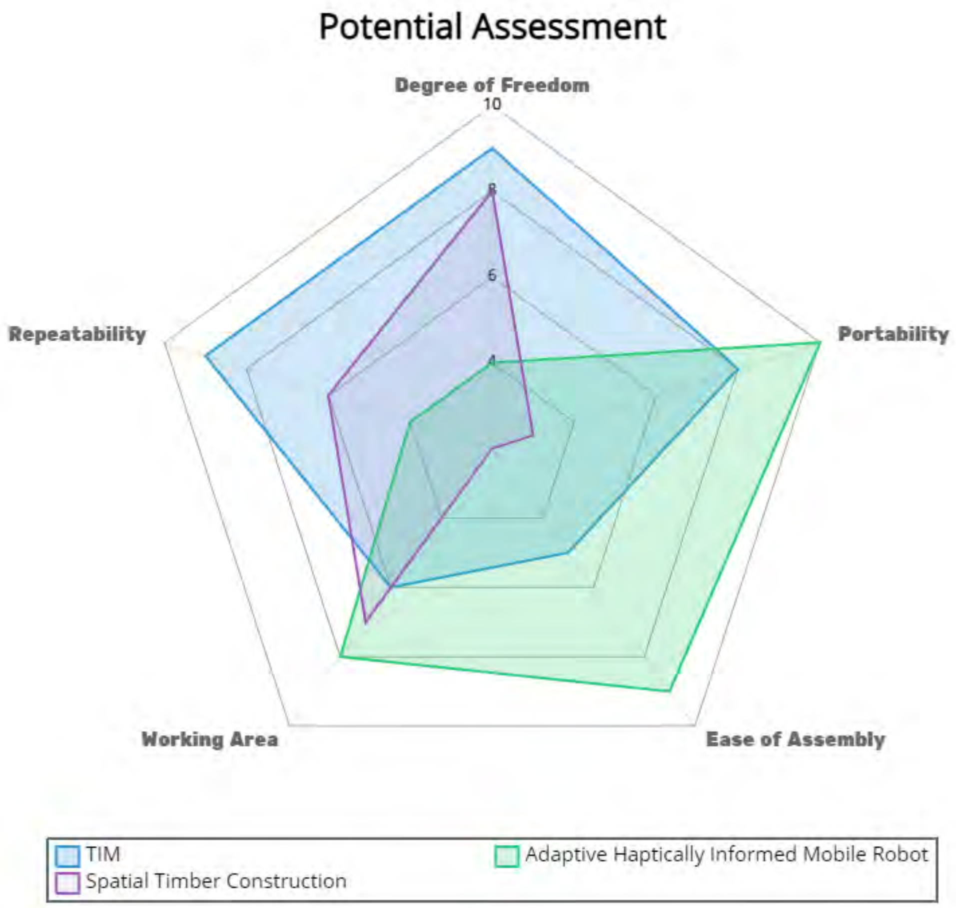


Figure 15: Potential Assessment based on [BA21]

Figure 16: Robotic Fabrication Laboratory [BLO18]

changeable end-effectors. To counter uneven footing and the unpredictable environment, the robotic system is anchored on a 14m² platform, on which all of the modules are transportable in a truck with the help of a heavy-duty forklift. After delivery to the site, it covers up to 100m³ of working space. This robotic system is capable of milling, nailing, gluing, and assembling. The completed wood piece is finally placed onto a nearby pallet with saw dust removal and transportation of the wood piece functioning manually.

6. Conclusion and Outlook

In this research paper, the potential of deploying an on-site collaborated robotic system for timber processing in construction site is explored and discussed, and the result shows that such system can indeed be cost and time efficient, as well as providing a degree of flexibility to the management of the construction project. However, due to the immaturity of research in this topic, various issues are yet to be optimized to its maximum potential. For example, the calibration and installation of the robotic systems when deploying into the construction site is extremely time consuming and these processes must be repeated every time it is assembled for different projects. Besides that, the lack of software that eases the collaboration amongst different robotic system is also seen as an obstacle to normalize this concept.

For a more sustainable and green construction, rapid and increased effort towards automation in timber construction is highly necessary. With further and more in-depth research done in the future, more unexplored possibilities will successively be brought to light and the automation in construction will continuously evolve and adapt to the current situation and need in this field.

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Mehmet Koc

Hong Phuoc Nguyen Nguyen

The Hybrid Electronic-Hydraulic Autonomous Excavator System on the Construction Area

Abstract

Today, an excavator performing digging tasks is increasingly less operated by a human, not only due to the complexity of the working environment but also to increase productivity and decrease the degree of insecurity to humans. In this research, we collected information about state-of-the-art technologies used in excavators and then indicate some own problems from hydraulic actuators and electric actuators. Afterward, we design a new model, which combines these two types of actuators into one system, and simulates it in a virtual simulation environment. This model can contain electronic devices for autonomously controlling. Our work creates a new concept for a “green” excavator, which increases accuracy, saves fuel consumption, and can be autonomously and continuously in hazardous places.

1. Introduction

Excavators can complete both small works like digging, tunneling, and big works such as making a place for foundation and tearing down buildings. The excavator operators face many dangerous and challenging situations. The weather, terrain types, and temperature conditions affect the operators during the excavation processes. The pile material also creates a huge effect on the operations. Each loop of scooping and dumping pile material creates a cost in the aspect of time and the accuracy of the process relying on the operator [Zh20]. Human-controlled processes also comprise many risks in the aspect of health issues. The excavation process has many uncertainties for the operators and the environmental conditions initiate many challenging situations. Therefore, the integration of autonomous systems into excavators creates an enormous advantage in many construction processes.

Previous research has established that there were many cutting-edge technologies applied in building autonomous excavators. For instance, the 5G technology [HTN20] and white light communication [Le15] that is used for transmitting data, or intelligent controller implemented for creating artificial intelligence and improving the performance of excavator [Li11] [Ho19]. Meanwhile, the development in software and hardware electronic components in recent days also contributed significantly to building autonomous excavators on the market [Ho19] [BU21]. Besides, new actuators are also designed to decrease the weight and increase the power as well as accuracy [So20] [Pr21].

However, the way to increase the efficiency of excavators in hard environmental construction sites is still limited to be mentioned. The hard-working-condition sites, such as on hazardous places, other planets, or under the sea, are the places where humans cannot easily reach and where it is very difficult to supply continuous power for operating the excavator. Therefore, this research article has focused on design a hybrid (electric and hydraulic) system at the arm of the autonomous excavator. Besides, we show the way to input the designed model into a virtual environment and simulate the excavator in virtual hard-condition construction sites.

The outline of this paper is: first, presenting the state of the art in different fields of the excavator. Next, the methodology and the result of the whole research are introduced in that order. Finally, the potentials and challenges are presented, following by the conclusion.

2. State of the Art

2.1 Hydraulic and Electronic Actuators for the Excavators

Linear hydraulic actuators, which are extremely powerful and usually made of structural steel, have been used widely, especially for excavators. Nevertheless, in recent research, hydraulic actuators have been developed in a new combination of materials: cylinder tube made of aluminum alloy wrapped by composite, aluminum-alloy attachments, and flanges, and piston rod made composite; additionally, the design decreased the weight by 88% compared to the original one and still ensured the large force, up to 70 kN [So20].

Besides linear actuators, rotary actuators are used commonly, especially

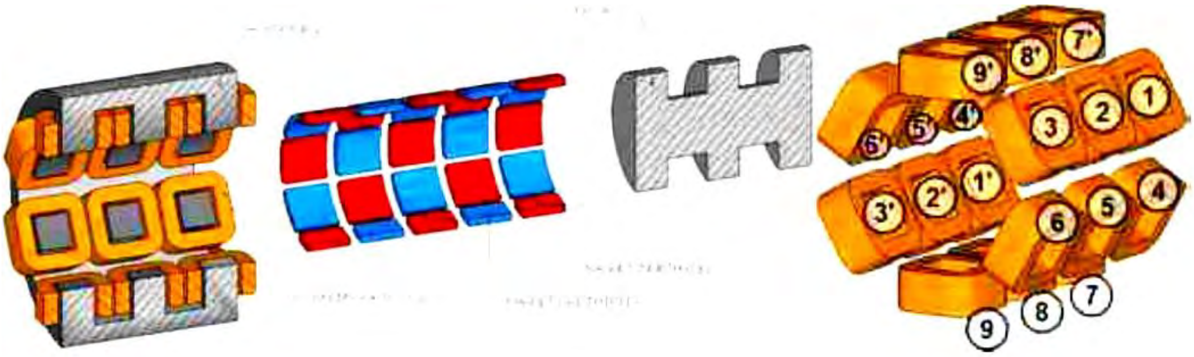

Figure 1: Rotary actuator components [Kr08]

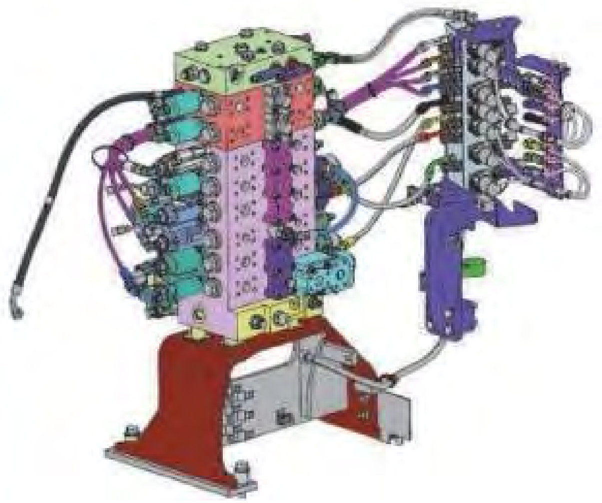

Figure 2: Hydraulic actuator model [Kr08]

electric ones. The model of the rotary actuator is illustrated in Figure 1. Electric actuators have a relatively insufficient power comparing to hydraulic actuators; in contrast, their accuracy is much higher than that of hydraulic actuators, easier to control, and also more easily to implement intelligent control algorithms, like Fuzzy [Pr21]. On the other hand, hydraulic actuators can be also digitalized by attaching electronic components, for instance, an electric valve, as controlling modules [Yu14].

Adding electronic components into hydraulic actuators supports controlling conventional excavators. Nevertheless, there are some limits that raw mechanical systems cannot overcome electric systems, such as the latency and the accuracy. To decrease the latency and increase the accuracy of the excavation processes, the implementation of autonomous systems and cyber-physical systems is necessary.

2.2 Autonomous Systems and Cyber-Physical Systems

Autonomous systems are the systems, during operating, that can react to unexpected events, without external control [Da05]. An autonomous system is neither AI (artificial intelligence) nor automation, but it uses AI as perception and relies on automation to trigger action based on information from the environment [Fo18]. Therefore, the autonomous system is based on self-learning and evaluating algorithms. Autonomous systems have been used in many fields of technology. In Figure 4, The Blooms' level is indicating the whole steps in the cognition process of the autonomous system. In the construction area, Figure 4 also shows that the scooping bucket was processed with different shovel types; with cameras, the image processor detected the bucket if it was full or empty, detected the shovel type of the bucket, materials, and from that the system could create a proper digging, scooping, and dumping process.

Additionally, autonomous systems are implemented in the excavators to decrease mechanical inaccuracy. For instance, the stroke of the hydraulic cylinder has many unprecise points such as sliding

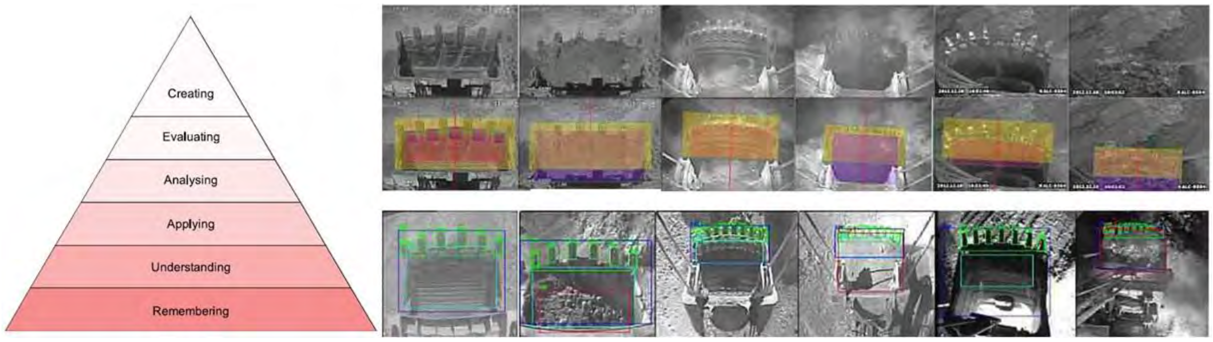

Figure 4: The Cognitive Learning Pyramid and Image processing of the excavation process [Ho19] [Ge10]

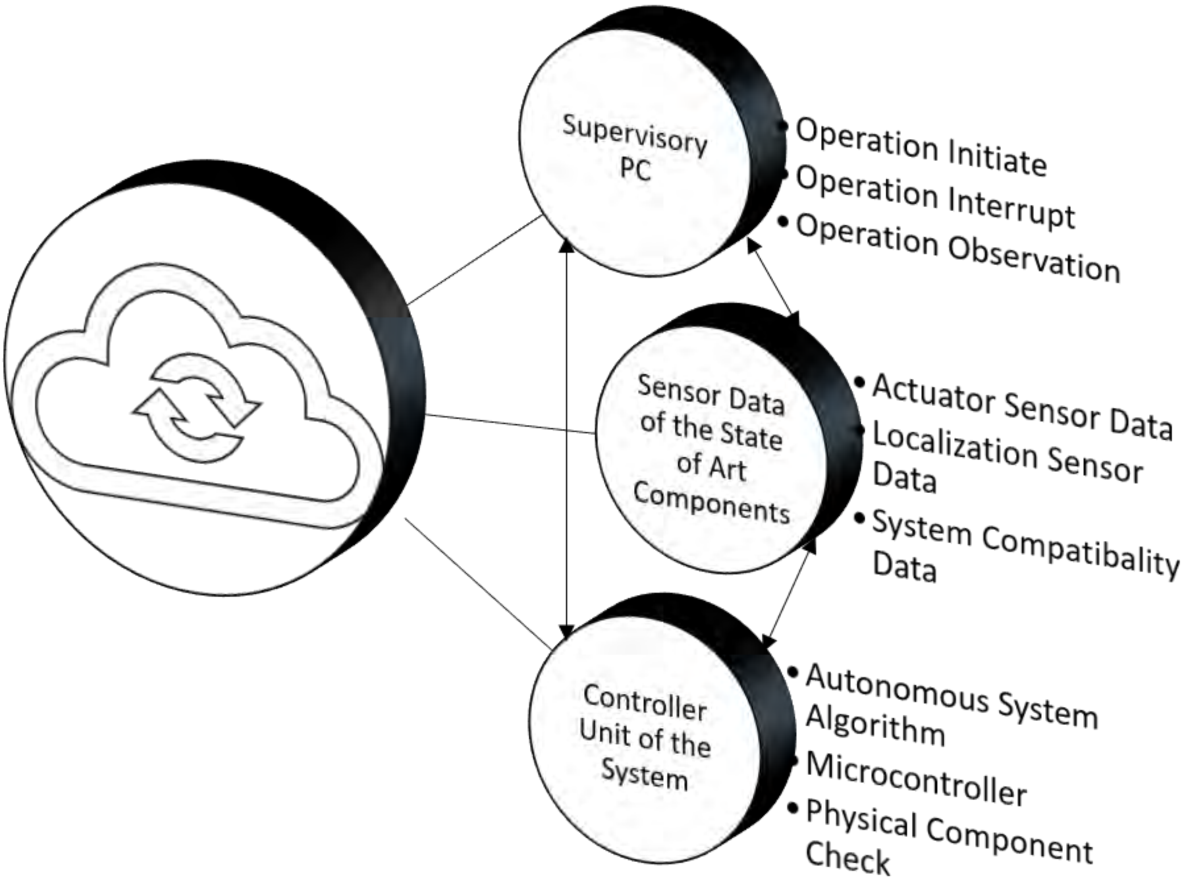

Figure 3: Networking Illustration for the CPS Networking Based on [Cl14]

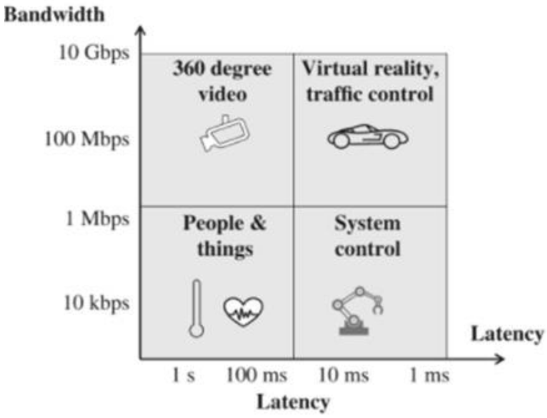

Figure 5. Bandwidth Application Areas Based on [CR14] [HTN20]

components, oil viscosity effect, sensor data, and indicator components, etc. The stroke cycling components are used as manipulator effectors of the bucket element and controlling those components has a big amount of importance for the autonomous systems [Ya98].

A cyber-physical system combines physical components with cyber components and those parts can be interconnected through interfaces [MD20].

Cyber-physical system is not only a core part in the autonomous system, but also support remotely operating excavator. For example, sensors play a crucial role in collecting parameters from construction sites and states of excavator; communication modules make the communication between other modules and communication with the remote operation center more convenient and faster.

Figure 5 shows the development of 5G, which is progress between 26/28 GHz frequencies to get high hot spot coverage and high-speed connection, used for the controlling system. The 5G frequency has a wider spectrum and this factor affect the efficiency. This bandwidth provides many advantages to provide better excavation operation on the construction site [HTN20].

Together with 5G technology, the laser is often used for data transmission. It is based on the photo-emitter and photo-emission concepts, which are related to the

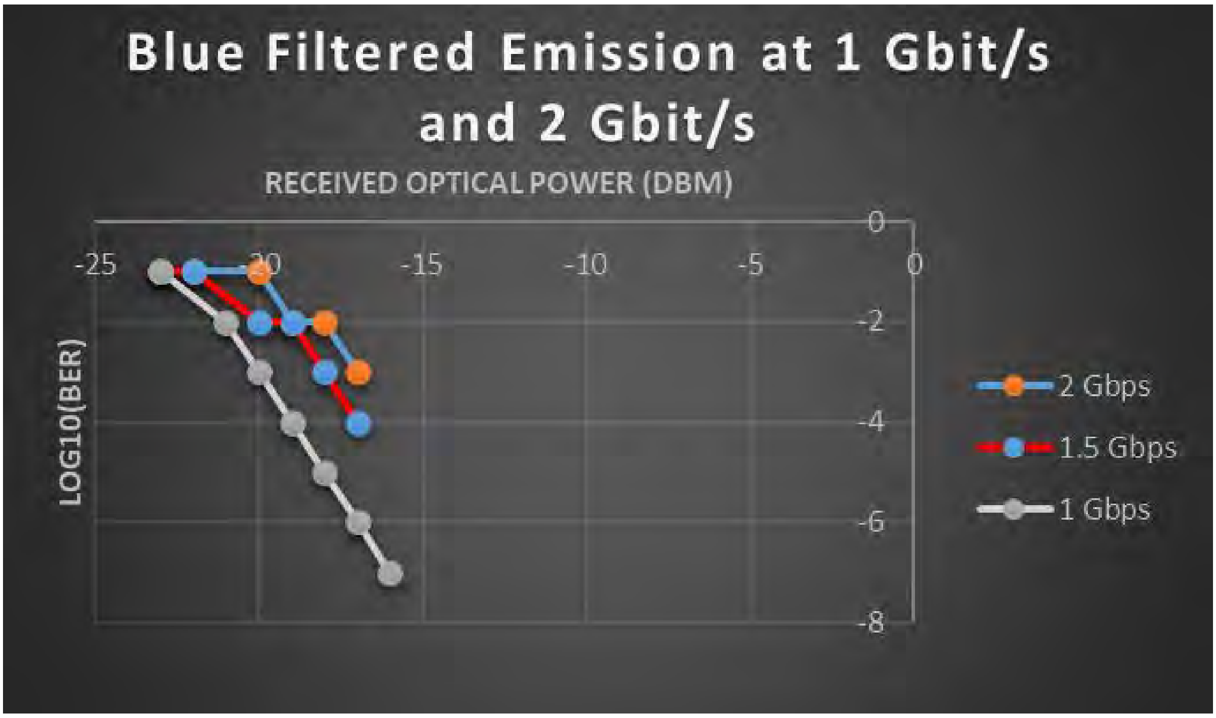

Figure 6: Blue Filtered Emission at 1 Gbit/s and 2Gbit/s Based on [Le15]

light drive measuring parameters. Figure 6 shows that blue light has a higher frequency and intensity. The signal frequency is related to wavelength and photon variance. The phosphor conversion processes the light emitted with a filter to change the blue light wavelength to other wavelengths and the human eye can observe that as white light. This data transmission concept can be used on construction sites. Construction sites are usually outdoor, so that wireless communication is essential. Each machine will carry a laser transmission module to communicate and transfer data with others in long-distance applications, which need a fast and accurate data transmission [Le15].

With the huge improvement of cyber-physical technologies, autonomous systems have been installed into excavators on the market.

2.3 The Autonomous Excavators

In Figure 7**Error! Reference source not found.**, a person is operating an autonomous excavator by an interface as a screen, and this system is called a “blended system” [Yu14]. The virtual reality aided control system is based on a Cyber-Physical system. With this concept, the operator can integrate and manipulate an unmanned excavator via a networking channel. The operator can access the system via a headset called a “Virtual-Reality Controlling System” [Ry17].

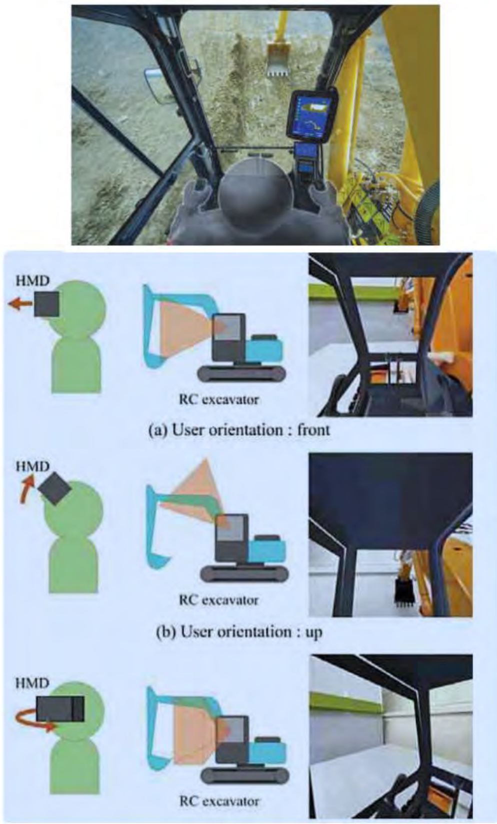

Figure 7: : Blended System and Virtual-Realited Controlling System [Ry17] [Yu14]

BUILT is a company using the great development of cyber-physical systems into building autonomous robots. The largest thing is the 37-ton fully autonomous

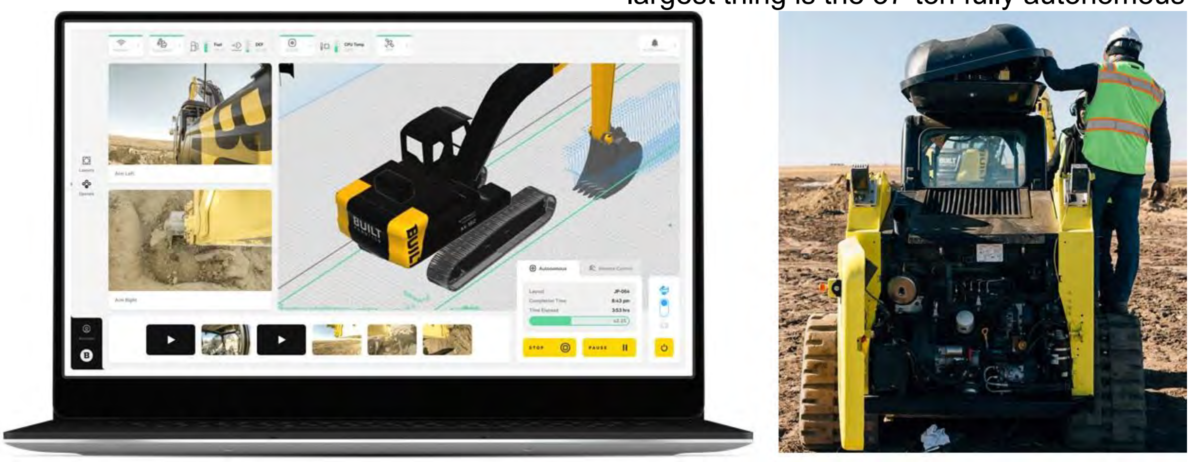

Figure 8: BUILT Company Autonomous Excavator Simulation and System Components [BU21]

Figure 9: Autonomous Excavators in Tunneling and Digging Process [Br21] [BU21]

excavator, which has a multilayers safety system ensuring safe for workers, animals, and other vehicles [BU21].

The hydraulic actuators have been used for many years on the excavator's arms; however, the digitalization concepts, environmental conditions, high energy-consuming issues, etc. effects have changed the direction of the development of the excavator technology. The electric excavator from Caterpillar contains a massive 300-kWh battery pack, which is used for operating the 122 kW motors and actuators in the system within 5-7 hours, reducing emissions [Ed19]. Another product from Komatsu combined electron actuators and the hydraulic ones into the moving platform, for using less fuel and reducing the emissions by up to 40% [Ko21]. Brokk also has an excavator model using hybrid systems, in particular, are the hydraulic actuators in the arm and the electric motors in the moving platform [Br21].

However, the purely electric or hydraulic excavator’s arm has its problems.

2.4 Problems

On the one hand, despite the advantage that electric actuators produce no emissions to the environment and also have a capacity for building autonomous systems, they have insufficient power comparing to hydraulic actuators. On the other hand, even if hydraulic excavators are currently occupying the majority of the market share, but they have a serious problem of emission, which leads to great pollution and damage to people; additionally, the energy supplement is another problem, because there are no people around to fill the tank when the autonomous hydraulic excavators work in hazardous environments.

Therefore, our project, to take the advantages and eliminate the disadvantages of two engines, has focused on combining electric and hydraulic actuators into one system, as well as the sustainable way to provide energy for the actuators. Furthermore, a specific application is proposed.

3. Methods

First, both forward kinematics and inverse kinematics of an excavator’s arm are analyzed and transferred into MATLAB for kinematics simulation. Second, we use Solidworks from Dassault Systems company to design a hydraulic-electric excavator model. Visualization of the concept is also completed by Solidworks. In the next step, the 3D model is imported into Robot Operating System (ROS). ROS, which is more powerful than other tools in robot simulating, is a middleware source, which is open-source and used for writing robot software and creating, simulating robots [Ro20]. After that, we modify the

dynamic parameters of the model, and design, create a virtual construction environment in Gazebo, which is a perfect program for dynamic simulation. The movements of the excavator can be visualized, and the result of the simulation also can be observed by Gazebo interface. The simulation's result supports the adjustment of the design process. Moreover, it will play a crucial role in the prototyping phase and control in the future.

4.1 Kinematics analysis

The boom, arm, and bucket of the excavator can be modeled by a serial 3-degree-of-freedom robot arm. Therefore, it can be described by Devanit-Hartenberg (DH) parameters in the figure below.

Joint	θ_i	d_i	a_i	α_i
1	θ_1	0	L_1	0
2	θ_2	0	L_2	0
3	θ_3	0	L_3	0

Figure 11: Joint Parameters by Devanit-Hartenberg

4. Results

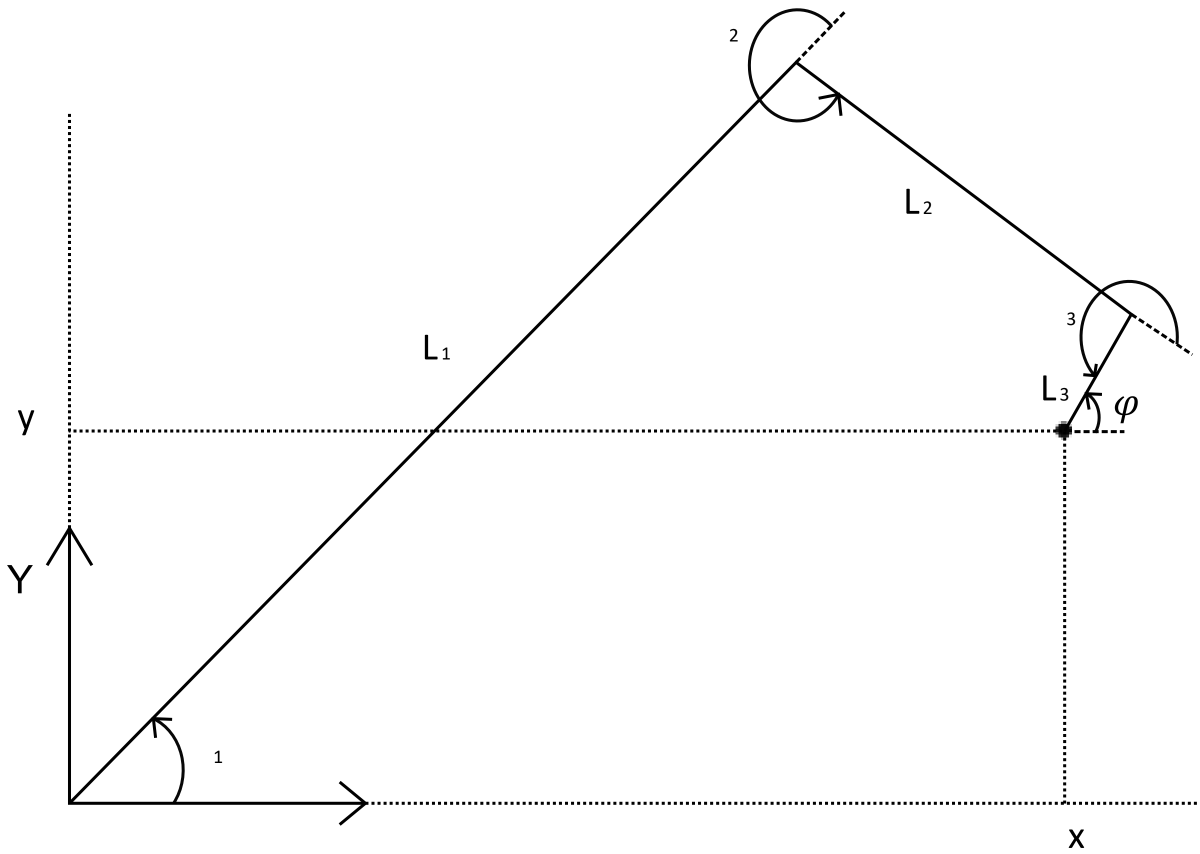

Figure 10: Kinematic Links of the Excavator Arm

The θ_1, θ_2, θ_3 are the angles of three joints and the L_1, L_2, L_3 are the length of three links boom, arm, and bucket respectively. The diagram below visually illustrates these parameters.

Not only the position of the bucket but also the positions of other parts of the excavator can be calculated with the angles of joints through the forward kinematics, which was drawn from the DH parameters. It can also be generated through the diagram and is shown below.

$$x = L_1 \cos \theta_1 + L_2 \cos(\theta_1 + \theta_2) + L_3 \cos(\theta_1 + \theta_2 + \theta_3)$$

$$y = L_1 \sin \theta_1 + L_2 \sin(\theta_1 + \theta_2) + L_3 \sin(\theta_1 + \theta_2 + \theta_3)$$

$$\varphi = \theta_1 + \theta_2 + \theta_3$$

Inverse kinematics is used for calculating the process of the variable joints based on the desired position of the bucket. In some complex robot arm systems, it is necessary to use numerical methods for the process because reverse kinematics cannot be solved by symbolic methods [Ni08]. However, the arm of the excavator is simple; thus its reverse kinematics was solved explicitly according to the forward kinematics. From the equations of x, y:

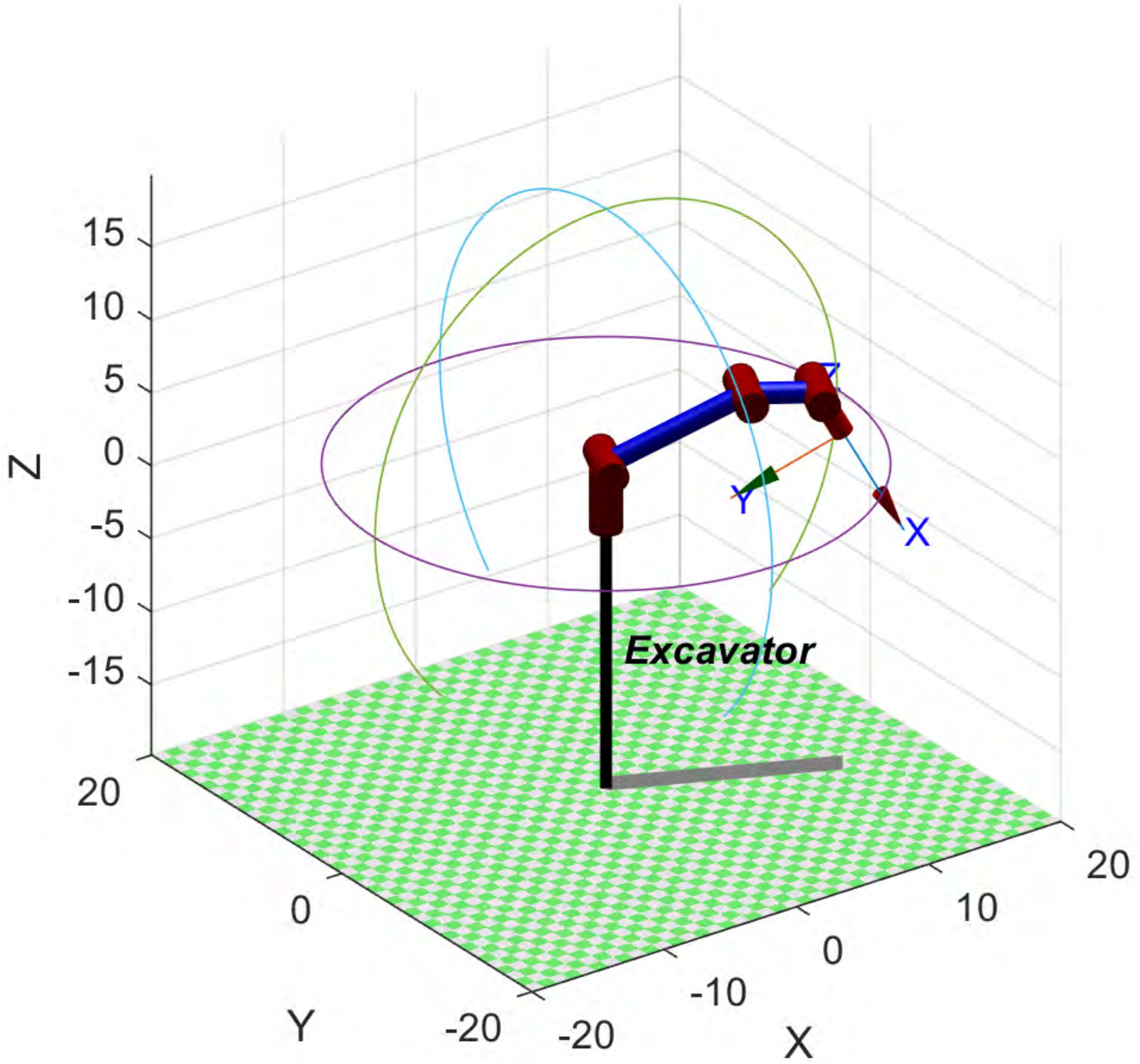

Figure 12: Kinematic model and workspace of an excavator's arm in MATLAB

$$x - L_3 \cos\varphi = L_1 \cos\theta_1 + L_2 \cos(\theta_1 + \theta_2) \;\; (1)$$
$$y - L_3 \sin\varphi = L_1 \sin\theta_1 + L_2 \sin(\theta_1 + \theta_2) \;\; (2)$$

Set $X = x - L_3 \cos\varphi$, $Y = y - L_3 \sin\varphi$ and square both sides of two equations:

$$X^2 = L_1^2 \cos^2\theta_1 + L_2^2 \cos^2(\theta_1 + \theta_2) + 2L_1 L_2 \cos\theta_1 \cos(\theta_1 + \theta_2)$$
$$Y^2 = L_1^2 \sin^2\theta_1 + L_2^2 \sin^2(\theta_1 + \theta_2) + 2L_1 L_2 \sin\theta_1 \sin(\theta_1 + \theta_2)$$

$$\Rightarrow X^2 + Y^2 = L_1^2 + L_2^2 + 2L_1L_2[\cos\theta_1 \cos(\theta_1 + \theta_2) + L_2 \sin\theta_1 \sin(\theta_1 + \theta_2)] = L_1^2 + L_2^2 + 2L_1L_2 \cos\theta_2$$

$$\Rightarrow \theta_2 = \cos^{-1}\frac{X^2 + Y^2 - L_1^2 - L_2^2}{2L_1L_1}$$

Expand and rearrange (1) and (2):

$$X = \cos\theta_1 (L_1 + L_2 \cos\theta_2) - L_2 \sin\theta_1 \sin\theta_2$$
$$Y = \sin\theta_1 (L_1 + L_2 \cos\theta_2) + L_2 \cos\theta_1 \sin\theta_2$$

Since θ_2 was solved above, these two equations are t he system equation containing two variables, $\cos\theta_1$ and $\sin\theta_1$. Thus, θ_1 can be solved from $\cos\theta_1$

$$\theta_1 = \cos^{-1}\frac{(L_1 + L_2 \cos\theta_2)X + L_2 \sin\theta_2 Y}{X^2 + Y^2}$$

And from the results of θ_1 and θ_2:

$$\theta_3 = \varphi - \theta_2 - \theta_1$$

The roles of forwarding kinematics and inverse kinematics are crucial. The angle trajectories of joints are generated through the inverse kinematics, depending on the tasks; besides, with sensors, the forward kinematics can calculate the positions of the arm to guarantee that it avoids obstacles and people surrounding while working. Furthermore, the kinematic helps in creating the model and simulating it in the virtual environment. Figure 12 shows the workspace of an excavator while standing in a specific position.

4.2 Model Design

The concept design focuses on the electric and hydraulic actuator system implementation and working in harmony. Figure 13 and Figure 14 show the whole excavator and the arm design respectively. In Figure 14, three electric rotary actuators (marked by orange) are attached at each joint, and three hydraulic linear actuators (can be seen as black-gray cylinders) are assembled between two links, like in conventional excavators. Electric actuators are used to initiate a rotary movement on

Figure 13: The hybrid-electro-hydraulic-autonomous excavator system renders

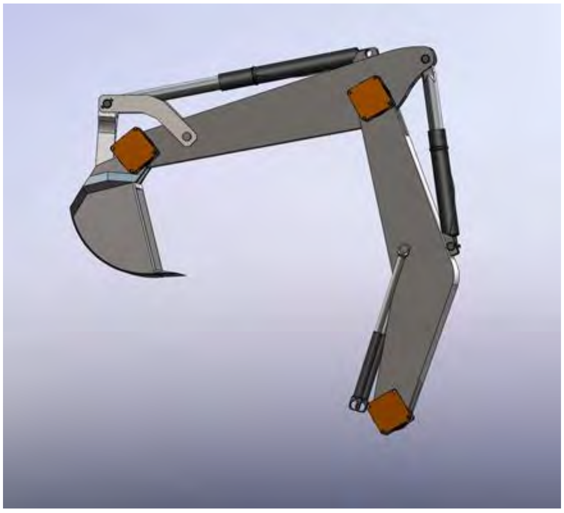

Figure 14: An electric actuator at each joint and a hydraulic actuator piston between two links model

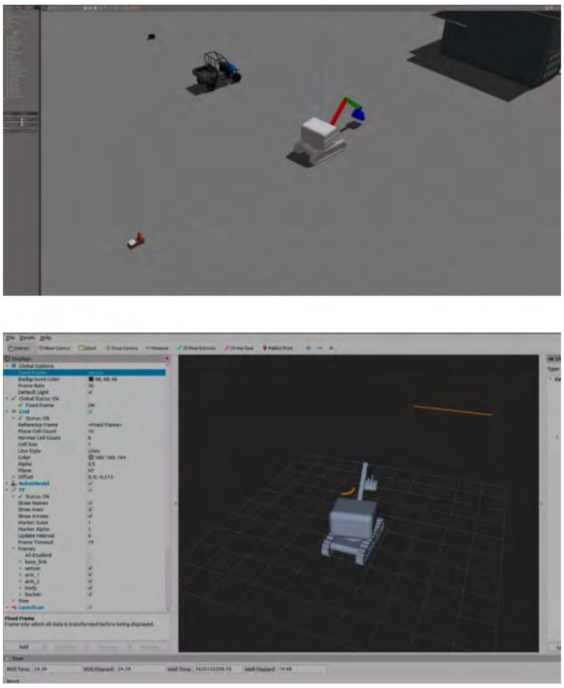

Figure 15: Simple excavator model in ROS/Gazebo

the joints of the excavator's arm. Moreover, the precision of electric actuators is higher than hydraulic ones; thus, implementing electric actuators into hydraulic excavators increases the accuracy of the system during processes requiring meticulousness. Hydraulic actuators are significantly more powerful than electric actuators. Therefore, we implemented them to support the electric actuators in heavy tasks. Using both two types of actuators creates a huge amount of petroleum energy saving while the excavator is doing light work or not carrying heavy things. Furthermore, if composite hydraulic actuators are used, electric power consumption from electric actuators will be also decreased, due to the lightweight of hydraulic actuators when the excavator operates without load.

The autonomous module, communication module, controller module, and other modules are inside the body of the excavator. With the appearance of the modules, the information, data from sensors, commands from operators, etc. are transferred in a fast and exact way, helping the desired operations become more precise and more efficient, increasing productivity and decrease the degree of danger.

After designing, the model is imported into ROS/Gazebo, modified with dynamic and kinematic component parameters, such as actuators' limit angles and velocities, and simulated. We temporarily use a simple virtual environment for simulation; in the future, other virtual construction sites, which are like real ones in real life, will be used. In addition, sensors, like the laser sensor in Figure 15 can be used and tested in Gazebo before deploying in the prototyping phase.

4.3 Proposed Application

The hard environment can be described as improper temperature, pressure, atmosphere, gravity, wind factors (dust, etc.), and external (physical and chemical) factors. In the real-life challenges, there are various situations occurring, and especially for the excavation process, there are harder environments existing. Moreover, excavation processes pose risk to the operator. As a result, human-controlled processes comprise numerous risks in the aspect of health issues as well as physical trauma. Furthermore, there are some special places, such as undersea or on other planets, where human beings cannot or should not be.

Therefore, we propose to use the hybrid autonomous excavator in the places mentioned above. In such a hazardous environment, autonomously operating the excavator is almost mandatory to avoid unexpected accidents to people as well as

Figure 16: Undersea tunneling application [LI20]

other health injuries.

In addition, in dangerous working places where people are not around, charging electric power is easier than supplying fuel for a fully hydraulic system. Supplement of electric power can be done by installing solar panels on the excavator or putting around working places a charging dock, which looks like the one used for robot vacuum cleaners. In other words, we suggest using the hybrid excavator at places where it is difficult to supply fuel.

5. Discussion

Manufacturing, deploying, and operating hybrid autonomous excavators faces many challenges in real life. First, despite having the perception module, there are still some unknown parameters from the environment, which can become big obstacles during working. Second, the accuracy of sensors or cameras should be considered, because a small mistake during measuring operation would cause a big problem, especially in construction sites, where a lot of people work. Furthermore, there is also a financial problem, which means the autonomous excavator requires a great expense in investment and installation. Finally, it needs long-term R&D, which is not suitable for small companies and construction projects.

On the other hand, hybrid autonomous excavator brings big opportunities. It can work in a dangerous, complex environment and with toxic materials without human intervention. Besides, it can be extendable and has great development potential, due to the progress of technology these days, exclusively in computer and sensor fields. Moreover, it can be tested and developed in a virtual environment before manufacturing and employing in real construction sites, which greatly reduces cost and time.

This hybrid autonomous excavator is going to decrease a huge number of emissions from fuel energies to the environment while ensuring the power required for heavy tasks at the same time. It will not only change the market in the future, especially in dangerous processes but also be a big step towards making the construction machinery more environmentally friendly.

6. Conclusion

In conclusion, autonomous systems

have an enormous deep to investigate and the potential of the application areas are incredibly wide. Besides, the development of actuator technologies is a great source of motivation for our design. In the shown concept, rotary electric actuators are added to the conventional hydraulic excavator. In the meantime, a cyber-physical system and an autonomous system are also attached inside the excavator, to create harmony between the system components and make the excavator operate without the physical attendance of people. Even though the hybrid autonomous excavator can be used in many applications, but we propose operating it at places such as other planets, where it is harder to refuel the petroleum, which creates many toxic gases for the environment and people, than charge electric power, which is friendly to the environment.

Nevertheless, although a part of dynamic parameters is mentioned, to simulate correctly and evaluate the performance of the dynamic model in ROS, it is crucial to analyze and modify other parameters, such as forces, torques, accelerators of actuators, the mass, the dimensions of the excavator's components, the sensor response rates, etc. This work is not included in the paper, but it will be done in the future, in the prototyping phase with specific parameters of actuators and physical components.

To summarize, our purpose of the research is to create a new concept for excavators that can be used in variable environments, where the human cannot operate or should not operate; meanwhile, this concept saves fuel-energy consumption, protects the atmosphere while still maintains the performance.

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Application of Mobile Platform Robots for Automated Construction Processes

ABSTRACT

The rapid development of information technology has not made a great impact on construction industry as it did on other areas. At present, the construction process is still highly dependent on manual work, which is costly and risky. Manufacturers and academic institutions have been studying mobile platform robots to achieve a higher degree of automation in construction process.

This article researches the question: what sorts of mobile platform robots are suitable for automated construction. The content concentrates on the technical features of mobile platform robots, especially the drive strategies and supporting sensors and software services. The shortcomings of these products are also shown in the article. In addition, different construction processes and their environmental characteristics will be discussed, for example prefabrication, on-site outdoor and indoor. Based on these results, particular technical combinations are suggested for different conditions.

This paper proposes that wheel drive and chain drive are the two most suitable motion techniques for most construction processes, while legged robots are currently less used due to its drawback in some perspectives. However, the development of a universally applicable drive is currently unrealistic.

Photo by Jelleke Vanooteghem on Unsplash

1. Introduction

The rapid development of information technology has been influencing many other industries. The German government introduced the concept of "Industry 4.0" (Industrie 4.0 in German), which aims to automate and digitalize traditional industrial practices. [Was ist Industrie 4.0?] Digital design, simulation and monitoring during processes have helped to improve efficiency in numerous industries, especially manufacturing. However, the construction industry has been in a stage of low automation degree for decades due to the complex, unstructured and dynamic environment (Figure 01).

From a technical point of view, despite the fact that computer-aided-design software as well as digital management solutions have been developed and widely used in the market, almost all processes on actual construction sites are still highly dependent on manual work, with limited help provided from tools such as hand-held drills, excavators and cranes.

The safety and stability of the robots during construction process are also difficult to be guaranteed. Therefore, the safety and efficiency situations dissatisfy not only workers but also other stakeholders like real estate companies.

In the early stage of automated construction, prefabrication (Figure 02) has

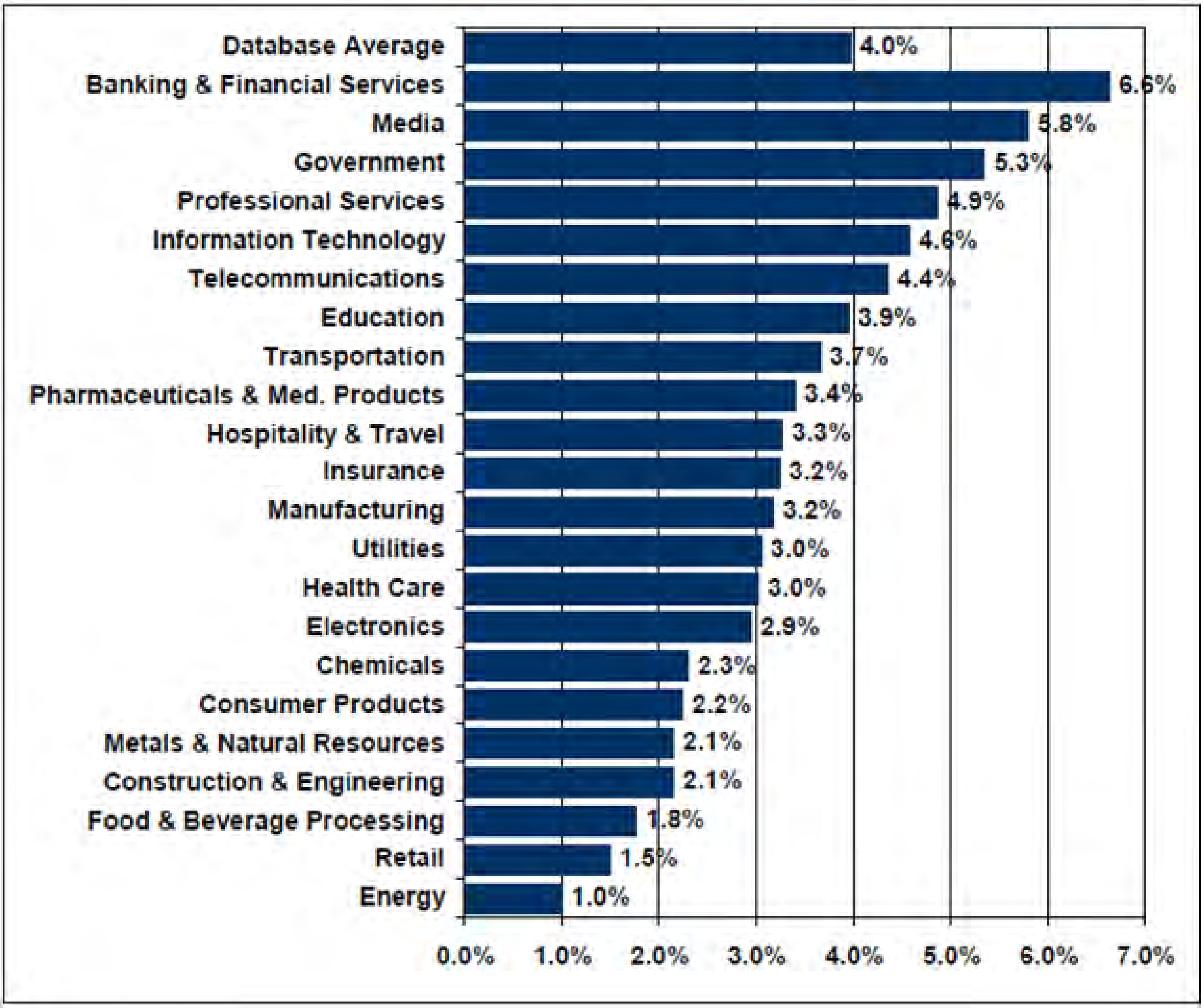


Figure 1: Automation Degree of Different Industries [BEC10]

Figure 2: Prefabricated Construction [Innovative Ways Prefabricated Buildings Are Used Today - Build Magazine]

been introduced and developed for years. This concept began in the 19th century and continued to evolve as productivity soared. Before the operations on site, the components are manufactured in factories. Then, they are transported to the site and assembled to corresponding positions. Automated robots can be applied in the processes of prefabrication and assembly on site to enhance manufacturing efficiency, utilizing workspace and improving accuracy.

On the other hand, automated machinery for on-site operations is still of relatively low development degree but it is urgently needed. Available commercial products are mostly uniquely designed for specific operations and then delivered to manufacturers. In this case, they may lack the ability to deal with various conditions. By contrast, a universal robot can finish different tasks by changing end-effectors instead of using different types of robots. Meanwhile, the cost for transport will also be saved. Universal robots have less restriction with regard to work space as well.

In this report, we study the current development condition of mobile platform robots – one of the most promising automated machinery types, comparing technical details of design methods and adapting them to construction processes. The goal of this report is to develop a concept to increase the robots' adaptability to the dynamics and variability to the unknown environments they may encounter. One further direction might be to increase human-machine interaction efficiency making it easier to use. Eventually, a fully automated on-site construction process should probably be achieved. Our proposed question here is: what sorts of mobile platform robots are suitable for automated construction?

2. State of the Art

Numerous commercial products in this field have been introduced into the market, while some of them have already been put into practical use in a limited range. Currently, there are two major types of mobile drives: wheel-driven mobile platform robots and chain-driven mobile platform robots.

As an example of wheel driven platform robots, platform KUKA KPM200 (Table 1 - [1]) has been applied in manufacturing in factories, as well as construction prefabrication.

This system can integrate autonomous robots (e.g. KUKA iiwa) and mobile platforms quickly and reliably into cells and systems. This mobile platform system can achieve the velocity of maximum 3.6 km/h. It is powered by electricity and can run for more than 3 hours. The Mecanum wheel is suitable for high-precision transport, even with the heaviest loads of around 170 kilograms. Mecanum wheel is a special wheel with an additional parameter of angle between wheel plane and rollers plane, influencing the velocity constraint conditions.

More importantly, it can move in all directions, which shortens the robot throughput time and reduces nonproductive time when searching for appropriate execution pose for a given task. The integrated laser rangefinder scans the surrounding environments and builds the map, and the embedded control software deals with motion planning and navigation, which enables reliable and flexible work sequences. Therefore, they can set a complete sequence of fabrication and assembly.

Baubot (Table 1 - [2]) produced by Printstones GmbH is a tracked mobile base attached with a 6-degree-of-freedom arm. Different from wheeled mobile platforms, which would be stopped by a variety of obstacles, Baubot can climb stairs and work on multiple floors. The robot also includes an on-board, industrial robotic arm from KUKA robotics, that enables a variety of applications. Nevertheless, it can be applied not only in the fabrication process but also for complex operation processes on-site such as welding, sanding, drilling, screwing, milling, and even 3D printing by using the onboard arm. Furthermore, it is a truly mobile construction robotic system where everything is on-board and no cables or stationary components are required.

This system has great advantages in endurance and carrying capacity, with run time over 8 hours and payload reaching nearly 900 kilograms. By comparison, the running speed of this system is relatively lower than KUKA KMP200.

ANYmal C (Table 1 - [3]) is an example

	Picture	Drives	Applied processes	Avaliable Manipulator	Payload	Run time	Energy strategy	Speed
[1]KUKA KMP200		Wheeled	Prefabrication processes	KUKA iiwa	170 Kg	> 3H	Electricity	Max. 3.6 Km/h
[2]Baubot		Tracked	On-site specific operation	Multi-axis KUKA manipulator	500-900 Kg	~ 8H	Electricity	Max. 3.2 Km/h
[3]ANY mal C		Legged	Inspection and mapping on-site	DynaArm	10 Kg	> 2H	Electricity	Max. 3.6 Km/h

Table 1: Mobile Platform Robots Products

of legged mobile robots. The function is very powerful, but it has some own limitations at the same time. This legged robot can cope with different terrain conditions and adjust its moving characteristics accordingly. The highly precise sensors and algorithm can also support it for collision detection and autonomous path planning. The specific shell design also ensures the water- and dustproof performance. However, ANYmal C has the lowest payload (10 kg) and run time (around 2 hours) due to its design features.

Apart from these mature commercial products, many prototypes have been developed for specific purpose during construction processes, such as brick laying, installation, scanning and so on.

Dakhli and Lafhaj from École Centrale de Lille proposed a set of autonomous robots for bricklaying [DAK17]. This proposal is based on a mobility system consisting of a scissor lift with wheels. Above the lift, surface lie the bricks as well as corresponding tools and machinery, e.g. cement mixer and bricks conveyor. The bricklaying operation is completed by an end effector on the head.

The report focuses more on the function of bricklaying, while horizontal mobility can only be achieved by ordinary wheels without additional treatment, so there are problems in overcoming obstacles and braking. Therefore, it faces a great challenge when encountering with difficult ground surfaces. It can barely handle it especially in case of slopes, rough or slippery surfaces.

A manipulator for construction sites is presented by researchers from Innovative Technology and Science Ltd [GME18]. Under the condition that a higher accuracy has to be guaranteed during the performance of upper robots, this paper focuses on the horizontal mobility style and drive strategies. After comparing mostly Swedish wheels and omnidirectional wheels, they presented a system composed from a mobile platform and a 6-DoF ABB robot. A drilling task was conducted afterward based on this design method.

Mobility system design of this prototype consists of 4 omni-directional wheels, which are more advanced than ordinary standard wheels. On the other hand, the drawback lies in the robot’s great mass. Under static and dynamic situations, normal stress and fatigue analysis must be conducted on wheels and their connecting components.

Researchers have also made great progress in chain-driven platform robots. S.Y. Lee, Y.S. Lee, and B.S. Park from Hanyang University, South Korea developed a chain-driven Multipurpose Field Robot and conducted an experiment of installing construction materials such as prefabricated window form [LEE07]. A caterpillar thread powered by DC motors with reduction gear enables the system’s horizontal mobility. For the vertical displacement of a top plate, it is achieved through a hydraulic cylinder. Additionally, an outrigger was added to prevent a robot from tumbling. Here two typical workspaces are discussed during the mentioned process, namely free space and constrained space. The motions in terms of speed and precision of operation vary. To solve it, sensors, remote control, and interaction algorithm between humans and robots are considered from the perspective of hardware and software.

This proposal has a digital platform, yet the technology is not very mature for now: some actions must be manually controlled, and the number of automated operations is rather low. It’s further development of functions depends on the corresponding additional modules.

A mobile robot platform named HORIZON XIX was developed by Erchen, Triller, and Sohlbach from FRoST Team, Frankfurt University [ERC20]. Their design distinguishes itself from other rovers like MER (Mars Exploration Rover) and Curiosity by using a chain chassis. Their chassis design by using 5 wheels which are connected to dampers via swing arms, separately on both sides enables the entire robot to operate normally on rough terrain. If an obstacle is crossed, the wheels can move up to 8 cm vertically. With the 5-DOF manipulator and the drilling unit as peripherals, the mobile system makes it possible to drill, excavate and operate in inhuman environments such as space or disaster areas. One obvious disadvantage of this design is that it’s too heavy to be transported, and it also lacks the convenience on construction sites.

Based on an advanced type of wheel “ASOC” from MIT, Julius Sustarevas and her team designed a Mobile Agile Printer

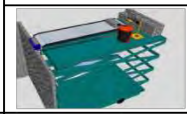
Project	Autonomous bricklaying robots	Holonomic mobile manipulator robot	Multipurpose Field Robot	HORIZON XIX	Mobile Agile Printer Robot
					
Main develpers and reference	Dakhli and Lafhaj[DAK17]	Innovative Technology and Science Ltd[GME18]	S.Y. Lee, Y.S. Lee, and B.S. Park[LEE07]	FRoST Team, Frankfurt University[ERC20]	Julius Sustarevas, Daniel Butters, Mohammad Hammid, George Dwyer[SUS18]
Drives	Fixed wheel with semi-autonomous scissor lifter	Omni wheels with semi-autonomous scissor lifter	3 DOF Caterpillar tread with a reduction gear	Two parallel chains, 5 wheels each side connected via swing arms	4 ASOC-type legs
Manipulators	Robot-laying head	An ABB 6 DOF-manipulator	6 DOF-manipulator from Samsung Electronics	5 DOF-manipulator and other drill unit	7 DOF- KUKA LBR iiwa 7 R800
Applied processes	On-site brick laying	On-site drilling	Construction material installation	On-site drilling	On-site additive manufacturing
Advantages	Easy to transport and requires little labor	Manoeuvrability, stability, and ability to overcome obstacles	Suits hazardous operation environments	Can cross difficult terrain, and suits for inhuman environments	Highly agility suits for a compact volume and dynamic environment
Obstacles	Not completely autonomous and requires clean and hard floor with no slope	High stresses and fatigue due to the considerable mass of the overall robot (550 kg)	Construction materials were limited to 60 N and below	Hard to transport and not suits for multi-floor on-site	Due to the omni-directionality and high-DoF, the MAP robot system is highly redundant

Table 2: Mobile Platform Robots Research Projects

Robot (MAP) [SUS18]. This design type used a mobile platform consisting of 4 ASOC-type legs, where the wheel and leg rotation axes intersect with each other. Thus, the omnidirectionally is assured. In this paper, the possibility of transforming the additive manufacturing process from gantry structures in factories to mobile robotic platforms is discussed. With the aid of mobile robotic platforms, it's not only achievable to proceed it on sites but also the property of high DoF can acquire a higher quality by adjusting adding material directions. However, mobility design in this model is based on more advanced, but also complex type of wheel "ASOC". This design increases the difficulty to control while improving flexibility.

To summarize, not only commercial products but also prototype mobile platforms are introduced here as an efficient method to enhance the reachability of the robots. For specific purposes, suitable platforms are selected together with a functional manipulator to operate in different working environments and processes. Wheeled platforms are usually applied in a predefined workspace and aimed at prefabrication. Tracked platforms are more suitable for the on-site processes because of the tolerance of the uneven ground. Legged robots are with the highest flexibility while with the limitation of the payload, they are discussed more in preconstruction processes like scanning or cooperation with lightweight manipulation.

3. Methodology

The research problem is what sorts of mobile platform robots are suitable for automated construction. To answer it, numbers of secondary data were collected and analyzed through public product manuals, academic articles, and scientific homepages. The abstracted qualitative requirements of different construction scenarios are the variables. Correspondingly, the characteristics of the mobile platforms are listed from both perspectives of drive strategy and autonomous navigation. Then methods and technologies are suggested to form hybrid concept prototypes. Additionally, the potentials and difficulties in further applying the advanced mobile robots which have been experimented with and applied in other industries, are described to form a well-rounded understanding of the mobile platform robots.

All these models are from the qualitative analysis without testing and comparing. Objectively, this article is a theoretical summary and integrated research.

3.1 Mechanical Technical Details

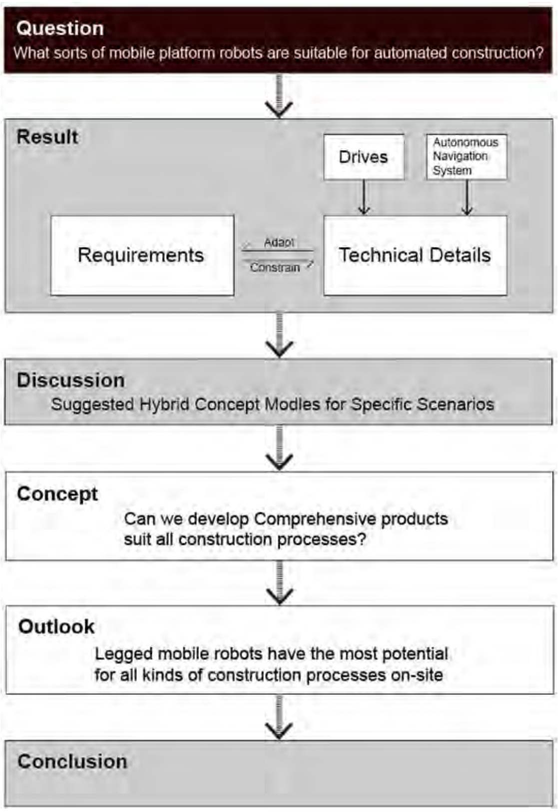


Figure 3: Methodology

Various motion principles can be found in nature: channel flowing, crawling, sliding, walking, running, and jumping. Some of them have been adopted by industry. For example, pipeline transporting is one of the dominating methods of transport petroleum and liquified substances, especially in long-distance transportation: one typical application is the Druzhba Pipeline (Figure 04) transporting oil from Russia to spots in Ukraine and Germany, etc. The stability of material properties is crucial in this process. This example follows the rule of channel flowing.

A series of legged robots have been developed by companies or academic institutes, including 4-legged dog-liked Spot Classic (Figure 05) and 2-legged humanoid Atlas from Boston Dynamics. However, legged robots tend to have more joints and links, resulting in many DoFs being controlled and making it more difficult to calculate and simulate.

We compare and analyze the drives from several different aspects and the results are listed in table. It can be seen that even though legged robot has its own advantages on flexibility over Degree of Freedom (DoF) and surface requirements, the overall applicability is not very good compared to wheeled and tracked ones.

Therefore, in this chapter, two simpler drive types: wheel drive and chain drive, will be analyzed, compared, and discussed in the context of construction engineering.

For robots moving on a horizontal surface, linear movement in both x- and y-directions, as well as rotation have to be guaranteed. Furthermore, when the reference coordinate system is moved from the robot platform center to a certain point (e.g., root position of end effector on a platform), the platform's own geometry properties also have to be considered. For each wheel, a rolling constraint (along wheel velocity direction) and a nonslip velocity constraint (perpendicular to wheel velocity direction) have to be satisfied in the calculation.

Figure 3: Druzhba Oil Pipeline [Gigantic Druzhba oil pipeline paralyzed for weeks | DW | 07.05.2019]

Figure 4:Spot Classic, Boston Dynamics
[Legacy Robots | Boston Dynamics]

A fixed standard wheel (Figure 06) is the most commonly used wheel in almost all fields. Its typical characteristic is the wheel's central axis is fixed. Based on this property, all positional and angular parameters are set, reducing the complexity to calculate or to proceed with simulation.

The steered standard wheel is of a similar format to the fixed standard wheel. The only difference lies in the ability to rotate around the axis. By updating from fixed to steered standard wheel, chassis can usually achieve higher flexibility.

The castor wheel (Figure 07) has a horizontal offset between the wheel center and the chassis connecting center: one common example is suitcases.

Swedish wheel (Figure 08), also known as Mecanum wheel, differs from all other types mentioned above by having an additional angle between wheel plane and rollers plane. Vertical vibration may occur due to the discontinuous contact between Swedish wheels and the ground surface.

Yet, the wheel design architecture also greatly influences mobility. In the robotics area, normally a mobile platform robot consists of three or more independent wheels to achieve stability under static conditions. By applying three or more Swedish wheels, an omnidirectional mobile platform can be achieved. By contrast, the design type of auto determined it's only possible to move straight forward and rotate around a point away from the axis.

Chain drive is another widely used drive method in the industry. All points on the same chain have the same linear velocity, which enables the driving power to be transferred from one to another. Among them, the roller chain and the Morse chain are two representative types. However, the difference between chain-driven machinery mostly lies in the design of wheels, while the driving principles are quite similar.

One of the main advantages of chain drive is that it can enlarge the linear speed of a certain part with a constant power through chain transmission and gears meshing. Another character is its ability to adapt to different terrains. The driving power applied to wheels would be automatically transferred to other parts on the same chain (Figure 09). Besides, contact surface area is increased due to the

Decision matrix for three types of mobile platform in construction processes								
	SUM	Flexibility	Stability	Surface Requirements	Kinematics Complexity	Speed	Run Time	Payload
Wheeled	0	0	0	-1	0	1	0	0
Tracked	3	-1	1	0	1	0	1	1
Legged	-1	1	-1	1	-1	1	-1	-1
Rank the performance of mentioned commercial mobile platforms from listed perspectives, the best one scores 1 point; second one scores 0; worst one scores -1.								

Table 3: Criterion Comparion of Wheel, Track and Leg Drives

Type			Characters			
Name	Image		Wheel rotation	Axial Rotation	Offside	Angle between wheel plane and rollers plane
Standard Wheel		Figure 06. Standard Wheel [standard Fixed castor + solid polypropylene wheel Ø 108 x W36mm for 150kg Prod ID: 91623]	√	√ for fixed × for steering	×	×
Castor Wheel		Figure 07. Castor Wheel[Castor Wheel Swivel Castors Casters Wheels Heavy Duty Wheels Fixed Castors, 100 mm: Amazon.de: Küche & Haushalt]	√	√	√	×
Mechanum Wheel		Figure 08. Mechanum Wheel[Reinventing wheels - Mecanum wheels that can move a vehicle in any direction - Patent Yogi LLC]	√	×	×	√

Table 4: Comparision between Wheels

application of track. Hence, normal pressure on the ground will be decreased by a large degree. In addition, commonly-used inverted trapezoidal design in practice also increases the ability of overcoming obstacles.

On the other hand, these types of equipment usually have a larger weight and drive power, combined with harder chain materials such as steel. It is likely to cause greater shearing stress, then damage to the road surface. During the rotating process, great shearing stress will be generated by difference from chain velocities, and the consequences would be more serious.

Nearly all chain driven vehicles share the same principle, except for only a few changes due to specific situations.

Overlapping wheels were used on tanks during World War II to increase the driving stability. However, this method has been abandoned because of its complexity and maintenance period.

Another common change is to equip rubber tracks. The main purposes are to reduce the noise, also damage to terrain surfaces, especially roads or floor slabs in

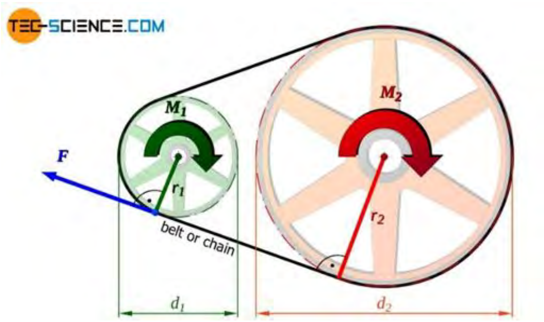


Figure 5: Torque Conversion of Chain Drive [How does a gearbox (transmission) work? - tec-science]

construction.

The different arrangements of wheels are also of vital importance. The most common method is to place all wheels at the same height, forming a plane (Figure 10). Trapezoidal arrangement (Figure 11) can help improving stability for highly dynamic equipment, while the inverted trapezoidal arrangement (Figure 12) aims to improve the ability to climb over obstacles.

3.2 Digital Planning about Mobile Platform Robots

For mobile platforms, the main function is autonomous navigation in an unknown, dynamic environment without collision. In practice, the robots can autonomously

<table>
<tr><th>Type</th><th colspan="2">Image</th><th>Characters compare to the ordinary type</th></tr>
<tr><td>Ordinary plane</td><td></td><td>Figure 10. Ordinary Plane Chain[Trac-Drive Mower and Snow Plower | RobotShop Community]</td><td>/</td></tr>
<tr><td>Trapezoidal Chain</td><td></td><td>Figure 11. Trapezoidal Chain [卡车也能改坦克，新西兰斯科菲尔德坦克，一款有趣的装备 - 知乎]</td><td>Higher Stability</td></tr>
<tr><td>Inverted Trapezoidal Chain</td><td></td><td>Figure 12. Inverted Trapezoidal Chain [T-34 Tank Tracks and Suspension]</td><td>Ability to Climb Over Obstacles</td></tr>
</table>

Table 5: Comparision of Chain Forms

travel to the desired pose via a series of waypoints. If obstacles are detected, they will stop and re-plan an optimized shortest trajectory to meet the endpoint based on previous path planning.

To fulfill this goal, perception systems and algorithms are of great significance, namely, the cooperation between hardware and software.

The hardware system can be recognized as the collaboration of several sensors. All these sensors can be classified into two types, proprioceptive sensors, and exteroceptive sensors. The proprioceptive sensors are used to measure the internal robot system, for example, the speed and load of wheels. While the exteroceptive sensors, such as optical sensors and sonar emitters, mainly percept the environment and extract dynamic real-time information. Through the wireless adapter, the feedback information and every control signal can be transmitted to the mobile platform through a communication module and a converter.

Here we mainly discuss the active range sensors, which is of great significance to communicate with the dynamic environment and avoid obstacles during the mobile platform operation processes. Initially, multiple sonar sensors were applied to detect the obstacles. The acoustic properties of the surrounding materials can cause a discrete impact on the reflection performance. Another limitation of ultrasonic ranging relates to bandwidth. It takes more time to get the signal back. Using ultrasonic, the update rate can have a measurable impact on maximum speed while sensing and avoiding obstacles. Because of the limitations of accuracy and update rate [SIE11], this method was soon substituted.

As a most commonly used scanning tool, Laser rangefinder allows the measurement of a wider range with higher resolution and accuracy, and it is generally not limited by surrounding conditions during the data acquisition process [JAS03]. However, the laser rangefinder requires considerable time to complete a full scan, because multiple scans must be registered at different locations due to limited data capture coverage and occlusions on the site to generate an as-built model for construction projects [ATA09], which is costly, labor-intensive and time-consuming.

Proprioceptive sensors		
Classification	**Functions**	**Sensors**
wheel/ motor sensors	Used to measure the internal state and dynamics of a mobile robot	Potentiometers
		Synchros, resolvers
		Wheel encoders
Acceleration sensor	Used to measure all external forces acting upon it, including gravity	Accelerometer
Heading sensors	Used to determine the robot's orientation and inclination	Gyroscopes
Exteroceptive sensors		
Classification	**Functions**	**Sensors**
Active ranging	Used to measure direct distance from the robot to objects in its vicinity, detect and avoid obstacle	Reflectivity, time-of-flight, geometric triangulation
Motion/ speed sensors	Used to measure relative motion between the robot and its environment	Doppler radar and Doppler sound
Vision sensors	Enables rich, intelligent interaction in dynamic environments	CCD/CMOS cameras, Visual ranging packages, Object tracking packages
Ground beacons	Used to identify the outdoors position of robots precisely	GPS
Tactile sensors	Used to detect physical contact or closeness	Contact switches, bumpers, Optical barriers
Heading sensors	Used to determine the robot's orientation and inclination	Compass, Inclinometers

Table 6: Comparision of Proprioceptive and Exterocepive Sensors

However, similar to ultrasonic ranging sensors, the coherent reflection of the energy will occur when striking a highly polished surface with light [SIE11].

Except for laser scanner, 2D Light Detection and Ranging (LiDAR) and mileage data generated method also yielded a high-accuracy surrounding information [PIL18]. On the basis of 2D LiDAR, custom-made 3D scanners are typically built by nodding or rotating a 2D scanner in a stepwise or continuous manner around an axis parallel to the scanning plane [SIE11]. It takes only several seconds for full 3D scanning, which depends on the desired resolution. As a matter of fact, the rotating Sicks developed at the ASL (ETH Zurich) were used on an autonomous car running at 10 km/h, where very accurate (up to centimeter) vehicle motion estimation was necessary to correct the errors in the 3D data caused by the movement of the car [SIE11]. Time-of-Flight camera has the same function as a lidar with the advantage that the whole 3D scene is captured at the same time without any moving part. Meanwhile, TOF cameras use less processing power than stereo vision, where complex correlation algorithms are used [SIE11].

What is more, Optical triangulation methods are also widely used, which use

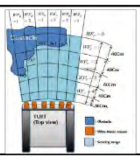
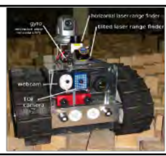
Active ranging sensors				
	Ultrasonic sensor	**Laser rangefinder**	**Time-of-flight camera**	**Optical triangulation**
Principle	Transmit a packet of (ultrasonic) pressure waves and to measure the time it takes	Transmit laser light and to measure the time it takes and also referred to as optical radar or lidar	Uses a modulated infrared lighting source to determine the distance for each pixel of a Photonic Mixer Device (PMD) sensor	Use geometric properties manifest in their measuring strat egy to establish distance readings to objects
Resolution	Ca. 2 cm	Ca. 35 mm	Ca. 1 cm	In high-precision industrial measurements far below 1 µm
Operating range	12 cm up to 5 m	10 mm up to 20 m	0.5 m up to 8 m	8cm up to 80 cm
Advangtages	Not expensive	Wider range with higher resolution and accuracy	Whole 3D scene is captured at the same time and without moving parts. Less processing power than stereo vision	Relatively high accuracy with very good resolution and high bandwidth without cross-sensitivities
Obstacles	Areas of error, bandwidth, and cross-sensitivity	Cannot detect the presence of optically transparent materials such as glass	Expensive	Limited in range
Example	(UTR) Unmanned Transport Robot by Bo-Hyun Yu [HYU08]	Autonomous Mobile Robot by Pileun Kim [PIL18]	The Swiss Ranger is applied to map building, and avoid obstacle [JAN10]	Using MS Kinect Placed on the Mobile Robotic Platform [ŤUP15]
Picture				

Table 7: Comparision of Active Ranging Sensors

geometric properties manifest in their measuring strategy to establish distance readings to objects. The Kinect sensor from Microsoft is enumerated as an example which consists of a 3D camera that uses an infrared pattern projector and an infrared camera to infer distance from the captured pattern. It comes with a color web camera, a microphone array, an accelerometer, and a tilt unit. With it, the robots can detect the human body and tracks its skeleton and make it possible to establish collaboration between robots and humans [VAS18].

To adapt different scenarios, currently, various methods have been developed and combined for multiple properties.

Meanwhile, another goal for the mobile platform is that it is supposed to be easy for the users to connect to the robot and control it. This could be achieved from two layers, an operation system, and a specific algorithm.

More specifically, different sensors are selected to put on the vehicle that will operate in real-world environments. The computational processing is done by using Robotic Operating System (ROS) at the same time. SLAM (Simultaneous Localization and Mapping) is implemented to provide localization estimates in environments.

There is a special transformation system has been written for ROS for the interactivity during the tracking process. During the process, we can use it to deal with complex relationships such as the relationship between a mobile robot and some fixed frame of reference for localization and the relationship between the various sensor frames and manipulator frames. It provides services designed for heterogeneous computer clusters such as hardware abstraction, low-level device control, implementation of commonly-used functionality, message-passing between processes, and package management. The transformation system can produce streams of transformations between nodes on the tree by constructing a path between the desired nodes and performing the necessary calculations. For example, the transformation system can be used to easily generate point clouds in a stationary "map" frame from laser rangefinder received by a tilting laser scanner on a moving robot [QUI09]. Additionally, it can be easily extended by adding new hardware components, like new sensors. To combine the sensors, we need to install the provided ROS software packages for each one. These packages create nodes. A node is an executable that uses ROS to communicate with other nodes. Over the ROS framework, it also allows the installation of third-party libraries on the robot controller to run ROS nodes [CHA20].

SLAM is a way to allow robots to estimate their current position and orientation as well as the environment map. The aim of SLAM is to recover both the robot path and the environment map using only the data gathered by its proprioceptive and exteroceptive sensors. These data are typically the robot displacement estimated from the odometry and features [SIE11]. There are three main paradigms developed to solve the SLAM problem, which are EKF SLAM, graph-based SLAM, and particle filter SLAM.

Via Extended Kalman Filter (EKF) SLAM, the state vector and covariance matrix are updated using the standard equations of the extended Kalman filter during the operation process. The result maps are more feature-based [SIE11]. However, this makes EKF SLAM computationally much more expensive. When it comes to the environment, it assumes that the position of the features is fully measurable from a single robot location, because most SLAM applications have been realized using rangefinders.

Graph-based SLAM represents robot locations and features as the nodes of an elastic net. The SLAM solution can then be found by computing the state of minimal energy of this net [SIE11]. The update time is fixed and requires less memory space by this way. Nevertheless, graph-based SLAM algorithms have shown impressing and very successful results with even hundred million features.

In particle filter SLAM, the mean and covariance of each feature are updated using distinct Kalman filters, one for each feature in the map to simplify the calculation process. A great advantage over EKF SLAM is that due to the use of randomized sampling it does not require the linearization of the motion model and can also represent non-Gaussian distributions [SIE11].

3.3 Process Environments

Construction industry covers a wide range of complex environmental conditions. First and foremost, the environment varies due to project types, e.g. residence construction or infrastructure construction such as bridges and tunnels. Within the same project type, more variables should be taken into consideration based on specific construction processes. This chapter intends to select several typical construction processes and conduct analysis on their characteristics.

The very first stage of automation in construction starts from prefabrication. Regarding these conditions similar to factory or assembly line, where robot's application has been really mature. The working environment is mostly indoor, with shelters, air conditioner and other equipment to maintain a relatively stable situation in the space. Besides, prefabrication factories are usually equipped with sufficient power portals or have stored enough energy supplies like batteries. In this process, raw materials are transported in then manufactured into certain products or components. The impact of natural environmental conditions is relatively small.

In the prefabrication processes, robots are generally supposed to cooperate in a specific sequence. They are used to improve the mobility and reachability of the manipulator. Precise mapping and trajectory without collision are necessary during these processes. More importantly, in a shared workspace the mobile platform should be direction sensitive.

On-site outdoor operations are mostly related to the original raw workspace. Under such conditions, the environmental characters tend to be harsh: the site conditions are mainly unstable natural soil and rocks, and the (adjective missing) temperature, humidity and dust conditions. These works can be autonomous or remotely controlled by workers.

For outdoor conditions, the machinery is usually directly exposed to sunlight, dust and rain. The changeable natural environment has a great impact on their performance. Therefore, mobile platform robots, along with their corresponding end effectors, are in this case at greater risk of overturning, water ingress and jamming. They are more likely to be influenced by temperature changing. How to cope with the terrain and weather conditions should be in the first place for these platform robots. Besides, the operation duration tends to be relatively longer. Conditions for charging or replacing batteries are also relatively backward. Therefore, the power supply is also of vital importance.

On-site indoor operations include more specific processes. Site condition scanning before or during construction, and manufacturing work (such as drilling,

Requirements								
	Sheltered	**Ground surface**	**Environment information**	**Operation frequency**	**Access to charge**	**Range of workspace**	**Payload**	**Interactivity**
Prefabrication	Yes	Good condition	Accessed	Successive	Easy	< 10M	200 kg	High
Outdoors operations	No	Harsh condition	Unknown	Continuous	Hard	> 20M	> 1T	Low
Indoors operations	Yes	Uneven surface	Semi-accessed	Intermittent	Easy	< 20M	200 kg	High

Table 8: Environmental Requirements estimated by the Authors

milling, additive manufacturing) are the two processes we will focus on later. The common point between them is that the working environment is mostly on a hard-firm ground with shelter and sometimes other environment adjustment devices, so the natural environmental factors are relatively stable. There are usually workers and materials or other stacked tools and instruments on the actual construction site. Therefore, the complexity of the environment is generally between that of prefabrication in factory and outdoor operation.

For site condition scanning process, the most critical requirement is to compute and predefine a rational trajectory with enough overlap to ensure validity. During the process, the robots are supposed to avoid collisions and re-plan the path according to the dynamic surrounding. They have to set markers and record the essential information real-time as well. In this process, sensors and algorithm play a more important role than mobility system. However, a higher flexibility of mobile platform robots is beneficial for operation.

The application of mobile platform robots on on-site manufacturing is achieved by attached powerful manipulators. By the cooperation from manipulators and platforms, task required position and orientation of end effectors can be reached. Requirements for these tasks are more about operation precision and working efficiency. Safety issues such as collision detection must be guaranteed to avoid breaking materials and hurting people. For more advanced application process, specific sensors and algorithm should be applied to achieve an intuitive human-machine-cooperation. We summarize the environment requirements for processes in this table.

4. Discussion and Outlook

The working environment for previously mentioned prefabrication process is closer to ideal simulation and calculation environment for robotics design. The flat, hard-firm ground condition has reduced the requirements for mobility system. A robot, in this case, should have higher velocity and flexibility, which is exactly one characteristic for wheel-driven robots. A well-designed wheel-driven robot can independently achieve linear velocity in both x- and y-direction, as well as rotation around its self-center, which requires no extra space. Typical aimed objects are segments of construction material such as steel sheet, rebars and timbers, and the payload of manipulator usually do not exceed 20 kg. A reference parameter from KUKA KMP 200, the payload of the whole platform is 200 kg.

Additionally, the cooperation between several robots is supposed to be considered. In another word, the lightweight and relatively small-scale mobile platform with a smaller turning radius is more suitable for organizing the collaboration in prefabrication work. Under this circumstance, the lightweight omnidirectional wheeled mobile platform with accurate laser scanners could be the best choice.

Outdoor operation conditions are somehow contrary to the preset conditions of wheel drive, as wheel drive mostly presupposes that the wheels should be on the same plane coordinate system, which is usually not the case for raw ground. By contrast, tracked and legged mobile platforms are more suitable for uneven ground, because of the track and a higher Degree of Freedom respectively.

Besides, due to a smaller contact surface area, the normal pressure caused by wheel drive equipment is also higher than that of chain drive equipment, leading to more frequent or severe problems of machinery sinking into the soil. For legged mobile platforms, it is also much more difficult to maintain balance and stability of the upper manipulators. Hence, we draw the conclusion that tracked mobile platform model could be a good choice for this situation. The required payload should be of tonnage class. Besides, large capacity batteries and diesel generators are the solutions to long-period operation time. Nevertheless, the legged mobile robots without manipulators are more suitable for inspection on-site for their flexibility and lightweight. In this case, the required payload can be less than 10 kg.

Different from indoor processes, ground beacons sensors can be applied to gather the geographic Information previously and get precise position via GPS. In this way, it takes less computational cost. Time-of-flight active ranging with wide range can be used to avoid obstacles in a nonassessable environment.

As previously discussed, on-site indoor operation environments have similarity to that of prefabrication, probably with less power supply portals or other equipment. On the other hand, tasks for condition scanning may cover several floors. This requirement can be fulfilled by using construction elevators or moving equipment manually, but a legged robot in this case can also be used. Another problem worthy to be considered is that concrete may have not reached the final strength after a complete curing process. Therefore, it can be risky to choose a tracked robot to conduct tasks on these surfaces, because of the potential damage caused by friction during robots' rotation.

Therefore, wheel-driven and legged robots can be used, and their diameter and motion strategies of mobile platform are dependent on different situations. For example, the mini chain-driven inspector robots are more suitable for pipes and ceiling checking. Legged robots suit better for the complex site with terrain difference, and wheel-driven robots can be applied to the completed environments. The requirement of the payload here is only for carrying the perception system, which is less than 10 kg here. TOF camera sensors can extract valid information with the simple algorithms. Laser rangefinder sensors can work in a wide range with accuracy and make it possible to plan the overlapped path for navigation.

Since the robots are equipped with powerful end effectors or manipulators, they can also help with welding, drilling, milling, additive manufacturing, etc. During these processes, to ensure the stability of the upper part, it is better to select the wheeled and tracked mobile platforms from the economic and operational perspectives. Under this condition, for the lightweight chain drive robots, shearing damage to the ground can be mitigated by applying a rubber track.

Robots are also expected to interact with humans. Structured light, haptic system, and even stereo vision module can be added to improve the precision and efficiency of this interactive process.

A common problem on-site is the energy supply. Current products are mostly supported by rechargeable and replaceable batteries. To solve the limitation of energy supply, it is feasible to set a charge station on-site as well. Except exchange the batteries on time, the robots could be designed to find a way to the station when the battery is about to run out.

The suggested hybrid models are just from the perspective of efficiency. On the basis of the matrix, we propose a further question here, can we change the parameters and improve the performance via additional tools to create a well-rounded prototype model, which suits as many scenarios as possible.

There is no denying that legged robots have the best mobility and can cope with more complex ground conditions. Nowadays, although their drawbacks in payload, stability and operation period are also very obvious, we can combine specific techniques to compensate for the obstacles. 4-Wheeled-legged integrated model can extend the limits of stability and payload. Once equipped with chargeable large capacity batteries, the operation time can be also extended. Another potential proposal is the 2-legged humanoid with

Suggested hybrid models						
Processes	Off site	On site				
	Pre-fabrication	3D scanning		Pre-work in raw environment	Specific operation on site	
Drives	Omni-wheeled mobile platform with Mecanum wheels	Legged mobile platform	Tracked mobile platform	Tracked mobile platform	Wheeled mobile platform	Tracked mobile platform with rubber
Context	Manufacture timber	Gather site information	Inspect specific construction like ceiling and pipes	Transport material	Single-layer drilling, milling, welding	Multi-layer drilling, milling, welding
Reasons	Direction-sensitve	Flexibility and mobility	Small scale with easier system	High payload and suits for bad ground condition	Stable without damage to the floor surface	Decrease the friction with wider range of operation
Necessary senors	Laser rangefinder and structured light sensors	Laser rangefinder and TOF camera sensors	Laser rangefinder and TOF camera sensors	Laser rangefinder and GPS	Laser rangefinder and structured light sensors	Laser rangefinder and structured light sensors
Energy supply strategy	Swappable batteries and charge station on site	Swappable batteries	Swappable batteries	Large capacity lithium battery and LiPo battery charger	Swappable batteries and charge station on site	Swappable batteries and charge station on site
Payload	~ 200 Kg	< 10 Kg	< 5 Kg	> 1 T	~ 200 Kg	> 200 Kg

Table 9: Summary diagram

precise manipulators. Since they have the highest flexibility and a size similar to human, the application range of them is larger than that of mobile platform.

Another challenging topic about legged robots is how to improve the stability and the interference-resistant of the manipulators. Furthermore, the complexity of joints design must be considered in terms of the models of kinematics. From the perspective of economics, technology, and even operation, the legged all-purpose robots still need to be further developed. The current theoretical research and prototype experiment results are still unable to realize such robots to work efficiently in a dynamic construction environment. On the other hand, due to the ease of calculation and simulation and better field performance, the wheeled and tracked mobile platform can potentially be applied widely in the near future.

5. Conclusion

The application of mobile platform robot is considered as one of the most promising solutions to improve the automation degree in the construction industry. When equipped with manipulators, sensors, and algorithms, mobile platform robots can help to fulfil different tasks even in harsh environment.

Wheel-driven and chain-driven mobile platform robots are two simpler design types. By comparison, the former has more alternatives for choosing wheels and designing, as it tends to have a higher velocity and is easier to control and calculate; while the latter's principle is relatively simpler, but its own advantages lie in perspectives such as lower normal stress and the ability to overcome obstacles.

Digital sensors and algorithms can be applied as well to enhance the functionality of mobile platform robots. Especially, the active rangefinder sensors are significant to detect and avoid obstacles, and path planning as well. When it comes to the outdoor environments, the integration of GPS and the rangefinder sensors can make it possible to explore the dynamic process precisely.

On the other hand, there are relatively big differences in working condition between processes in the construction industry, for example, in the objects of work, natural environmental conditions, and energy supply conditions. Therefore, this wide variety requires different characters of construction robotics. We have concluded that in different construction processes, due to their specific work requirements and environmental conditions, certain or several specific technical combinations can achieve higher work efficiency and economic effects than other combinations.

In the future, even though the application of legged robots can be a potential development direction in this area, due to its own complexity and high construction cost mean that, despite the potential advantages (economical and spatial) in construction processes, it is still uneconomic to develop a universal robot that copes with all construction processes, while wheeled and tracked robots can be mature and sufficient choices under most conditions.

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Zhuopeng Li

Wei Guo

Façade structural health monitoring and replacing system

Abstract

As urbanization accelerates, the demand for curtain wall glasses become higher every year [MAR21]. Curtain wall glass is subject to spontaneous breakage, damage from extreme weather and strikes from disoriented birds. These factors pose a great challenge to the durability and reliability of such building components. The unplanned nature of incidental damage necessitates constant inspections, which incurs high costs. In a regular Once the defect occurs, workers have to be sent to an elevated height to complete the hazardous glass inspection and replacing task [VOL20].

In the research part, we first investigate the features of usual curtain wall glass, focusing on the sorts, types and so on. Then we study two curtain wall examining approaches and introduce a previously developed structural health monitoring platform. Afterwards, we review the literatures, patents and commercial solutions regarding curtain wall structural monitoring and replacing.

Based on the researched theories, we propose a solution to handle cracked glass, comprising a curtain wall structural health monitoring sub-system and a drone-based replacement sub-system.

The monitoring is achieved with infrared-laser examination sweep technique, controlled and planned by the aforementioned web-based platform. The replacement can be carried out in two different approaches. One is to transport glass panel by heavy-lift drone with maximum payload capability over 200kg, the another is to complete the replacement with drone formation consisting of multiple cooperative unmanned aerial vehicle.

As the conclusion, we roughly propose a concept of UAV-based curtain wall replacement system. It's expected that such system could relieve workers from hazardous replacement task. However, due to the lack of prototyping and the restriction of the payload capability of current UAVs, we consider the implementation of such system faces great challenges.

1. Introduction

To date, most of the status check for curtain wall glasses is performed by manual inspection, while de facto glass cracking happens sporadically due to impact or structural failure, and thus it is hard to anticipate. If a small crack is produced and has not been taken care of promptly, it might rapidly develop into the crack of the whole piece of glass and inflicts human injuries. According to the statistics mentioned in [SHE20], curtain wall glasses have a self-cracking rate of 3‰ to 5‰ due to the limitation of current manufacturing techniques. For example, among the 30,000 panes of glasses installed on a skyscraper, the number of nonconformities could reach 150, which could crack any moment and may be found by people after a long while. Considering the unforeseeable events like bird strike or extreme climate, the possibility of glass cracking is even higher, and the working load and cost for manual examination are therefore higher too.

The maintenance operation of building façade is a dangerous work, because the workers need to operate at the height hundreds of metres from ground. Working at height is a hazardous and difficult work, while conventional method of replacing curtain wall glass requires exterior assistance. According to the statistics from the Occupational Safety & Health Administration of the United States of America, in 2019, over 700 workers were killed at work due to falling to lower level [BUR20]. In order to reduce the risk of traditional maintenance work, the implementation of robotics-based automation should be taken into consideration.

Automation technologies and robotics are increasingly being applied to the operation monitoring and maintenance for completed buildings [BAL08]. Moreover, many researches have depicted the development in monitoring of structural health [MEI19]; [ROC13] and maintenance of building façade [QI20].

Though a number of construction companies have employed machines or robots in the tasks at elevated height during the construction, still many works could only be done by manual workers [YU07], since many places in construction cannot easily reached by the robots. There are already many kinds of glazing robots being developed, such as the ones presented in [LEE07], [YU07] and [TAG18]. However, these robots are mostly unmanned ground vehicles designed for construction phase, which are not suitable for the consequent maintenance due to its bulk.

In this article, we address the research question, namely, how to achieve a more efficient façade structural health monitoring and a replacing method without endangering human labour force.

We first present the background and methodology of our study, then review the related literature, state-of-the-art and commercial solutions in current marketplace. As the central part of this paper, we investigate the possibility to incorporate the aforementioned technologies and propose an application which monitor the status of building façade and drone-based defect glass panel replacement. Based on the proposal, the discussion concerning the potentials and challenges of the application is carried out, and the conclusion is drawn in the end.

2. State of the art

In this section, sorts and characteristics of curtain wall, related literatures, patents and commercial solutions regarding structural monitoring and curtain wall replacement are reviewed.

2.1 Curtain wall

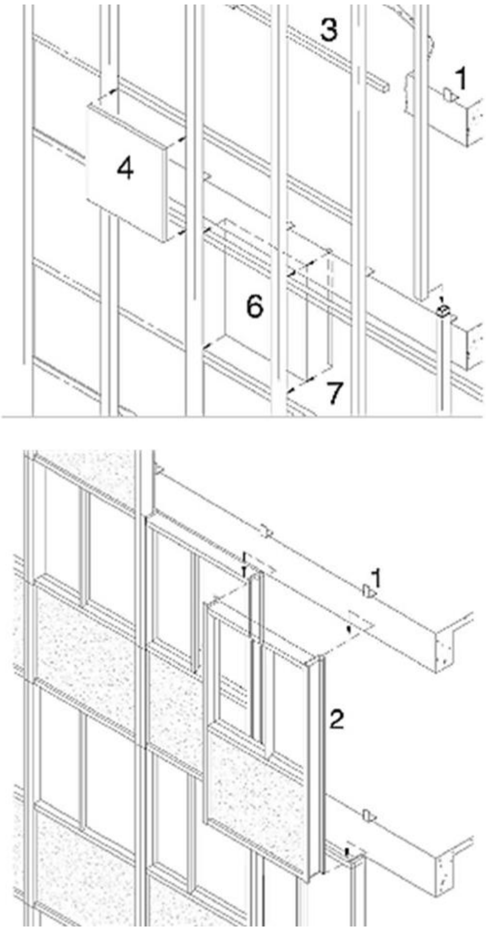

Figure 1: Stick curtain wall system and unitized curtain wall system, source: [CHR16]

A curtain wall is an envelope component of the building, in contrast to a wall, it does not offer any load-bearing capability for the upper-level roof or floor. In general, curtain walls are installed on floor by means of brackets, therefore the weight of curtain walls are sustained by structure system of the building [TAG18]. In principle, there are two types of curtain wall used for building construction, stick curtain wall system and unitized curtain wall system.

Stick system refers the type of curtain wall envelope assembled with bracket and glass separated, the bracket is disassembled and transported in the form of mullion and rails therefore called ‘stick’, together they form frame grid to keep the curtain walls fixed. This kind of system has advantages like lower cost and minimized bulk but has the most significant shortcoming of in-situ assembly [GEM16]. Unitized system pre-assembles the aforementioned elements. The frame and glass are assembled and affixed in advance before delivered to the site, which reduce the on-site work load and the construction time, but it also makes the curtain wall unit bulky [HAR19]; [INT20], requiring more space, some even need the special joint and installation procedures during assembly, thus making them more difficult to remove [GEM16]. These two curtain wall systems are shown as Fig. 1.

A regular curtain wall glass has to be sturdy and shatterproof in order to withstand the wind pressure and strike, therefore it usually consists of two glass panes with thickness from 6-10mm [INT20], considering the glass density of 50 to 60 kg/m^2 [SHE20], and the average dimension of 2m×3m, the weight of a curtain wall panel often exceeds 200kg.

As shown in Fig.2, there are four usual types of glasses classifying by the strength [EAS21]. The most basic type is annealed glass, it is formed from the float glass

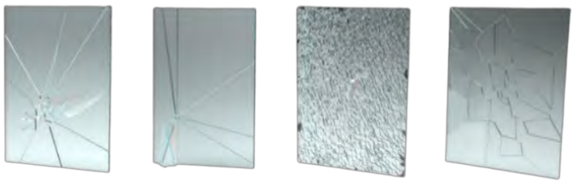

Figure 2: Annealed, heat-strengthened, tempered and laminated glass, source: [EAS21]

process, and has the weakest strength. Heat-strengthened glass is produced by applying rapid heating-cooling on the annealed glass, it is better resistant to breakage and 2 times as strong as annealed glass. Tempered glass is produced like the heat-strengthened glass but with even rapider cooling speed, making it 4 times strong as annealed glass and shatters in small pieces instead of long sharp shards. Laminated glass is made by combining two or more pieces of any of the abovementioned glasses, the interlayer between glasses is usually polyvinyl butyral (PVB), this kind of glass offers advantages like sound-proofing and penetration-resistant [SHE21].

Many factors can cause a glass breakage, such as wind load, thermal stress, chemical corrosion, incompatibility with materials and water leakage. Removal of glass is necessary when breakage happens, the process of curtain wall depends mainly on its installation manner, which varies from one to another, whereas several steps are the same in principle. 1) Remove sealant and adhesive. 2) Remove cracked glass with adhesive tools such as suction cups. 3) Install the new one. In addition, some curtain wall system include exterior constrain mechanism which needs to be removed from outside of the building [BTB16]; [BAI20].

2.2 Structural health monitoring

Curtain wall structural monitoring

There are generally two approaches to examine the cracking tendency of a curtain wall glass, one is stress examining approach [HU18]; [XIE12], the other is the visual examining approach [SHE20]. The stress examining approach is to examine stress of the glass material and compare with the reference data of the cracked glasses, so as to check if the cracking is imminent.

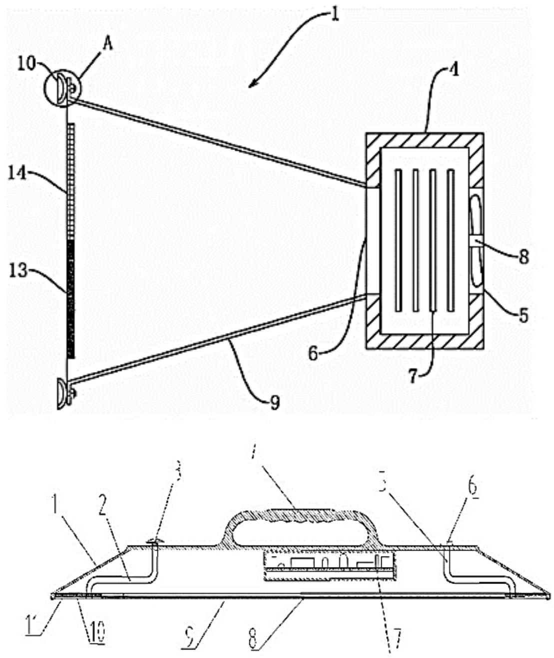

Figure 3: Two applications using the stress examing approach, source: [HU18]; [XIE12]

In [HU18], the inventor adopted the method of using a heater, temperature sensor and stress sensor to build up the temperature-stress graph and compare with the reference. In [XIE12], the inventor made a portable device which can be placed on the glass and measure the stress directly. These two methods both use piezoresistive effect to get material stress data and could only examine one piece of glass panel at a time. The overviews of these two applications are shown as Fig. 3.

The invention noted in [SHE20] is a monitoring unit which includes a scanner and a identifier. The unit is to be installed at the perimeter of the building with the light projector pointing at the façade of the building. The scanner in the monitoring unit casts infrared laser with the wavelength 700nm-1100nm onto the glass and repeatedly sweeps through the entire

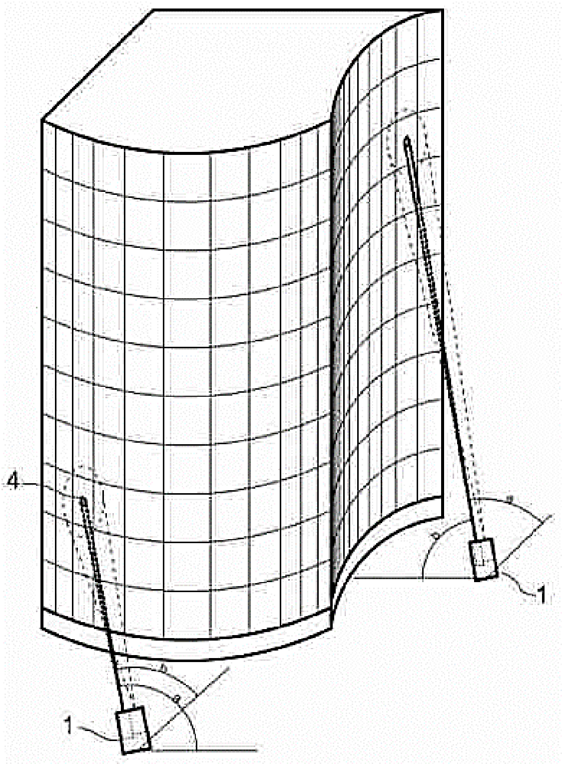

Figure 4: The overview of the visual examing approach, source: [SHE20]

façade in designated pattern. An identifier consisting of a band-pass filter, an imaging lens and a camera follows the light projector and captures real-time image. When the glass is intact, the light will pass through the glass or specular reflect, and the image captured by the identifier will present as the continuous light track with medium brightness. When the glass is shattered already, there will be spider-web-alike, dense gaps in the glass, where the extraordinary bright light spot will appear when the projector sweeps by. The overview of this approach is shown as Fig. 4.

Apart from the monitoring methods mentioned above, there are some other approaches which could be used to detect structural defect, for instance, ultrasonic sensor for detection of breakage of a metal component or the frame displacement. Many different sensors can be utilized in a comprehensive manner so as to completely detect any possible defects that could happen in the life cycle of curtain wall façade.

Structural health monitoring platform

In February 2021, Lappe et al. developed a monitoring dashboard called *structural health monitoring (SHM)* platform, using the ECMAScript-based developer tool *'Xeokit'* [LAP21]. SHM platform is capable of collecting data, analyzing data, simulating possible structural defects and verifying them, and the data is visualized through the WebGL engine. In a usual case implementing SHM platform, sensors should be first set up at vulnerable points of structure components, then the data sent to the cloud server will be fetched by the platform and if appropriate, it will be further processed and aggregated by specific service and in the end presented in the form of 3D visualization. The web interface is shown as Fig.5.

Figure 5: SHM platform, source: [LAP21]

2.3 Multi-purpose field robot

A *Multi-purpose Field Robot (MFR)* is defined as a robot platform that can use different end-effectors to cope with various tasks in different on-site occasions [LEE07]. It comprises three main components, first, a mobile platform to mobilize around the construction field; second, a manipulator which is mounted on the platform and is able to execute the particular operation, which is usually the robotic arm; third, the sensor and end-

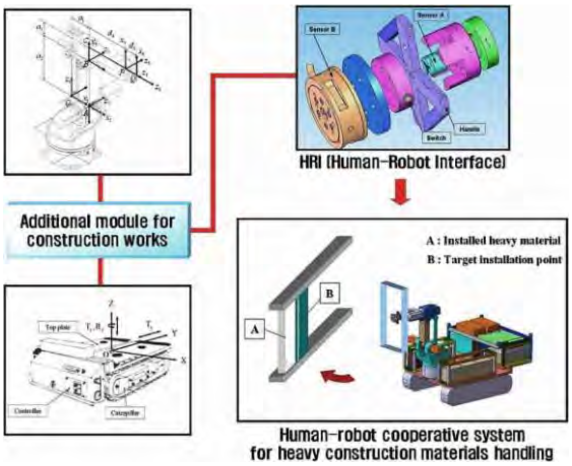

Figure 6: MFR for handling construction materials, source: [LEE07]

effector to identify the surrounding or the contact with external objects [LEE97]; [WON00]. The concept of MFR is depicted in Fig.6. In [FAR01], Farritor et al. have furth er classify the aforementioned into 2 components, one is the “basic system” consisting of the mobile platform and the manipulator, the other is the “additional module” consisting of the sensor and end-effector. Through such design, the robot system can execute different assignments by switching to different modules. Also, maintenance of the robot system is simplified due to the modification.

2.4 Curtain wall installation robot

From 2005 to 2007, a group of Korean researchers attempted some application on the automation of curtain wall installation process. The system involved is later defined in [LEE15] as *Hybrid motioned curtain-wall glazing robot (HCGR).* Based on the abovementioned MFR concept, HCGR is designed as a macro-micro manipulator. An earth-moving excavator performs as the macro motion manipulator, and the robotic end-effector acts as the micro motion manipulator.

In [YU05]; [YU07], based on the manual assembly process, which will be introduced later, a series of design principles is set up as follows:

1. Performance, the maximum payload of the manipulator shall safely bear the curtain wall weight under any condition, including during the process of elevation, assembly and translation.

2. Manoeuvrability, the robot should be intuitive enough to be operate, a teach pendant could be adapted if necessary.

3. Efficiency improvement for the overall process.

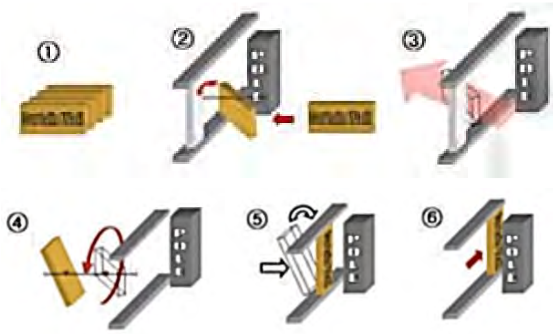

Figure 7: Process of curtain-wall installation, source: [YU05]

Furthermore, the researchers analysed the steps for a robot-driven automated curtain wall installation process. First, a curtain wall will be selected from material pile. Second, rotate the selected panel to a position where the operator can pass it through th e building more conveniently. Then pass the curtain wall panel to the

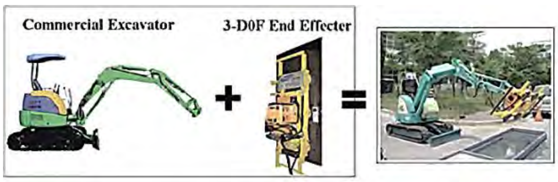

Figure 8: Schematic of curtain-wall installation, source: [YU05]

exterior and rotate it to the vertical position. Last, move the panel back and make micro adjustments to complete the assembly. The steps for this process are illustrated in Fig. 7.

As the result of the analysis, the researchers identified the 3-DOF modules for the end-effector, which can execute the actions including panning, rotation and translation. For the mobile platform and manipulator, in consideration of the convenience of acquiring the basic system, a general-purpose usage excavator is selected. The combination of the system and additional module is shown as Fig. 8.

In addition, a performance test is carried out at a real construction site using this system. Regarding lifting ability needed, the power of the boom and vacuum suction cup reaches 14.3kN and 4.4kN respectively while it is expected only 7.8kN and 2.9kN required in the estimation. Regarding the task time, the researchers first divide the task into three parts:

- The preliminary task including assembling the I-bolt at the curtain wall and hanging wire from the winch in the upper floor.
- The assembly task including assemble the curtain wall to the bracket slot and installation.
- The finishing task including fasten the curtain wall with anchor clip using a fastener and aligning the curtain wall panel.

The tasks are conducted 3 times and then the time is averaged. As a result, the robot requires more time than a human for the task.

One of the main reasons that the robot-aided assembly is slower is that the assembly work requires two workers, one operates the excavator and boom, the other operates the 3-DOF end-effector, and the effective communication is needed to complete the collaborative work, whereas the noisy site affects the cooperation.

In the conclusion, the researchers describe the idea of using the excavator with a macro motion system in such delicate installation process as "problematic", because the excavator is not designed for this kind of moving actions, particularly with heavy material. Also, a two-way control system which requires two workers to operate the basic system and the end-effector simultaneously is inefficient, as the ambient noise in the construction site hinders the necessary continuous communication.

Adhesive mechanism

Due to the physical nature of glass, suction cups are often used for the transport of heavy glass panel. A glazing robot is a machine aiding human workers to install the curtain wall glass. This machine

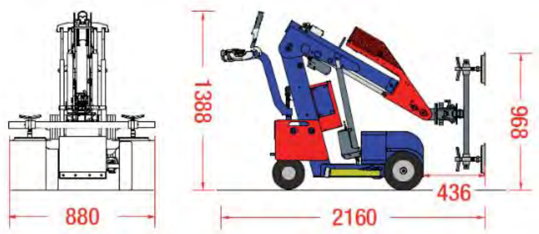

Figure 9: Technical data of a typical glazing robot, source: [GGR19a]

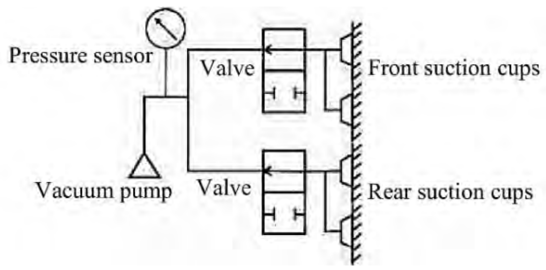

Figure 10: Pneumatic circuit, source: [TSU15]

Type	Maximum payload capacity	Range	Crusing speed	Flight time	Wind withstand ability	Fuel
SKYF P2-1	400kg	350km (w/ 150kg payload)	70km/h	8h (w/ 50kg payload)	Stable in wind speeds up to 12m/s	Gasoline
VoloCopter	200kg	40km	80km/h	0.5h		Battery
Griff 300	235kg	15km	50km/h	0.75h		Battery

Table 1: Technical specifications of some HLDs, source: [ARD18a]; [ARD18b]; [THE20]; [DRO21]

consists of a wheeled moving platform linked with a hydraulic robotic arm and a 3-DOF suction cup as the end-effector. There are already many kinds of glazing robots in the marketplace, whose payload capability ranges from around 200kg to over 1,000kg[GGR19]; [HIR20]. Fig. 9 shows the technical detail of a typical glazing robot.

The mechanism of a vacuum adhesive system is shown as Fig. 10; suction cups are connected to a vacuum pump, when the pump is activated, the space between cups and the object will become vacuum, which allows negative pressure to keep the object attached to the cups. In practice, when a drone tries to attach the glass panel, it might occur that there is a tilted angle between the suction cup and the glass surface, [TSU15] introduces a structure using a tube for tolerance for such error, so that the drone can better affix to the pane, the structure is shown as Fig. 11.

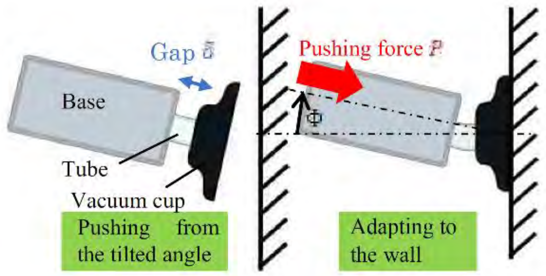

Figure 11: Structure using a tube for tolerance for the error, source: [TSU15]

2.5 Transport quadrotor

Heavy lift drone

At present, most of the curtain wall glass panes are even metres long or wide, weighing over a hundred kilograms [YAN14]. Therefore, heavy lift drone (HLD) is a potential option for a drone-based curtain wall replacing process. The basic components of a multi-rotor drone include frame, propellers, motors, battery, flight controller, power distribution board (PDB) and electronic speed controller (ESC) [SMI17], the load-bearing ability of a drone mostly depends on the motors, which provides motive power for the system

There are a number of HLDs in the marketplace, while most of the products achieve the maximum payload capacity (MPC) under 100kg. Table 1 describes the technical specifications of the 3 types of drones with MPC over 200kg.

Perching drone

Perching allows a drone to stick on the surface after performing a series of maneuvers as shown in Fig. 13 and Fig. 14.

Figure 12: Concept of perching, source: [MYE15]

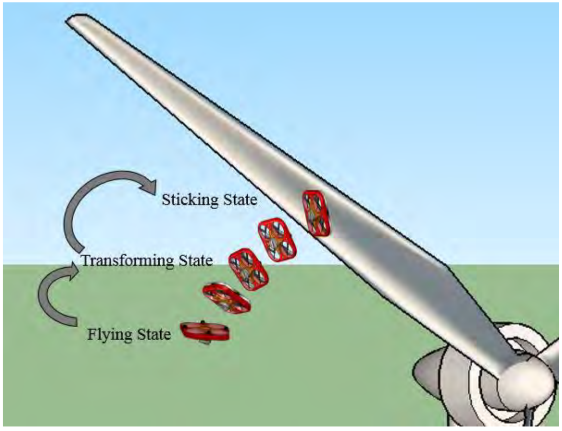

Figure 13: Perching process, source: [JUN15]

Perching drone is originally developed for close inspection [JUN15] or reducing energy consumption [AND09].

The process for a drone to perch on the surface includes 3 states, flying, transforming and sticking. At the beginning, the robot needs to detect the target surface and conduct measurement using sonar or on-board distance sensor. Then, the robot will try to change its pose by adjusting the

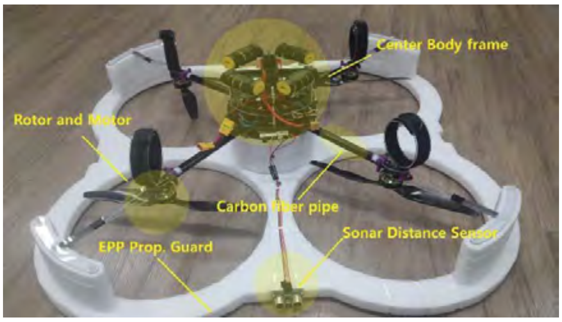

Figure 14: Design of a perching drone, source: [MYE15]

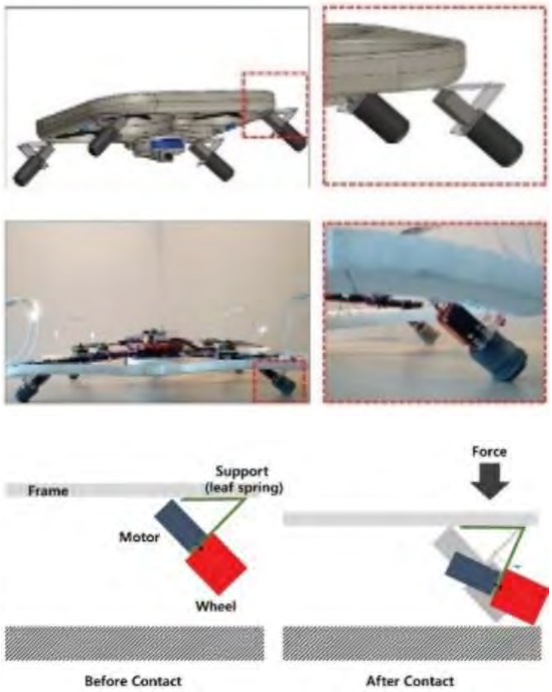

Figure 15: Wheels with adhesive material and the contact process, source: [MYE15]

thrust of the propellers and stick on the wall. When the transforming is complete, the drone will use thrust force and other adhesive methods to stick on the wall [JUN15]; [KAS15].

In [MYE15], researchers have developed a differential equation-based pose change control algorithm to manipulate the transforming. It has been proved mathematically that the transforming cannot be accomplished with slow motion because the process should be finished before the robot loses ascending speed. As the drone approaches the vertical surface, it will measure the distance between. With the given parameters of dimensions, mass and moment of inertia of the drone, it can calculate the amount and ratio of thrust force of front and rear, angular acceleration and perching trajectory. The design of the perching drone mentioned in [MYE15] is shown as Fig.15 and Fig. 16, in addition to the usual components of a MAV, it equips a sonar distance sensor and four wheels with

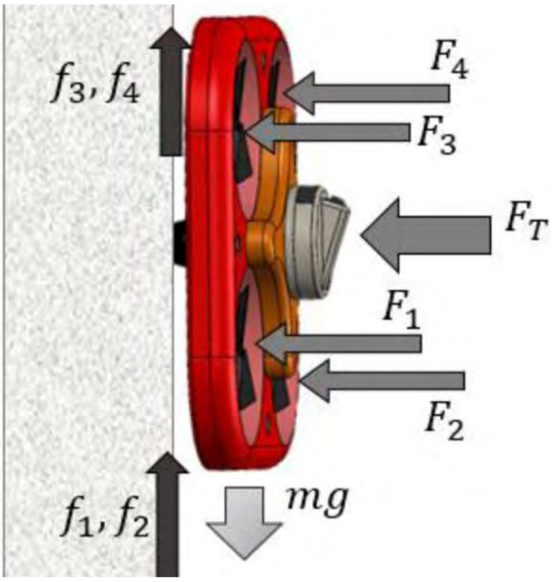

Figure 16: Force analysis of sticking, source: [JUN15]

adhesive material, the wheels are connected to the body frame with polycarbonate folding sheet. When the drone lands on the object, the sheet will transform like a leaf spring so that the wheel gets more contact area with the surface.

The drone maintains sticking on the vertical surface using thrust force. Forces on the drone is analyzed in Fig.17, where the maximum static frictional force between wheels and the wall should be bigger than its weight. The maximum static frictional force can be calculated as the product of frictional coefficient and normal force,

Figure 17: Two quadrotors carrying a payload, source: [LOI18a]

which is the thrust force from propellers. The requirements of perching are as shown in Eqs. (1) and (2),

$$f_t = \sum_{n=1}^{4} f_n = \mu F_T = \mu \sum_{n=1}^{4} F_n \quad (1)$$

$$f_t > mg \quad (2)$$

Where f_t is the sum of frictional forces, f_n is the friction force of each wheel, μ is the friction coefficient, F_T is the sum of thrust forces, F_n is each rotor's thrust force and m is mass of the drone.

Drone formation coordination

In [LOI18a], Loianno and Kumar presented the basic models, control and estimation algorithms for the cooperative drone transportation. The transportation task is not accomplished by cable connection but is achieved with the rigid connection between the quadrotors and the

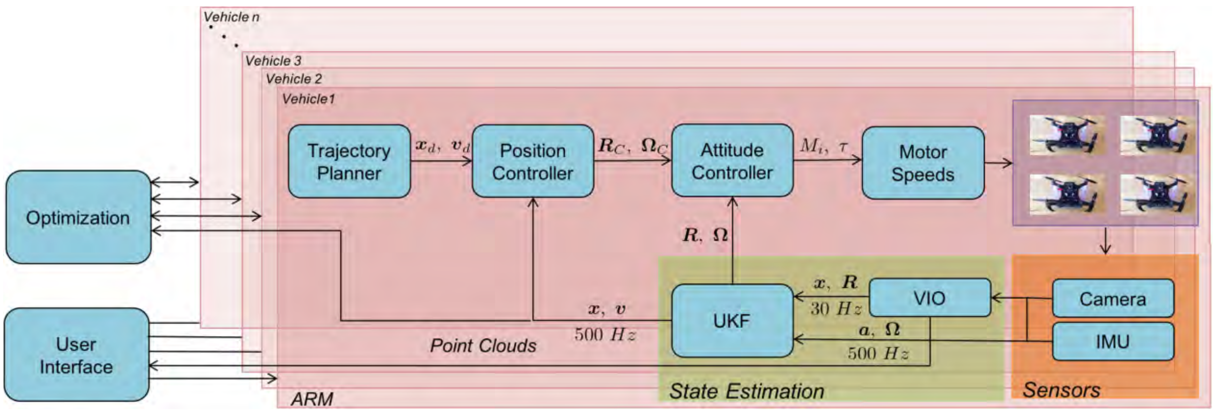

Figure 18: The architecture overview, source: [LOI18a]

payload, via permanent electromagnets (see Fig. 18). The architecture overview of the process is shown as Fig.19, the algorithm also works for the coordination of multiple drones carrying one payload.

3. Methodology

Based on the nature of curtain wall and the literature, state-of-the-art and commercial solutions reviewed in section 2, the requirement needs to be addressed can be summarized as 1) constant and efficient façade structural monitoring, 2) man-in-the-interior curtain wall replacement.

In terms of structural monitoring, we seek to achieve a high-accuracy automated process to monitor the entire façade and process the acquired data with the web-service and dashboard so as to provide a more efficient status monitoring. As for the replacement task, which will be triggered after the breakage is detected, we conceive two approaches, one is to achieve with a single HLD, the other is to accomplish with cooperative drone formation.

4. Results of literature review

There are different ways to install curtain wall, but eventually, the glass pane is still fixed to the frame or bracket by using sealant or adhesive material, which can be removed from inside of the building. Despite there are different factors giving rise to the cracking, they all in the end cause a crack propagation similar to a spider web.

When coming across the gap or crack of the broken glass, the light will be reflected, absorbed or scattered, instead of transmitting. The optical difference enables the feasibility to detect the breakage by optical examination.

The design of MFR sets the example of module (end-effector) design. By integrating existent marketplace products

Sort of robot	Working area	Size	Payload Capability	Operation manner
Hybrid motioned curtain-wall glazing robot	Ground / Inside	Large	High	Direct control
Glazing robot	Ground / Inside	Big	High	Remote control
Heavy lift drone	Aerial / Outside	Large	Medium	Remote control
Perching drone	Aerial / Outside	Small	Low	Remote control & formation coordination

Figure 19: Comparison between different robots for glass replacement

as the basic platform, the research can focus more on the development of an end-effector. However, the HCGR developed by Yu et al. is still too bulky due to the adoption of excavator, thus it is not fit for the maintenance where the access of heavy machine is limited.

Compared to the HCGR, the existent ground-based glazing robot mentioned in the chapter 'adhesive mechanism' is an improved product with smaller size and is already widely employed in the practical replacement task. Tsukagoshi et al. have depicted the design of usual pneumatic circuit in their paper, and further researched how to minimize the effect of imperfect perch attempt by adopting a flexible tube to connect the drone and its vacuum cup.

As the basic platform of the replacing drone, several HLDs with impressive payload capacity are studied in section 2.6.1. Though there is no data on the airflow created when the HLD works, it should still be noted that the high-power propeller will move large volumes of air in a downward direction and thus accelerates the air to relatively high velocities. Take a usual helicopter as an example, air velocity under the propeller may reach 60 to 100 knots (around 30 to 51 m/s) [CAN06].

Another more feasible option for the basic platform is the perching drone, this kind of drone can stick itself onto the vertical surface. Though it only has a limited payload capacity due to its smaller size, it is possible to replace the broken glass with multiple perching drone, using the formation coordination algorithm. The comparison of the abovementioned robots is shown as table 2.

5. Concept and discussion

Based on the literature review, we propose a preliminary concept for a design in this section. Though there is no actual prototype made, we discuss the potential benefits and some obvious challenges when it comes to implementation.

5.1 Concept

The façade structural health monitoring and replacing system consists of two constituents, the monitoring sub-system and replacing sub-system. The complete procedure is shown as Fig. 20.

The monitoring sub-system comprises the infrared monitoring units and SHM platform mentioned in section 3.1, for regular monitoring, a series of monitoring units can be permanently installed on the ground around the monitored building. In terms of data exchange, we select Message Queuing Telemetry Transport (MQTT) as the working protocol since it uses little bandwidth, thus can distribute the information more efficiently and lower

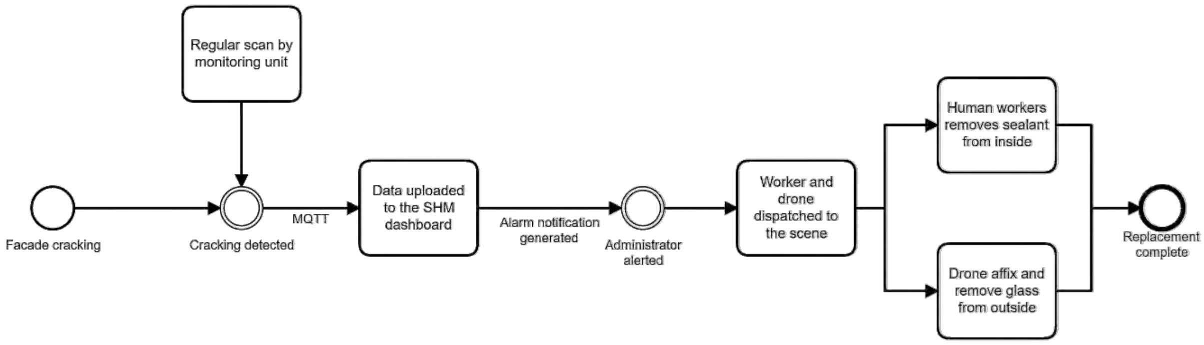

Figure 20: Overall procedure

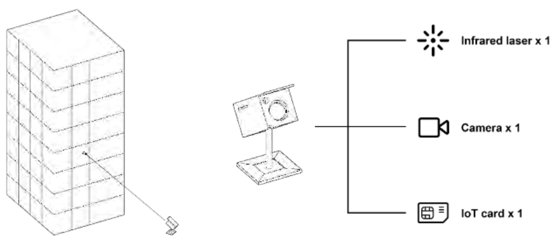

Figure 21: Working pattern and components of infrared monitoring unit

operation cost.

When cracking happens, the identifier of monitoring unit will capture the extraordinary bright spot projected by the infrared laser pointer. In order to send the alert message to the MQTT broker server, an IoT SIM card will be installed in the monitoring unit (as shown in Fig. 21). Then, the SHM platform will retrieve the alert and trigger an alarm for the system administrator, which will indicate the detailed location, time of occurrence and other significant information of the cracking, using BIM visualization. SHM platform also serves as a resource coordination platform which enables the administrator to allocate manpower or equipment to designated location.

Upon the instruction of operation, the transport drone and workers will be sent to the scene to replace the damaged glass. The replacing sub-system encompasses the transport drone(s), logistic unit and assistant human workers.

Drone design

We designed two types of transport drone for the replacement assignment, both are modified on the products which can be acquired from the marketplace. The first type of drone (Type I) is HLD equipped with multiple suction circuits, which is able to lift the curtain wall glass panel with one single vehicle. Another type of drone (Type II) is the quadrotor with one or two suction circuits.

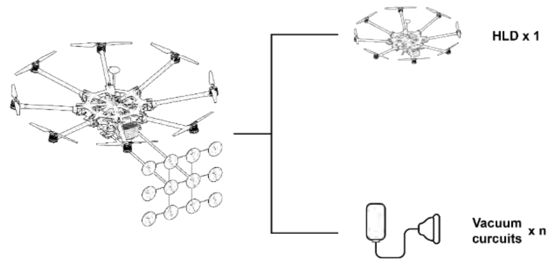

Figure 22: Components of drone Type I, designed by the authors, 3D drone model source: [WUH19]

Type I (shown as Fig. 22) is modified based on an HLD, with vacuum suction system installed. The vacuum pump is located at the rear of the drone while the suction cups array is at the front.

Type II is modified based on a UAV; the vacuum system is installed at the ventral part of the drone. Algorithm for performing perching maneuver is also adopted by th, which helps the drone to conduct minor locomotion for position adjustment after sticking to the curtain wall glass. The origin drone is shown as Fig. 23.

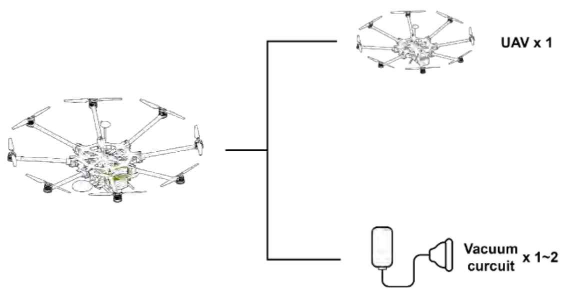

Figure 23: Components of drone Type II, designed by the authors, 3D drone model source: [WUH19]

These two types of drones have different adhesive mechanism; Type I approaches the vicinity of the glass panel, then use suction cups in the front to affix it. The working patterns of is shown as Fig. 24.

Fig. 25 shows the working pattern of Type II, which achieves the replacement in

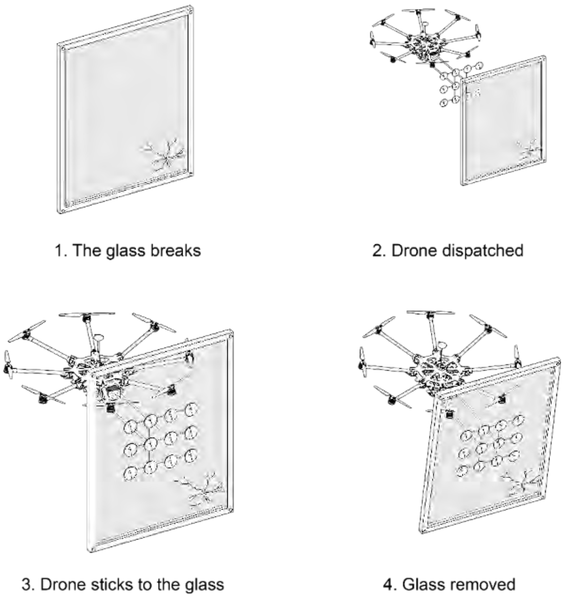

Figure 24: Working pattern of Type I, designed by the authors, drone 3D model source: [WUH19]

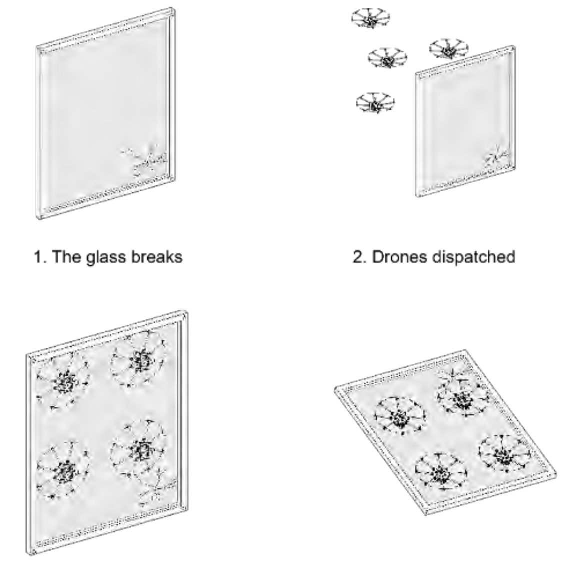

Figure 25: Working pattern of Type II, designed by the authors, drone 3D model source: [WUH19]

the form of formation cooperation - a group of UAVs will perch on the curtain wall glass and use the ventral suction cups to affix it.

When the sealant is removed from inside, the drone formation will start the propellers, with a general increasing power from the upper side to the lower side, so as to 'lift up' the lower part of the glass and

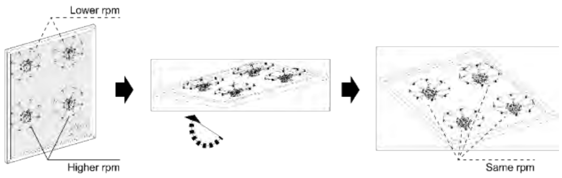

Figure 26: How the glass panel 'flips', drawn by the authors, drone 3D model source: [WUH19]

adjust the general attitude. When the drones and the glass become level again, the drone formation will balance the lifting force and begin to transport. During the transportation, the drone formation will 'suspend' the glass panel at below. This process is depicted in Fig. 26.

Generally, human workers are still needed to remove any sealant and adhesive from inside. After the glass is removed, it will be collected by the ground logistic unit, which also provides the new glass that will be installed in the same manner.

6. Discussion

6.1 Potential benefit

By implementing the proposed solution, a more comprehensive façade structural health monitoring and more efficient replacement method can be achieved. The infrared scanning unit can constantly and automatically monitor curtain wall façade. Combining the SHM platform, it produces a complete, high-efficiency and economic monitoring. In addition, the drone-based replacement method introduces a new human-machine cooperative approach to cope with building component defect at elevated height.

The system is expected to reduce the cost of façade monitoring, as it frees manpower from repetitive tasks. Moreover, human workers can avoid doing hazardous task at elevated height, improving productivity and ensuring the safety of labour force.

6.2 Challenges

This system still faces many challenges before being implemented in actual operation:

Curtain wall type

Despite most of the curtain wall is fixed by the sealant applied from inside of the building, some curtain walls are either applied with sealant on both sides, or installed onto the rails. If the defected curtain wall belongs to either of these types, then the exterior workers are still needed to remove the glue or the constraints first.

Monitoring unit

The accuracy of optical monitoring unit might be affected by weather. The infrared laser and the identifier might be affected by the rain drops or fog, the light may be heavily reflected if rain is heavy, and the identifier can only capture a limited view during foggy days.

Type I

For drone type I (HLD), the wind generated may heavily affects the stabilization of the transportation. The chopper alike HLD could move enormous air when operating, which causes a strong wind pressure to the nearby objects. In worst case, the glass may break or fall to the ground before it is removed, due to the high wind payload, and inflicts human injury.

Also, even for SKYF P2-1, which has the greatest payload capability among the researched UAVs, some heavy glass panels still exceed its weight limit.

Type II

For drone type II (perching drone), the development on formation control algorithm is needed, although some researchers have already develop the relevant algorithm, but considering the amount of drone to be used and the weight of glass panel, the work for optimized and reliable algorithm is still necessary.

More importantly, most of the literature researching perching drone uses the micro aerial vehicle (MAV), which has a significantly light weight and lower payload capability compared to the drones used in the proposal and therefore easier to transform flying attitude.

The airlift transport lacks safety measure. During the transport of curtain wall glass, the suspended object is affixed by the suction cups, which still has possibility to drop if the suction force temporarily vanished.

Law and regulation

There is no current practice on commercially using drone to transport heavy objects over 100kg on the height more than 10m. Although the logistic industry has considered using cargo drones for parcel delivery, but the payload is way lighter than the glass panel, usually no heavier than 2kg [BAU20]. It can be anticipated that this application can hardly grant permission to run from the authority unless more effective safety measures are used.

7. Conclusion

In this paper, we analyse the current situation of curtain wall structural monitoring and glass pane replacement. Based on the reviewed literature and existent solution, an application consisting of automated infrared façade scanning sub-system and drone-based replacement sub-system is proposed, we propose two solutions for replacement sub-system, one uses heavy lift drone, the other adopts coordinated drone formation and drone perching techniques.

This system could greatly improve the efficiency of the overall operation and ensure safety of human labour force. However, due to the limitation of current UAV payload capability, and especially the restriction of law and regulation, this application faces severe hardship to be implemented. Finally, the proposal requires prototyping and more detailed design to improve the preliminary concept.

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Yaxuan Zhang

Jiaqi Fu

Utilization of Autonomous Tower Crane in the Construction Process

Abstract

Tower cranes are involved in many different tasks and are frequently shared equipment on construction sites of mid-rise and high-rise building projects. They are particularly ideal for dense urban environments because of their small footprints. However, the efficient utilization of tower cranes still relies on manual operation nowadays. To realize the tower crane's automation and improve the procedure, the assists of electronic control devices, monitoring equipment, and operator supporting software are significantly required. Furthermore, conventional cranes have difficulty preventing heavy loads from oscillation caused by wind, resulting in a collision with other objects. This paper introduces the state-of-the-art technologies used in autonomous tower cranes and analyses the challenges and opportunities of the automated tower crane. In the end, a proposal is presented, based on the primary concepts of the autonomous grasping machine and the technology of cable-driven lifting robots, to expand the applications of autonomous tower cranes and to enhance the stability and precision of lifting movements.

1. Introduction

The tower crane is a standard facility in construction projects. There are currently six types of tower cranes commonly seen in the market: fast erection cranes, mobile construction cranes, top-slewing cranes, boom cranes, derrick cranes, and crawler cranes. These tower cranes have a wide range of applications, not only for small projects but also for dense areas or some unusable places or other places. The main task of tower cranes is to locate materials or equipment, to transport them to the target location, and to assemble goods in some coastal port areas [JER18].

Tower cranes are essential in transporting materials in high-rise buildings located in densely populated places, such as commercial centers. The construction sites of these buildings always have strict requirements on the size and the location of tower cranes to avoid inconvenience to the surrounding environment. However, the operation of the tower crane has not been fully automated in some respects yet. For example, it still requires human assistance to locate and hook up aimed objects. Moreover, the tower crane hook connects only with ropes, which allows the operator to have limited control of the hook. As a result , the lifted object may sway back and forth in windy weather, hitting the tower crane itself or the surroundings. The uneven weight distribution of the lifted object is also another factor that increases the difficulty in keeping stable during the lifting operation. To realize the automation of tower cranes and to improve construction safety, it is necessary to collect data on the construction environment before construction and during the transportation process. Furthermore, an advanced software platform such as BIM is needed to analyze the data and calculate the correct coordinate position so that the tower crane can deliver the object to the target location precisely. With these sensor systems and software platforms, the operation of tower cranes can be automatized and easier for users.

The main research questions of this thesis are how to make the tower crane autonomous and which part of the tower crane is not automated yet. Based on the analysis of the existing autonomous tower crane technologies, this thesis proposes an innovative concept of an autonomous tower crane combined with an autonomous grabber and a rope-driven lifting system to improve the automation and stability of the lifting movement.

2. State of the art technology

Transporting materials and equipment in the construction of high-rise buildings can be a time-consuming and labor-intensive task. Moreover, especially for manual work involved in lifting with crane, it’s a lack of percussion and safety during the construction process. A series of technologies are developed to improve efficiency and enhance automation during the lifting process.

2.1 Autonomous tower crane

There is a cabin for operators at the end of a conventional tower crane jib, which offers only a limited view. Besides, as tower cranes are working at height, it can easily cause tension and exhaustion for operators. It is also very inconvenient to get off the crane when the operator needs to leave in an emergency. As tower cranes are working at height, it is also inconvenient to get off the crane when the operator needs to leave in an emergency.

As a result, an increasing number of automated cranes work in conjunction with various sensors, computer software platforms, and computer algorithms to enable unmanned crane operation.

Firstly, a drone is used to survey the terrain and collect data such as the location of buildings, roads, etc., before the crane works, a special algorithm is used to determine where the crane should be placed. The sketch of the building is then used to determine the height, footprint, and number of stories of the building to select the right crane.

Once the type and location of the tower crane have been determined, artificial intelligence algorithms and computer software, such as BIM, can be used to simulate the working process of the tower crane to select the optimal path. In addition, visual sensors can be used to collect real-time data during the lifting process to avoid errors in the database of the tower crane due to the presence of obstacles or deformation of the building, which can result in collisions with the facilities or failure of delivery to the goal location. Finally, all the planned route data is imported into the crane's built-in system. The program is set up as a cyclic process so that the crane can automatically work until it transports all the goods to the target location and stops working. During the crane's work, sensors also constantly collect data which will then be transferred to the software platform for repeated analysis and calculation to ensure accuracy.

Furthermore, there are two challenges of tower crane while lifting loads. One is that the hooks used in tower cranes cannot automatically position the load so that the manual placement of the load is still required. Another challenge is about the stability of crane’s lifting process. Because the only components in contact with the load is a hook with retracted ropes, they cannot guarantee a smooth and sway-free lift in windy conditions or with an unevenly distributed load. Therefore, several approaches are proposed in this paper to address the existing challenges in making the tower cranes stable and automated.

2.2 The Mighty Jack System

In addition to tower cranes, there are also other techniques for transporting goods on construction sites.

The mighty jack system is an automated erection system produced by the Shimizu corporation specifically for the erection of steel beams, which can be used in some cases as a substitute for the tower crane to transport materials [HAN05]. This system consists of two grippers, a lifting device, and a hydraulic drive. Mighty Jack's manipulator can lift two to three steel beams simultaneously and then place these steel beams at the target position through remote control. The specific working process of Mighty Jack is shown below: At first, the suitable grippers should be selected according to the size of steel beams, and they will be set in the right place on the manipulators. Next, the sensors on the crane collect the position information of the steel beams, and then the data will be transferred to the Mighty Jack’s system. Next, the Mighty Jack's manipulators will be moved to the top of the steel beam through remote control according to the data information. Then, the position of the manipulator will be precisely adjusted so that the grippers on the manipulators correspond to the two ends of the steel beam. Finally, the programmed program is imported into the Mighty Jack controller. The system can automatically grab the steel beam with cyclical manipulators and then transport the material to the target locations. It usually takes about 40 minutes to assemble six beams in a building project, but with this system, it takes nearly half of the time, which shows a significant increase in efficiency [TAK88].

However, the system is not fully automated, it does not use any sensors, and most of the preparation work before the installation of the beams is carried out manually by remote control.

2.3 The cable-driven lifting robots

The figure in [ROG96] shows two kinds of NIST RoboCrane, the world's first cable-suspended robot. The primary design idea of the RoboCrane is the stalwart platform parallel linked manipulator. The unique characteristic of the NIST approach is to use cables as the parallel links and use winches as the actuators. The cables are attached to a work platform to keep all cables in tension so that the load is kinematically constrained. The work platform can resist perturbing forces and moments with equal stiffness to both positive and negative loads. As a result, the suspended load is restrained with a mechanical stiffness determined by the elasticity of the cables, the suspended weight, and the geometry of the mechanism [DAG89]. Due to the flexible structure of the triangular, the payload-to weight ratio of RoboCrane is higher than conventional cranes, and lower support reaction forces are provided [AIA04]. The efficient control of RoboCrane allows even novice operators to position a load accurately without sway within a few millimetres and control orientation without oscillation within one degree in roll, pitch, and yaw.

Although this system provides as much stability as possible during the lifting process, it still cannot automatically locate and identify objects and requires a worker to place the load.

3. Methodology

This paper focuses on the automated working process and technologies used in existing automatic tower cranes. The presented results are based on extensive literature research. In addition, the product parameters are extracted from the internet research of available manufacture websites to demonstrate an actual level of the autonomous tower crane.

The literature research was conducted through Google Scholar, Research Gate, Science Direct, Wiley Online Library, and ASCE library. As keywords formulations, various terms are used for literature research in English: lifting machine, automation, construction environment, autonomous tower crane, digital software, simulation, visualization, Building Information Modelling (BIM), sensor, cable-driven lifting, autonomous grasping machine, robot, control, algorithm. Over 25 pieces of literature were extracted and subsequently reduced to the references named in this paper.

In the following paper, a partition is made about autonomous technologies used in tower cranes. First, based on the introduction of state-of-the-art autonomous lifting machines mentioned in chapter 2, required technologies from other disciplines are addressed and researched in chapter 4, which are crucial for improving automation in tower cranes. Then, as listed in chapter 5, after analysing the methods in different aspects from chapter 4, the proposed concept is elaborated and evaluated with illustrations in detail.

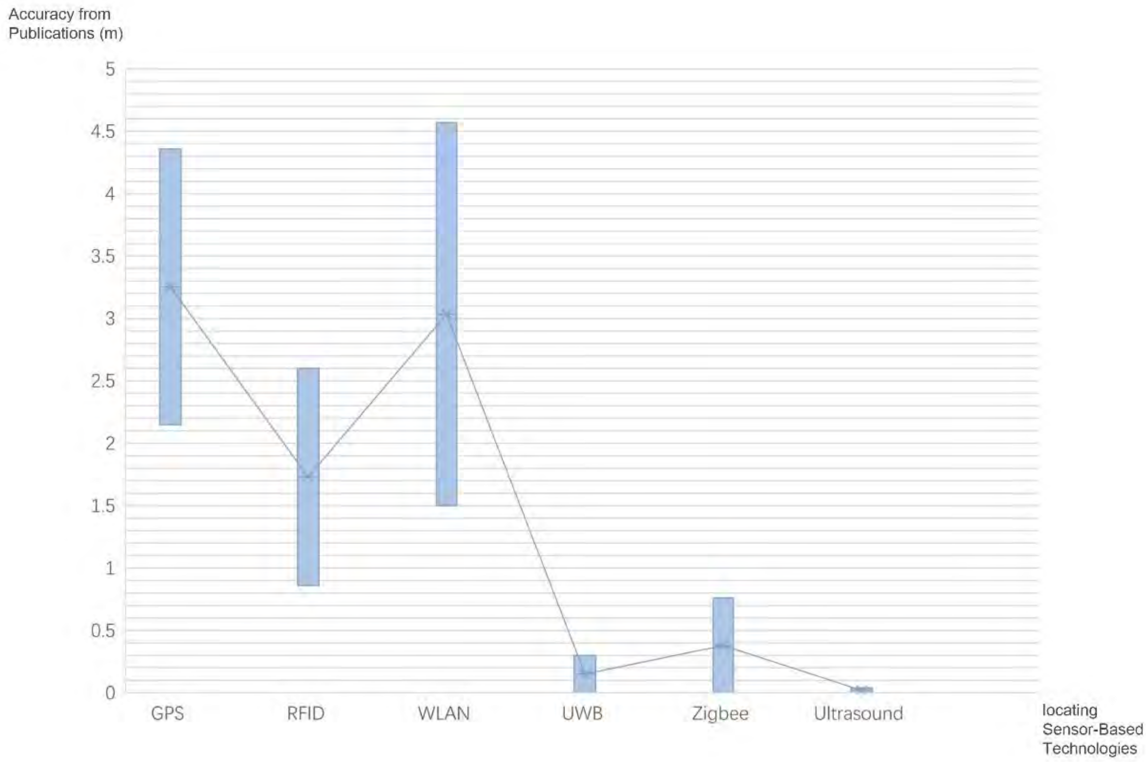

Figure 1: Accuracy of locating sensor-based technologies [MIN17]

4. Research Results

4.1 Sensor-based technology

Sensors are crucial devices to collect, transfer, and process information to monitor, control, and collaborate autonomous machines on complicated construction sites. The collected data can be used as input for other devices or analyzed with specific algorithms for operators to understand the dynamic construction environments better.

It also improves the efficiency and accuracy of real-time construction safety management by tracing and transferring the dynamic data of the movements and interaction of people, goods, machines, and even the deformation of structures. As the table shows above, the commonly used sensor-based technologies on construction sites are locating sensor-based technology, vision-based sensing, and wireless sensor networks. And different technologies have different levels of accuracy and limitations of the work environments (see Table 1). According to other construction conditions and targets, appropriate sensor-based technologies should be chosen to maximize their work potentials. [MIN17]

A practical application combining a wireless sensor network with the Internet of Thing (IoT) to manage the construction safety of tower crane groups was carried out by Dexing Z., Hongqiang L., Jiuqiang H. and Quanrui W. A set of customized sensors, including horizontal and vertical position sensors for the trolley, angle sensors for the jib and load, tit and wind sensors for the tower body, was applied to detect the operating status of each tower crane [DEX].

Sensor-Based Technology		Algorithm Complexity	Layout Complexity	Construction Environment Limitation
Locating sensor-based technology	GPS	Low	Low	Suitable for outdoor environment
	UWB	Low	Moderate	Accuracy affected by the arrangement of signal transmitters and receivers
	Zigbee	Low	Moderate	Signals blocked or interfered by obstacles
	RFID	Low	Moderate	Signals interfered by metal objects
	WLAN	Low	Moderate	Signals blocked or interfered by obstacles
	Ultrasound	Low	Moderate	Signals blocked or interfered by obstacles Signals interfered by metal objects
Vision-based sensing technology	Imaging sensor	High	Moderate	Vulnerable to the impact of surrounding environment, such as lighting condition and background color
Wireless sensor network	Temperature sensor	Moderate	High	Signals blocked or interfered by obstacles or other electronic signals in network communication Difficult to solve the energy supply problems
	Displacement sensor	Moderate	High	
	Light sensor	Moderate	High	
	Optical fiber sensor	Moderate	High	
	Pressure sensor	Moderate	High	

Table 1: Comparison of the three sensor-based technologies' adaptability [MIN17]

4.2 Algorithm

Crane selection

There are two essential tasks in the work of a tower crane, one is to position and lift the load, and the other is to transport the load to the designation. In both cases, a large amount of data must be collected and calculated by computer algorithms to ensure that the tower crane can transport the goods to the target location more accurately and in a shorter time. The following Figure 2 shows the proposed algorithm for almost all the data that needs to be calculated during the work of the tower crane [HAS10].

Firstly, three aspects are to consider the working characteristics of a tower crane, namely lifting capacity, working radius, and lifting height. This part needs to ensure that any configuration conditions given in a construction project need to meet the lifting capacity of the tower crane. The weight of

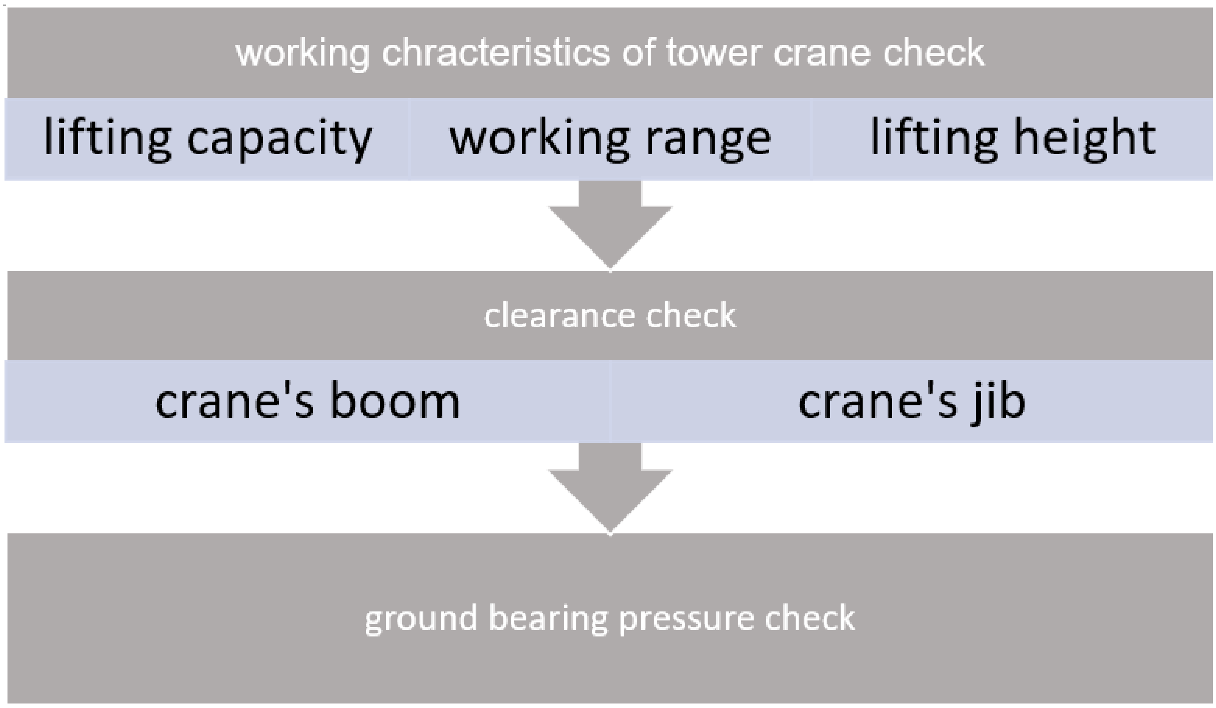

Figure 2: Proposed algorithm structure of the crane selection [DIW11]

Lifting capacity	Working range	Lifting height of boom	Lifting height of the jib
$G >= G'$ where $G' = G_L + G_{SL} + G_{SP} + G_H$ (G: lifting capacity; G': total lifting weight G_L: equipment weight; G_{SL}: sling weight; G_{SP}: spreader weight; G_H: hook weight)	$R >= R'$ where $R' = \max(R_S, R_t)$ (R: working radius; R_s: distance from the end of the jib to the staging location; R_t: distance from the end of the jib to the equipment installed)	$H_1 = \sqrt{(L_1 \wedge 2 + D_1 \wedge 2) - (R - X) \wedge 2}$ $H = H_1 + Y$ (H: lifting height, L_1: the length of the boom; D_1: vertical offset; R: working radius; X:distance from boom and slewing centerline; Y:distance from boom and ground)	$R_1 = L_1 \times \cos \alpha$ $H_1 = L_1 \times \sin \alpha$ $R_3 = R - X - R_1$ $H_3 = \sqrt{(L_3^2 + D_3^2) - R_3^2}$ $H = Y + H_1 + H_3$ $H' = H_{ob} + H_L + H_{L2H} + H_{LMT}$ $H \geq H'$ (α: boom angle; L3: jib length; D3: vertical offset; Hob: distance from bottom of the tower crane to ground; HL: distance from lug to bottom; HL2H: vertical distance from lug to hook; HLMT: limit distance from hook to the lifting sheave)

Table 2: Formula of the lifting capacity [DIW11]

the tower crane must be greater than or equal to the weight of the entire load to be lifted, the working radius of the tower crane cannot be less than the distance from the end of the jib to the tower crane installation, and the lifting height of the tower crane cannot be less than the total height of the building. Table 2 shows the specific function of the capacity of the tower crane [DIW11].

Next, the clearance between the tower crane jib and where the tower crane is placed and the clearance between the tower crane jib and the building needs to be checked to ensure enough space for the tower crane to extend as it lifts the load. The following Table 3 shows the calculation process [DIW11].

Finally, it is necessary to consider the ability of the ground to withstand the

Clearance between the jib and the equipment installed	Clearance between the jib and the building
$\tan\alpha \times x - y - \tan\alpha \times \left(X + \frac{S_1 + C'}{\sin\alpha}\right) + Y = 0$	$\tan\alpha \times x - y - \tan\alpha \times \left(X + \frac{S_1 + C'}{\sin\alpha}\right) + Y = 0$
$d = \frac{\tan\alpha \times x_1 - y_1 - \tan\alpha \times \left(X + \frac{S_1 + C'}{\sin\alpha}\right) + Y}{\sqrt{\tan^2\alpha + 1}} \geq 0$	$\tan\beta \times x - y - \tan\beta \times \left(X + L_1 \times \cos\alpha + \frac{S_2 + C'}{\sin\beta}\right) + Y + L_1 \times \sin\alpha = 0$ $d_1 = \frac{\tan\alpha \times x_1 - y_1 - \tan\alpha \times \left(X + \frac{S_1 + C'}{\sin\alpha}\right) + Y}{\sqrt{\tan^2\alpha + 1}} \geq 0$
(x, y: the coordinate of the potential intersection point; X1,y1: the coordinate of the highest point; S1: one half height of the boom; C': minimum clearance; d: distance from highest point to linc)	$d_2 = \frac{\tan\beta \times x_1 - y_1 - \tan\beta \times \left(X + L_1 \times \cos\alpha + \frac{S_2 + C'}{\sin\beta}\right) + Y + L_1 \times \sin\alpha}{\sqrt{\tan^2\beta + 1}} \geq 0$ (beta: jib angle; S2: one half height of the jib; d2: distance from highest point to linc2)

Table 3: Formular of the clearance check [DIW11]

<table>
<tr><td>When |e|<L/6</td><td>$$P_x^{\mathrm{I}} = \frac{G_g}{2bL}\left(1 + \frac{2w}{B}\right)\left(1 + \frac{12ex}{L^2}\right)$$
$$P_x^{\mathrm{II}} = \frac{G_g}{2bL}\left(1 - \frac{2w}{B}\right)\left(1 + \frac{12ex}{L^2}\right)$$
(Px: ground bearing pressure; L: the length of the crawler pressed; b: the width of the crawler; the distance between two crawler; Gg: total resultant force; w: the offset perpendicular to direction of the crawler;
e: the offset in direction of the crawler)</td></tr>
<tr><td>When |e|>L/6</td><td>$$P_x^{\mathrm{I}} = \frac{G_g}{9b\left(\frac{L}{2} - |e|\right)^2}\left(1 + \frac{2w}{B}\right)(L - 3|e| + |x|)$$
$$P_x^{\mathrm{II}} = \frac{G_g}{9b\left(\frac{L}{2} - |e|\right)^2}\left(1 - \frac{2w}{B}\right)(L - 3|e| + |x|)$$
(Px: ground bearing pressure; L: the length of the crawler pressed; b: the width of the crawler; the distance between two crawler; Gg: total resultant force; w: the offset perpendicular to direction of the crawler;
e: the offset in direction of the crawler)</td></tr>
<tr><td colspan="2">$$GP = \max[\max(P_x^{\mathrm{I}}), \max(P_x^{\mathrm{II}})]$$
$$GP \le GP'$$
(GP: the ground bearing pressure;
GP' : the ground support)</td></tr>
</table>

Table 4: Formula of the ground to withstand pressure check [DIW11]

pressure, ensuring that the ground can withstand a force that is less than or equal to the ground support. The following Table 4 shows the calculation process [DIW11].

Path planning

In practice, real-time conditions during the lifting process can be monitored by using wireless sensor systems and specific software platforms, which can collect data to calculate the operating range of the tower crane according to the locations of the road and buildings and then determine the delivery position. At the same time, in order to prevent data deviation through conventional teleoperated devices in the transport process from causing martial waste and collisions with the tower crane itself or surrounding buildings, it is necessary to design a suitable lifting path planning algorithm to locate the goal location accurately, to effectively choose the best way without obstacles, and to collaborate with other on-site construction machines without collisions.

As shown in Table 5, tower cranes are currently equipped with different search

	Localization & Path planning	Object Tracking	Image Matching	Noise &Error Removal	Classification & Machine Learning
Algorithm	• Triangulation • Angle of Arrival (AoA) • Received Signal Strength Indication (RSSI) • Time of Arrival (ToA) • Time Difference of Arrival (TDoA) • Roundtrip Time of Flight (RToF) • Received Signal Phase Method (RSPM) • A* search • Genetic algorithms (GAs) • Quick Link • Random Guess • Remove Redundant Nodes	• Feature-based Tracking Algorithm • Model-based Tracking Algorithm	• Area-based Matching Algorithm • Feature-based Matching Algorithm • Computer Vision	• Kalman Filter	• K-Nearest Neighbor Classification (KNN) • Decision Tree • Support Vector Machine(SVM) • Naive Bayes Classification • Artificial Neural Network (ANN) • Convolution Neural Network (CNN)

Table 5: Commonly used algorithms to improve the construction safety [MSA05] [MIN17] [SHI05]

algorithms to obtain the best working path and erect a building automatically. The preliminary experiment is to create data and geometric models based on the basic CAD method and use it to simulate the working process and construction environment. By constantly improving and practice, scientists have developed several algorithms focusing on different aspects of tower crane's movements to improve the construction safety and get the cheapest path. However, more construction costs are needed at the end because of a large amount of calculation [LIH18].

4.3 BIM

BIM is a digital platform that can achieve collaboration and information share based on a 3D model between different project stakeholders so that all users are allowed to enter, change, update and correct all relevant information stored throughout the lifecycle of a construction project, in which maybe one or multiple digital building models are used to manage and support

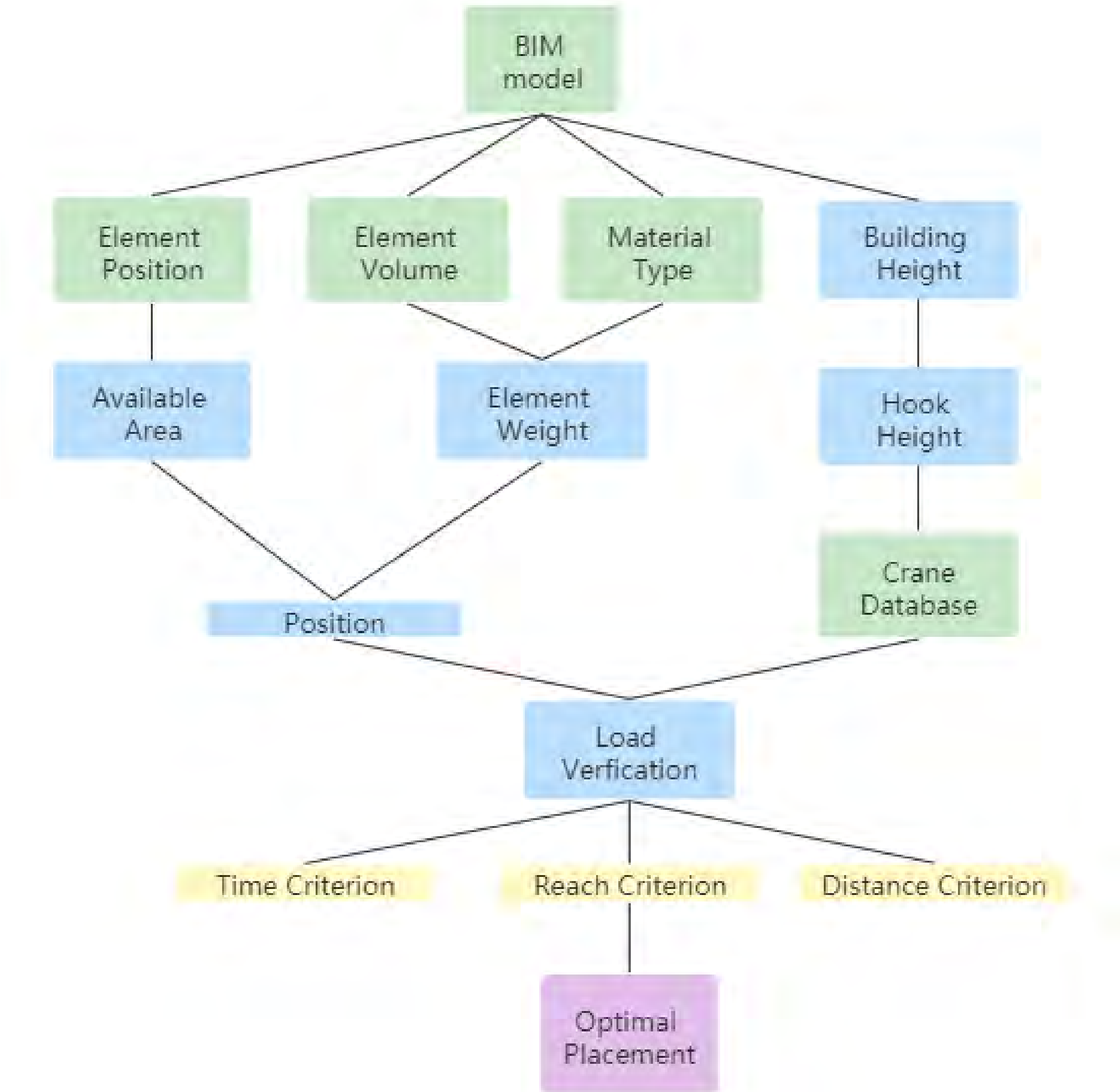

Figure 3: Workflow of the site plan development [TFU16]

the construction process. [STR12] BIM also provides an opportunity to allow users obtain input data directly from a 3D virtual model without manual analysis of the object. [FUN16] In a 4D BIM model, the project schedule can also be integrated and visualized in the 3D model, increasing planning efficiency and reducing the time consumed for the meeting. [KHO12]

T. Funtíka and J. Gašparík developed a site plan development methodology to automatically obtain an optimal tower crane placement with the combination of BIM. As shown in Figure 3, the BIM model was used as input to extract the position, volume, and material type of elements. After analyzing the model data with C#, the algorithm can generate the time of material transport, the required length of jibs, and the optimal transport paths of elements. And the optimal position of the tower crane was also finally visualized and analyzed through BIM-based simulation [TFU16].

4.4 Mechanical

As mentioned above, two challenges currently limit the automation of the tower crane, which mainly focus on the manipulation of hooking objects. Firstly, the hook cannot grab objects automatically because it doesn't have enough DOF. Secondly, the hook and ropes will sway or collide with surroundings during the transport process due to wind or uneven weight distribution of the lifted objects. To improve the stability and increase the automation degree of the lifting part of the tower crane, existing robotic technologies, such as the autonomous grasping machine and the cable-driven lifting robot, can be developed in combination with the conventional tower crane. In this case, the payload of the complete machine should be reconsidered to ensure that the lifting load is less than the compliance weight which these mechanical devices can support. Table 6 below shows the payload of the tower crane and the payload of various mechanical devices.

Type	Payload
Fast erecting crane	8 tons
Mobile construction crane	8 tons
Top-slewing crane	Massive
Luffing jib crane	80 tons
Derrick crane	8 tons
Tower crane equipped with track	8 tons
Autonomous grasping machine	Depending on the type and working characteristics
Cable-driven lifting robot (Robocrane)	2270kg

Table 6: Comparison of the payload of the tower crane and the machinery device [JER18]

In addition to the payload of the tower crane and the auxiliary mechanical devices, the working characteristics of the auxiliary mechanical devices must also be considered. For the cable-driven lifting robot, several different types are available depending on the building site, the height of the building, and the operating space of the crane, as shown in Table 7 below. This robot is effective in preventing swaying oscillations caused by high winds or uneven distribution of the load's gravity, thus improving the stability of the crane during the lifting process.

Another mechanical part is the robotic gripper, which is more automated than the cranes on the construction market today. The robotic gripper is assisted by sensors to automatically position and grip the goods. Besides, the robotic grippers with different DOF [Table 8] can be selected according to varying weights of goods or various transport tasks.

4.5 Simulation and Visualization

Computer simulation has been proved to be an effective tool to assist crane users with modeling complex construction operations. [MOH17] And a combination of visualization and simulation of crane operation can not only be a crucial tool for decision-makers to select and locate crane and plane the path, but it also provides detailed and intuitive information for users from diverse fields. Furthermore, visualization of simulated construction operation also provides more substantial and comprehensive feedback from simulation analysis to identify space conflicts, site layout, construction sequences, workspace requirements, and schedule errors to save time and reduce costs and risks before implementation.[KAM02] The panners can quickly generate any number of views from

Type	Characteristics
Cable-suspended robot	Lightweight, robust and efficient cable robots with a cable-driven electric motor that controls the load platform to slide freely on elevated pulleys. These robots have a very large working space, a high load capacity and a high resistance to pressure and precision. They can be used in material handling, on the International Space Station and in large outdoor buildings.
Six DOF Robocrane	This robotic crane offers precise six-degree-of-freedom control and intelligent control technology for computer numerical control of various tool parts, such as clamping, assembly, etc. the robot can work in a minimum working space of 100 cubic metres by radio remote control from two or six metres with an angular movement of approximately 0.5 degrees.

Table 7: Comparison of the RoboCranes' work characteristics [ROB18] [ROG96]

Type	Work characteristics
Six DOF robot gripper	The six-degree-of-freedom robot gripper is a typical mechanical device with a rotating structure, six degrees of freedom means that the mechanical gripper can move forwards, backwards, upwards, downwards, leftwards and rightwards in three dimensions, these mechanical grippers can be pointed to the required coordinate accuracy of +/- 0.5 cm.
Seven DOF robot gripper	The seven degrees of freedom robot gripper is a more flexible device derived from the six degrees of freedom and is able to avoid errors caused by directional singularities and obstacles. The seven degrees of freedom gripper has joint sets that can perform shoulder roll and pitch movements, elbow roll and pitch movements and wrist roll and pitch movements, making the gripper more anthropomorphic and therefore more flexible.

Table 8: comparison of the difference degree of freedom of the tower crane [BTO06] [PAR20]

3D drawing or 3D animation files through the entire crane operation for evaluation and assessment before the approval of the plans for execution from the 3D simulation modeling. [LIH18]

A construction case of a four-story, sixty-eight-unit building in Canada demonstrates the methodology of 3D visualization modeling for crane selection, collision-free path planning, and lifting activities optimization. For simulation and visualization modeling, several data need to be first collected as input: building information from project management, crane geometry from manufacturers, and load rigging databases. Then the algorithm for selecting crane is developed in computer applications, and the crane location calculation is implemented in the 2D coordinate in 3D Studio Max. [LIN11] [HUS05] [HAS10] Then, the lifting schedule, reaction influence chart, 3D animation, site layout, and collision-free path of the crane operation is generated as output data. As a result, three scenarios with crane information, including crane type, required capacities, and possible paths, are identified for decision-makers. [SAN12]

5. Discussion

5.1 Analysis

In the work process of the tower crane, the operation of delivering objects to the goal position can be automatically achieved with the assist of the sensor system and software. However, the orientation and movement of hooking-up objects cannot be operated autonomously because only simple hooks and cables are used, without sensors, cameras, or anything like that to detect the target location. In addition, the hook connects to the cable directly, which is short of external forces and the degree of freedom, so the hook cannot move and rotate on its own. It can only rely on the telescopic rope to complete the pull action. Therefore, the current commonly used method in construction sites is to hang items on the hook manually.

While existing cranes can lift a specific weight load, it is still challenging to resist the disturbance power caused by horizontal wind direction and maintain stability. The trolley, cables and hook blocks are on almost a vertical plane, and workers can only control the length of the lifting cable between the jib and the object in the vertical direction. It is hard to avoid swaying the load and against the perturbations such as wind, even with expert operators. They have limited strength to prevent the hook block from swaying or colliding with objects in the environment. In some cases, the swaying movement can be more than a meter away, which is inefficient for precise orientation and dangerous for construction.

5.2 Concept

Based on the missing automation aspects of existing autonomous tower cranes, a concept of combining the cable-driven lifting robot and the autonomous grasping machine with a set of sensors is proposed to develop a novel autonomous tower crane. The operation system of this tower crane will be integrated with the BIM platform to generate a better data flow for collaboration with all stakeholders and enable the real-time simulation of the operation process. Algorithms will also be applied to the system with collected data from sensors to generate the optimal crane selection and path planning.

Figures 4 and 5 of the simulation model show that a cable-driven stalwart platform replaces the conventional hook block. A

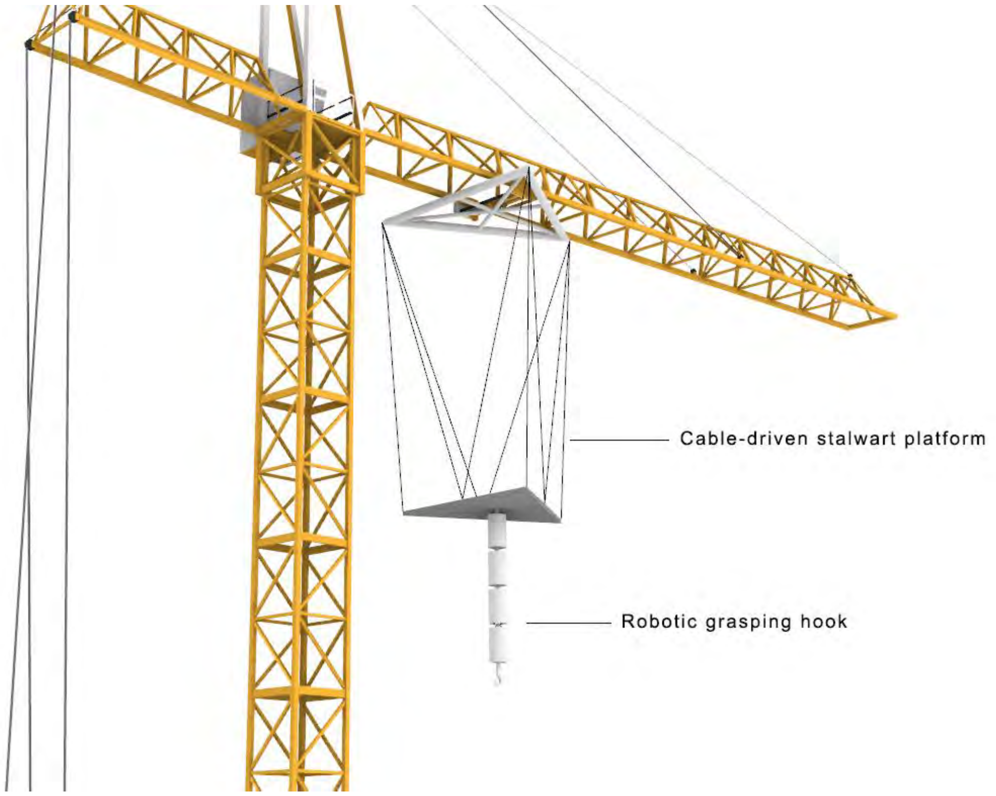

Figure 4: Further view of simulation of the tower crane

Figure 5: Simulation of the proposed tower crane

grasping device is attached to the platform with a set of customized sensors. Due to the cable-driven stalwart platform, the tower crane can resist wind perturbations and stabilize objects' load. Furthermore, the tower crane can perceive the dynamic data and precisely recognize, locate, and automatically grasp different types of goal objects with the grasping machine's built-in autonomous robotic grasping system and the sensors system.

5.3 Potential and Challenge of concept

The crane studied in this thesis is more stable and automated than the existing conventional cranes. This is due to the equipment of other mechanical devices to the traditional tower crane, for example, the cable-driven lifting system, which uses the triangular stabilization feature to structure the lifting ropes in the shape of a three-dimensional conical net so that the lifting movement can be controlled from multiple directions. Moreover, the autonomous gripper assisted with computer programming software and visualization sensors enables the crane to automatically locate the load. And thanks to the multi-directional degree of freedom of the robotic gripper, the crane can automatically pick up the load once it has identified the position of loads and then deliver it to the target position. This saves a lot of manpower and time to increase the efficiency of the tower crane.

Compared with the traditional tower crane, the proposed tower crane has added other automation technologies, such as robotic gripper, cable-driven lifting system, crane camera, and sensors, which will increase the cost of the tower crane itself and the cost of maintenance. Because the cable-driven lifting system occupies a relatively large space. It is necessary to consider the clearance distance between the tower crane and the building before installing it to avoid collisions between the lifted object and the tower crane or building. Besides, there is also a payload issue of the whole system. The weight that a conventional tower crane can carry is very high. However, the bearing capacity of the cable-driven lifting system and the robotic gripper can cause a limit to the payload of the complete machine. So, it is essential to think further and find ways to improve these issues.

6. Conclusion

The tower crane is one of the most shared equipments on the construction site, which can be involved in different lifting tasks. However, due to the complexity of the construction environment, several factors can influence the crane operation, such as delivery material information, site constraints, crane type, location, and path, which is a challenge for practitioners.

Nevertheless, with the aid of advanced electronic detection devices such as sensors and well-formed digital platforms, information of construction sites can be systematically collected and automatically recalculated for optimal tower crane operation planning and 3D simulation modeling, which provide a more precise and efficient working method than conventional tower crane operation.

Even with advanced detection and monitoring devices, most state-of-the-art autonomous tower cranes still use the conventional hook to achieve the lifting work, which needs the assistance of workers to hook up objects and can hardly keep stable with perturbations like the wind during the lifting process. This paper proposes a novel autonomous tower crane after analyzing the challenges and opportunities of the existing autonomous tower crane. This kind of crane assisted with robotic gripper and cable/driven lifting system, which can improve the automation degree of the tower crane and stability, to realize a more efficient construction tool.

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HANNES REUTHER

Mycelium heat insulation
Research on mycelium as a sustainable insulation material

ABSTRACT

Sustainable construction needs a continuous search for new, more environmentally friendly or efficient building materials. Mycelium is a purely organic fungal product with promising attributes for the construction industry. In this work, Mycelium is examined against the background of whether it is a potential replacement for conventional insulation materials. Mechanical properties of Mycelium are compared with those of modern insulating materials and the implementation to on-site production processes is investigated. It turns out that the sustainable insulation panels can keep up with modern materials in many, although the thermal conductivity still at a somewhat lower level. The on-site production is mainly limited by the factors time, space and growth conditions, which turn out to be challenges that prevent its on-site application until now.

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1. Introduction

Sustainable materials for the construction industry are becoming increasingly relevant in times when climate and society are constantly changing. The construction industry alone is responsible for 35% of final energy consumption and 38% of total CO2 emissions [GLO20]. Considering the need to counteract global warming, it is of utmost importance to reduce these figures and to rely on sustainable resources.

To achieve this goal, it is essential that a building material is efficient and needs little maintenance throughout its life cycle. For some time now, there has been an approach to produce thermal insulation materials based on mycelium. This involves the exclusive use of organic products to produce a material that is intended to replace classic thermal insulation and at the same time be cheaper and more environmentally friendly.

Thereby, the material itself and its properties, but also the production process, play a significant role. After all, there is still disagreement as to whether mycelium is really the savior of sustainable construction. Automation of the production process could save costs, create a certain standardization at the quality level and optimize the production process. However, there are also difficulties to be overcome here, which are caused by the growth process of the mycelium.

All these issues will be addressed in the following paper in order to answer the questions whether mycelium can be an alternate to thermal insulation materials and if automated on-site production of mycelium insulation panels is possible.

2. State of the Art

Mineral wool such as stone or glass wool together with the synthetic insulation materials like expanded polystyrene (EPS) and extruded polystyrene (XPS) are among the most widely used insulation materials the construction industry [DOM10]. All the above materials have classic insulating properties and good thermal conductivity characteristics. However, they each require finite resources that must be recycled over the long term.

As Table 1 shows, the production of insulation requires fossil energy resources and electricity even if these are not part of the material itself but are consumed in the production process. The consumption of these is rather high compared to the other building materials listed. [BAS19]

Material	Coal	Oil	Fossil Gas	Biofuel	Electricity
Rock wool	2.00	0.36	0.02	-	0.39
Glass wool	2.86	0.52	0.03	-	2.00
Cellulose Fiber	0.51	0.09	0.01	-	0.14
EPS	0.28	3.89	3.72	-	0.63
Foam glass	-	0.04	3.22	-	0.42
Concrete	0.09	0.10	-	-	0.02
Plasterboard	-	0.79	-	-	0.16
Lumber	-	0.15	-	0.69	0.14
Particleboard	-	0.39	-	0.39	0.42
Steel (ore-based)	3.92	0.86	1.34	-	0.91

Table 1: Specific end-use energy (kWh/kg) to produce selected building materials [BAS19]

Another common feature is the production of the parts in prefabrication. This is because each of the insulation materials involves at least one production step, which makes on-site fabrication, fundamentally more difficult and perhaps uneconomical. In the case of rock wool, for example, this is the melting of the starting material at 500 °C, which is even significantly exceeded by glass wool at 1700 °C. These process steps require enormous, high-performance furnaces, which are usually location-bound due to their sheer size.

The production of expanded and extruded polystyrene also requires the use of large machinery, especially the EPS, which is traditionally produced in big billets using steam [MIH08]. In the manufacturing of XPS, a certain pressure and temperature is required along the production route in order to produce the finished insulation material from the granulate [GIA20]. In addition, both materials are coated with a bromine fire retardant, that is a toxic and thus dangerous substance that requires fully secure handling.

All these factors complicate the on-site production of the insulation materials. Even though in this report no valid statement is made as to whether on-site manufacturing would not also be possible with the above-mentioned materials. It is a fact that this is not taking place at the moment.

3. Methodology

The research methodology is mainly based on the principle of systematic literature review. Initially, two literature databases were selected, namely Scopus and ScienceDirect, which were then examined for scientific writings on the subject of mycelium. The search was

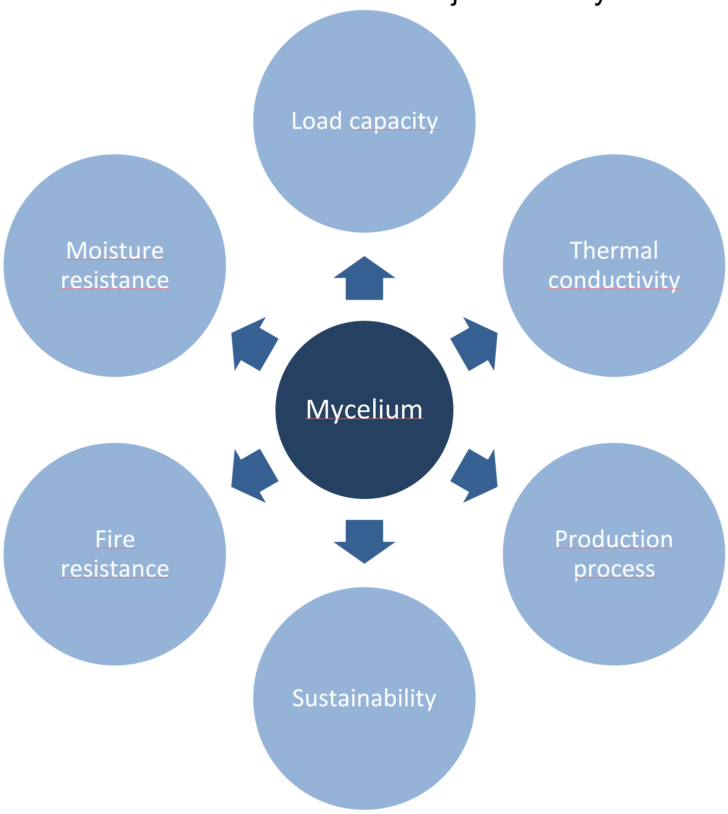

Figure 1: Systematic literature review (own graphic)

conducted using predefined keywords, which should lead to a high-quality pre-selection of literature. A constant term in the search was the building material itself, mycelium. This was then paired with the properties thermal conductivity, load capacity, moisture resistance, fire resistance, sustainability, and production process in order to find the papers that addressed the research question in the most precise way (Figure 3).

The resulting literature database was now first analyzed by means of the titles of the papers. If this proved helpful in answering the research question, the abstract was consulted and in the next step, if useful, the entire paper was read. The knowledge obtained through this literature review was filtered until it contained the most useful information and compiled into the results. The findings were first collected and sorted in order to put them into a qualitative context in terms of the research question.

4. Results

4.1 Mycelium production

Mycelium is the name given to the root plexus of a fungus. This is used by fungi in a natural environment to establish themselves and spread. If you want to work with this substance as a building material, you exploit this very spreading. Because in the right environment, the mycelium decomposes organic material and absorbs the nutrients contained therein to expand [HAN17]. The production of a mycelium composite material is compared to conventional construction methods rather like a growth process. In comparison to other organic raw materials, this takes place within days and does not require energy-intensive manufacturing processes. It is fully compostable and can be fed back into biological cycles as a biological nutrient in the sense of the circular system and the "cradle-to-cradle" principles [MUL10]. As indicated in the previous, the fungus alone is more or less useless, because it needs nutrients to grow mycelium. These are mostly provided by a substrate that feeds the fungus [APP19](Figure 1).

Suitable for this purpose are delicacies such as agricultural waste, wood, straw, cotton, coffee ground or sugar. So the mushroom is not really picky about food, but for optimal growth a balanced mixture of sufficient calcium, proteins and vitamins is essential [HAN17]. The building industry usually relies on lignocellulosic substrates, which, however, differ in terms of the type of wood. Here, everything is possible in terms of geometry from larger chips to sawdust. Also rice husks and wheat grains are often used [JON18b, DIA21].

The different substrates produce results with different properties after they have

Figure 2: Feedstocks mycelium production [KOE20]

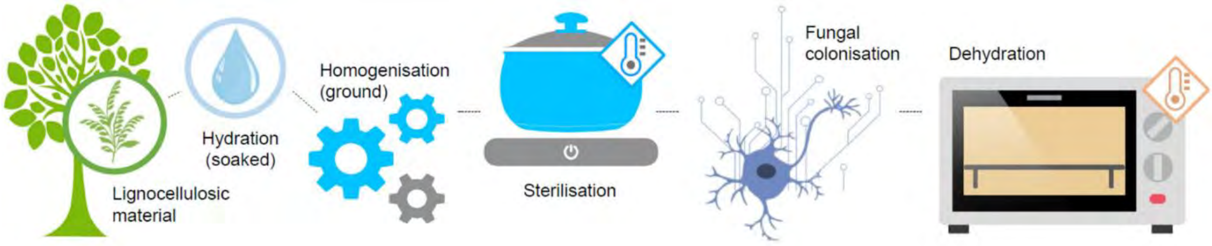

Figure 3: Classic manufacturing of mycelium objects objects [JON20]

been grown together by the mycelium. Depending on the substrate, the strength, surface structure, morphology or any other characteristics can vary. In addition, it is possible to work with additives. These can have a further positive influence on the properties of the end product. For example, the use of fine glass can improve the fire resistance of a finished insulation material made of mycelium composites. [JON18a]

The manufacturing process of a Mycelium component proceeds as shown in Figure 3. First, a decision is made regarding the fungus used, the substrate, and possible additives, which of course depend on the desired material properties of the final product [APP19]. As soon as this happened, the lignocellulosic material,will be hydrated. It is mixed with water and then processed into a homogeneous mass. This is done by blending, grinding or milling the substrate to guarantee a uniform structure of the initial material. The substrate is now sterilized. This serves on the one hand to remove the water that was added in the previous stage, but above all to neutralize all organisms in the material. The substrate should be completely free of other bacteria or fungi that might compete with the intended fungus and thus endanger its growth and homogeneity [HAN17].

Now the actual growth phase of the mycelium begins. The substrate is distributed with fungal spores in a mold. For most forms of fungi, it is helpful to create a slightly moist, rather warm and nutrient-rich environment. Under these conditions, it now usually takes several days or weeks for the mycelium to develop and fuse the entire shape [APP19]. Once this is done, the final production step is initiated. This is the complete dehydration of the overgrown material, which serves to neutralize the fungus, thus effectively killing it, so that it no longer tries to grow further and exists only as organic, but dead, material. In addition, further water is extracted in this process, which causes the material to gain in stiffness [HAN17].

The different approaches and methods of producing mycelium are shown in Table 2. It can be seen that there are differences between various studies by diverse research groups, but nevertheless tendencies can be identified which ensure optimal growth of the mycelium.

There are several approaches to optimize and automate the production of mycelium, including the use of additive manufacturing processes, such as 3D printing of growth scaffolds [KOE20] or even the material itself [SOH20]. The potential of such automation becomes clear when considering that 90% of the total costs of Mycelium production are labor wages [JON20].

Another possibility to decrease costs would be the use of robots in the production chain, which would replace the cost-intensive labor. The mushroom can be grown regardless of location and climate, so it can be used almost anywhere on the planet. But it is also true that for a good and

Fungal species	Feedstock	Sterilization method	Growth conditions	Growth time	Drying method	References
Coriolus (Trametes) versicolor and Pleurotus ostreatus	Hemp hurd, wood chips, hemp mat, hemp fibres, non-woven mats	Boiling water for 100 min or 0,3% hydrogen-peroxide	Dark conditions. 90 to 100% RH. Fresh air and CO2 content should be kept high, Room temperature.	30 days	Oven at 125 °C and dried for 2 h.	[LEL15]
Ganoderma lucidum	Quercus kelloggii (Red Oak) wood, macerated into 5.0–15.0 mm chips	Not specified	Pending IP prevents full disclosure of the nutrient solution and growth conditions.	Not specified	220 °C for 120 min. 10–20% Moisture content, via convective heating using solar dryers.	[TRA16]
Irpex lacteus	Macerated sawdust pulp of Alaska birch of 5 mm or smaller in size, millet grain, wheat bran, a natural fibre, and calcium sulfate.	Pasteurization	Not specified	14–42 days	Dryer at 60 °C for 24 h.	[YAN17]
Not specified	Rice husk 50% + wheat grain 50%, Rice husk 70% + wheat grain 30%, Rice husk 30% + wheat grain	121 °C for 15–20 min	Not specified	Not specified	Drying machine at 50 °C for 46 h.	[ARI13]
Pleurotus djamor	A standard Northern Bleached Softwood Kraft (NBSK) pulp sheets	Not specified	20–25 °C, pH 5–8, 80% RH, Darkness	5–25 days	Oven at 55 °C for 2 h	[AHM16]
Trametes ochracea and Pleurotus ostreatus	Beech sawdust nd rapeseed straw, supplemented with bran. Non-woven low-quality cotton fibre.	Not specified	25 °C in the dark for 14 days. Plates were demoulded and kept at the same conditions for 10 more days. Humidity of 55–70%	24 days	Heat (150 °C) or cold (20 °C) pressing was performed with a mechanical multi-plate press for 20 min at F b 30 kN.	[APP18]
Trametes versicolor	Flax, flax dust, flax long treated fibres, flax long untreated fibres, flax waste, wheat straw dust, wheat straw, hemp fibres and pine softwood shavings	Autoclaved at 121 ℃ for 20 min	In a micro box with a depth-filtration system at 28 °C for 8 days. After 8 days, the samples were demoulded in the laminar flow and incubated in a micro box for another minimum of 8 days without mould	16 days	70 °C for 5 to 10 h	[ELS19]

Table 2: Growth conditions during production of mycelium components [ELS20] (Table redrawn and reduced to insulations and foams as well as the aspects most relevant to the research question)

as homogeneous as possible growth and thus standardized material properties, a controlled environment must persist. This would suggest a tendency towards prefabrication rather than on-site production.

The insulation material is also very far ahead in terms of carbon dioxide emissions. The production of Mycelium with 2.2 CO2/kg consumes about 3 times less than that of extruded polystyrene with 6.98 CO2/kg [CHA17]. At the same time, about 56% of the emissions in mycelium production are due to dehydration process [ECO20].

4.2 Physical properties

It is important to understand that due to the relatively young age of the material and the associated optimization potential, the current research results can become outdated very quickly. We are dealing with a building material that is still in the infancy of its development and for which improvements can still be made through continuous exploration [HAN17].

Since the mycelium is only to be used as insulation in our application, the load-bearing capacity of the material is of secondary importance. Studies attest the building material a load-bearing capacity of approx. 29 kPa - 567 kPa [YAN17], which is slightly below comparable insulation materials such as expanded polystyrene [LÓP16]. However, an insulation material must in the first place insulate well, for this purpose the thermal and sound conductivity must be considered that depend to the density. For compressed mycelium, this is approximately 94-135 kg/m³. Compared to extruded polystyrene (XPS) with a density of 15-18 kg/m³, it is slightly heavier, but lighter than rock wool with 470-2250 kg/m³ (s. Table 3). Density is therefore important because the air trapped in the insulation panels significantly affects the performance of the material.

This relatively low density paves the way for low thermal conductivity [DIA21]. The lower the conductivity, the better the insulating performance of the material. Here, Mycelium is still somewhat behind the classic insulation variants. It achieves a value of 0.0419-0.578 W/(m·K) [ELS19] (Table 2). In comparison, glass wool can reach values up to 0.033 W/(m K) and extruded polystyrene 0.025-0.035 W/(m·K) [PAP05].

However, since these materials are already much more investigated and, above all, the quality of these fabrics is already much more consistent, further potential of the mycelium can still be found here. Table 3 shows that Mycelium is already in stroke distance to the best commercial insulators.

In addition to a thermal control function, insulation materials should also provide acoustic protection. For this purpose, the acoustic absorbance of mycelium panels was investigated in research studies. Panels with different substrates were tested and even the worst performing samples achieved an absorption of 70-75% of the sound at 100 Hz [PEL17], what is even better than commercially used XPS [WEB15].

In terms of fire protection, mycelium performs somewhat like extruded polystyrene. The ignition time of the two materials are observed to be similar under the identical conditions [JON18b]. [DOM10,

Insulating Material	Thermal Conductivity [W/(m*K)]	Density [kg/ m³]	Source
Mycelium-flax composite	0.0578	135	[ELS19]
Mycelium-hemp composite	0.0404	99	[ELS19]
Mycelium-straw composite	0.0419	94	[ELS19]
Rock Wool	0.030-0.045	470-2250	[DOM10]
Glass Wool	0.033-0.045	13-100	[PAP05]
Extruded polystyrene	0.025-0.035	15-18	[PAP05]
Kenaf	0.034-0.043	30-180	[ASD15]
Sheep wool plates	0.038-0-054	10-25	[ASD15]

Table 3: Properies of mycelium insulation material [ELS19]

GIA20, ELS19, PAP05, ASD15]

Due to the fact that mycelium is a purely organic insulating material, even the neutralized fungus in combination with some humidity can form mold, i.e. new fungal infestation [DIA21]. At the same time, researchers have shown that the mycelium insulation material has a high affinity for water, which further complicates the problem [APP19, LÓP16]. In this experiment, the material increased its weight by 40-580% when it was in contact with water for 48-192h. Once again, the result is clearly depending on the composition of the material.

While the contact to water with substrates such as cotton fiber or rapeseed straw led to a water uptake of 220% the weight of the initial material after 3h, it was only 23% in the same time when using saw dust [APP19]. This large difference is mainly due to the fact that the fungal structure is rather hydrophobic [APP18] while the organic substrate is usually hydrophilic [ZIE16]. Most fungi form a water-repellent layer on the substrate surface which counteracts excessive water absorption. Water absorption will be one of the key factors in durability and probably the biggest hurdle the building material will have to overcome before it is ready for mass production. However, an insulating material is naturally more likely to be installed in dry locations.

This also creates a direct transition to the life cycle assessment of the building material. It describes a complete life cycle of the component from construction to disposal. The sustainability of the mycelium-based building material stands out in particular, as all the materials used are either compostable or even recyclable as animal food or new mycelium building components. This so-called "cradle-to-cradle" philosophy [MUL10], in which all materials used can be returned to their original state, distinguishes the mycelium insulation. Furthermore, it is shown that the production costs of Mycelium insulation can keep up with competing products [JON18b].

5. Discussion

Mycelium can compete well with the today's classic insulation products in terms of the important material properties of insulation materials. It has only slightly higher thermal conductivity than comparable materials, so it can find a field of application in the wide range of construction industry. Especially in cases where it is not only a matter of maximum efficiency, i.e. the most space-saving variant with the highest possible insulating power, but rather a sustainable implementation of a building project. At the same time, other factors such as sound insulation or fire resistance also perform at a very high level.

The supposed weakness of the building material is its water resistance, because as soon as the building material comes into contact with moisture, new mold can quickly form on the organic surface. However, it is also the case that many other insulation materials used are struggling with moisture resistance. In addition, the raw material is still at the beginning of its development, it is quite possible that it can still make leaps in some category, this is also favored by the diverse possibilities of production. The sustainability of manufacturing must also be emphasized, because the CO_2 savings in production are enormous compared to similar insulating materials.

Whether on-site production of mycelium insulation panels makes sense depends primarily on the location and the associated conditions. As shown in Table 3, special conditions are required for the optimal growth of mycelium. This optimal growth is in turn essential to obtain a high-quality insulation material and of course to reduce the time it takes to grow to a minimum.

The growth conditions are the main problem for an application on construction site, as they are often very specific. During the German winter, one would have to provide a room on the construction site with a constant temperature of about 20 °C, and that around the clock. Care must be taken here not to negate the many climate benefits from the use of the sustainable raw material and the elimination of transport routes to the construction site.

Another critical factor is certainly the growth time, which is often two weeks to over a month. This is a long time during which the production facility of the insulation on the construction site must be maintained. Other factors, such as drying at comparatively mild temperatures, do not seem to pose any major problems.

6. Conclusion and Outlook

This article compares the attributes of the unexplored building material mycelium with the established raw materials on the basis of a systematic literature research. The aspects of thermal conductivity, load capacity, moisture resistance, fire resistance, sustainability and production process were examined and evaluated for their suitability.

Mycelium has proven in that it can keep up with mineral and organic insulation alternatives. Especially in the most important point, the thermal insulation capacity, it is already within striking distance of commercially used products, although it is still somewhat behind. Many other properties of the building material are also convincing with regard to the field of application.

When it comes to sustainable production, none of the competitors can compete to Mycelium, this is where its strengths lie. The production of Mycelium panels consumes significantly less fossil raw materials and energy than the classic variants. This is also due to the simple production without the use of a lot of additional technology, but a lot of time, which, as we know, does not need or emit carbon.

What consumes energy over time, however, would be for the on-site production of mycelium needed rooms on the site, which would have to maintain a certain temperature and humidity level to ensure a homogeneous growth over several weeks. At this point, one must be careful not to add up the saved resources elsewhere. In the same way, the entire life cycle of a building must be considered, where even small differences in thermal conductivity can lead to very different consumption in the long term. The time factor may also challenge the general construction planning, because on many construction sites there is already a lack of space due to retention areas for building materials or site equipment. As a result, economically and ecologically superior on-site production is still a long way off at the current state of research, and new ideas are needed to ensure this.

Mycelium is a very exciting building material that could continue to develop in the future. The research on mushroom insulation is still young and therefore there are endless possibilities for further research, very exciting would-be long-term experiments that address the maintenance needs and simulate a real insulation situation. Alternatives to the classic growth environment would also be advantageous, as would the use of robots to automate the production loop.

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Challenges and Potentials of Unmanned Aerial Vehicle (UAV) Applications for Construction Progress Monitoring

ABSTRACT

UAV`s (unmanned aerial vehicles) have gained popularity in a lot of industries including the construction industry. Research in the construction industry mainly considered and employed UAV's for the automation of surveying and monitoring to enhance efficiency and productivity and to reduce the costs of manual surveying. In this research, the implementation of UAV's/MAV`s (micro aerial vehicles) on the construction field for progress monitoring will be analyzed and how technological advances in the computer vision and sensor technology enables autonomous flying even in GPS-denied environments will be reviewed. The purpose of this paper is to provide an overview of the state-of-the-art UAV and surveying technology, to evaluate their challenges and opportunities and to discuss the current situation of UAV`s for construction monitoring. The research paper will discuss the future of UAV's as an alternative to manual construction progress monitoring practices in the light of researches aiming to achieve full/partial autonomy and optimization of data collection via drones. UAV`s can acquire visual data that can be processed to 3D point clouds and as built models. By comparing these as built models and as planned BIM (building information model) real time quality control and progress monitoring can be achieved. For the implementation of UAV`s, some challenges need to be tackled like the physical limitations of UAV`s especially the weight and payload of small sized UAV`s or commonly known as MAV, as well as legal constraints and the need of huge amounts of processing capabilities. Although these challenges are yet to be solved, aerial platforms offer a lot of possibilities for the construction industry by conserving the lost data during the manual surveying and monitoring applications and automating the process of data collection and reconstruction.

1. Introduction

UAV`s also known as drones are a technology that has gained huge popularity over the recent years in the construction and manufacturing industry among other industries like technology media and telecommunication, transportation and logistics or agriculture, mining, gas and electricity. In the year 2018, the drone sector increased by 239% in the adaptation of technology [Pe20]. As stated by [El18] drone technology can lead to savings of £3.5bn of the UKs GDP by 2030 in the construction and manufacturing industry (Table 1). Automation of workflows, lower costs and enhanced productivity can be the reasons for the biggest immediate impact on the savings [El18].

In the construction industry UAV`s are mainly used for site surveying, progress monitoring and safety applications [Ha16]. Surveying and monitoring, that are traditionally carried out manually by the surveyors can benefit from the automation with drones in the terms of cost reduction, productivity, and efficiency. According to [El18] a construction site survey done with the help of UAV`s can be up to 400 times quicker and the surveying costs can be reduced by approximately 40% compared to a survey done manually.

2. Research Framework

This research paper is divided into four parts. The first part provides an overview of the state-of-the-art drone and data collection technology for construction surveying and monitoring. Next, research from the field will be reviewed to illustrate core aspects of UAV-assisted progress capturing studied by the scientific community. The challenges and opportunities of the state-of-the-art technology will be evaluated. The last part of the research paper answers the question how and to what extent UAV`s can assist current surveying and monitoring applications on site and that provides an outlook how this could change in the future. (Fig. 1)

3. State of the art technology

An important research topic in the field of unmanned aerial vehicles is the navigation of the UAV. Equipped with appropriate sensors and GPS technology UAV`s can follow a preprogrammed GPS controlled flight path [TL17]. The UAV can follow the flight path autonomously. These preprogrammed flight paths can be used so that the drone can take images or videos from the exact same position and aerial perspective to track daily or weekly construction progress. Not only the path

Sector	Gross Cost Saving from Drones Uptake	Net Cost Savings from Drones Uptake	Multi-factor Productivity Impact by 2030
UK Wide	£17bn	£16bn	3.2%
Technology, Media and Telecommunications	£4.9bn	£4.8bn	12.4%
Financial, Insurance, Professional and Administrative Services	£4.1bn	£4.1bn	2.8%
Construction and Manufacturing	£3.5bn	£3.5bn	3.1%
Transport and Logistics	£2.8bn	£2.8bn	8.4%
Public and Defence, Health, Education and Other Services	£1.3bn	£1.1bn	0.4%
Agriculture, Mining, Gas and Electricity	£0.2bn	£0.1bn	0.4%

Table 1: Gross and net savings and multi-factor productivity impact by 2030, by UK Sector [El18]

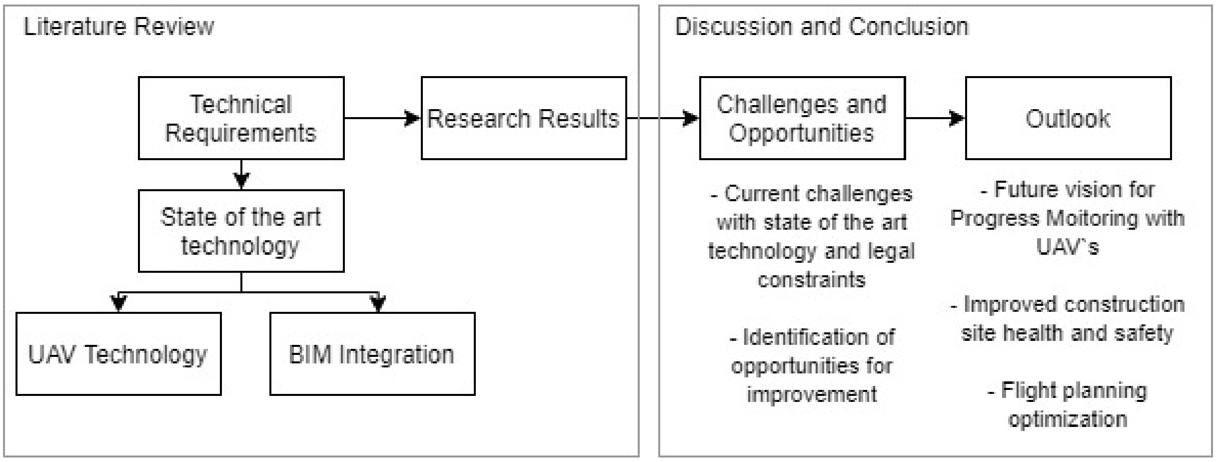

Figure 1: Methodology

can be programmed but also the drones speed, altitude, and camera angle can be arranged based on the need and the flying environment. Included in the preprogrammed flight path are safe starting and landing that the UAV can do by itself [TL17].

In order to capture data drones are equipped either with LiDAR (light detection and ranging) or passive optical sensors (POS) like thermal or RGB cameras [Pe20]. LiDAR systems are equipped with sensors that send out laser rays and measures the time it takes the ray to come back [Wi21]. Although LiDAR is common practice as a mean of surveying, it does not provide valuable scene information such as texture or color. In contrast, photographic systems provide a large number of overlapping high resolution images [TL17]. These images can be combined using photogrammetry software to create 2D and 3D models. These models contain information about elevation, texture and color of every point included in the model. In a report published by Wingtra (2021), which is a drone producer from Switzerland, they evaluated and analyzed photogrammetry and LiDAR for drone surveying operations [Wi21]. According to the report, with photogrammetry, new camera technology makes it possible to create high precision point clouds, with about one centimeter accuracy in the horizontal plane and two to three centimeters accuracy in the vertical plane. They underlined the importance of the accuracy of the point cloud is the data processing. With taking all current state of the art technology into account LiDAR systems can provide an accuracy of 10 centimeters in the horizontal and five centimeters in the vertical plane. The coverage of both systems when attached to lightweight drones is around 10km² per flight which allows to survey even big construction sites [Wi21].

While photogrammetry provides photorealistic models with higher accuracy LiDAR has its advantages for example in areas with high vegetation as it still can provide information of the ground even when there is vegetation in the way [Wi21]. Drones equipped with cameras and sensors that capture thermal data can be used to identify energy leaks in a construction or a building [TL17].

4. BIM Integration

The point clouds generated by the drone and its sensor and camera technology can be integrated into BIM to generate as-is BIM models and to compare the as planned BIM model with the actual as built environment. In the master thesis of van Schaijk (2016), a 3D model is reconstructed through point cloud data captured by an UAV during the construction process (Fig. 2) [St16]. This point cloud data shows the advancement and the progress on the construction at five different points in time. With BIM integration the point cloud model was compared with the as planned IFC (industry foundation classes) model. This procedure helps to identify deviations between as built and as planned and potential bottlenecks in material delivery. With the comparison it can be identified which element was installed on time and which element was delayed. For real time and continuous process monitoring a high frequency of data acquisition along with as planned and as built comparisons are required [Tu17].

The comparison of as planned and as built models also offers the possibility of construction progress monitoring and quality control. For real time quality control, the point cloud data captured by the UAV must be synchronized with the as planned BIM model. A research team from Curtin University developed a system that converts the point cloud data to the BIM model and that calculates the deviation between the as built and the as planned model to evaluate the construction quality. Their findings have proven the importance of the frequency of collected as built data for quality control by the UAV.

5. Research Results

UAV's have revolutionized the landscape of surveying and monitoring applications in many different areas such as forestry, mapping industrial environments, and agriculture [FLR19], [Ca20]. Nevertheless, UAV based applications for construction progress monitoring are still mostly limited to land development and earthworks surveying tasks. Laser scanners are the most used equipment to carry out progress monitoring on construction sites along with labor-intensive manual data collection methods, yet they lack the rich multi-dimensional data that image-based methods offer [Go09]. Furthermore, laser scanners are expensive equipment that requires warm up time before each use and the data acquired

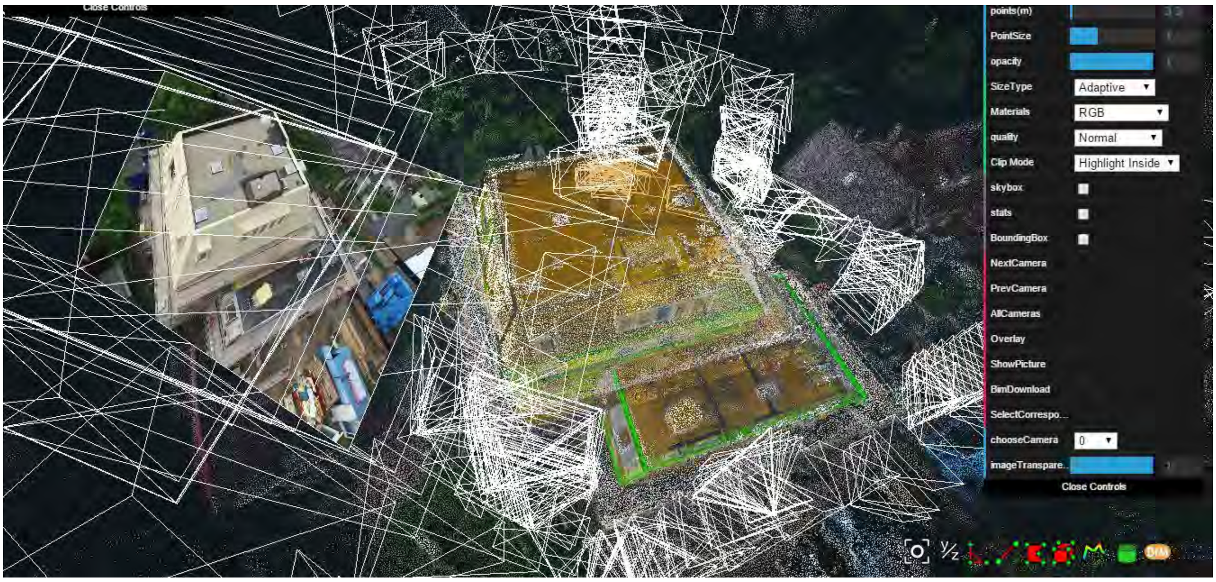

Figure 2: SfM to reconstruct BIM [St16]

needs to go through manual processing. Hence, through image-based progress monitoring methods, the progress situation can be more comprehensively understood since they offer more elaborate semantic information. Moreover, the advances in computer vision techniques and photogrammetry as well as UAV technology provide an outlook on the use of UAV's with passive optical sensors as an alternative method for progress monitoring.

To collect adequate performance data, UAV flight path must provide a volume of images and media taken from the most optimal angles and views. Visual data collection on construction site via UAV's are usually done from above, to avoid GPS signal loss and shadowing effects of other buildings [Ha16]. In addition to such signal disruptions, UAV's are in practice still not the preferred option for progress monitoring, due to the absence of accurate localization means which gives cause for mid-air collisions [ISG19]. In the meantime, vision-based state estimation and localization techniques have long been studied in the robotics related research. In their research, Shen et al. (2013) built a micro aerial system that depends on its on-board processor, camera, and inertial measurement unit (IMU) sensors to follow a flight path autonomously in a complex 3D environment [Ss13]. Upon reaching destination, the system successfully follows the same path and lands on the landing platform with a small drift from the position (Fig. 3). Swarm gradient bug algorithm research lead by McGuire et al. (2019) used a swarm of drones to address a similar concept for a rescue mission use case, with UAV platforms weighting as small as 33 grams while avoiding collision with each other [Mc19]. The success of these studies provides a promising outlook towards achieving autonomous UAV operations in GPS-denied environments while being computationally feasible, allowing on-board state estimations and mapping.

Achieving these results while addressing comprehensive simultaneous localization and mapping (SLAM) problems may be computationally expensive [Ss13]. At this point, building information models can provide articulate information, rendering the data acquisition and analysis

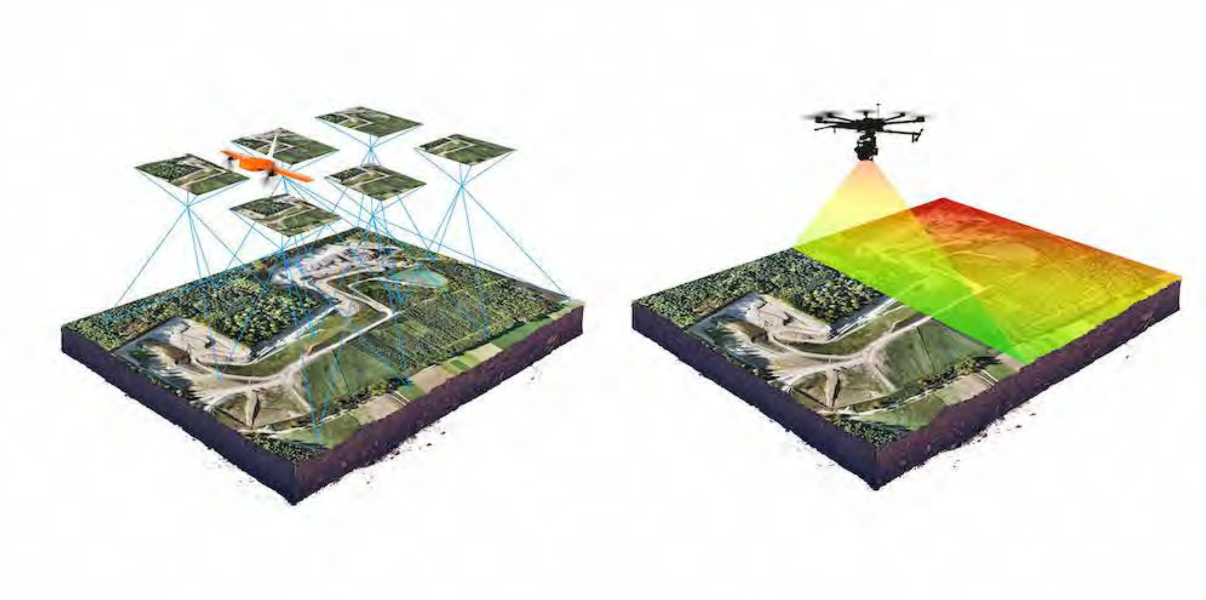

Figure 3: Photogrammetry and LiDAR on UAV's [Wi21]

tasks to a much simpler level [Ha16]. In their research, Golparvar-Fard et al. (2009), implemented a structure from motion (SfM) methodology to develop a color-based progress monitoring system using drones [Go09]. The camera location estimations are first bonded to the absolute coordinate system. Then, the system communicates the construction progress by superimposing the geo-registered as-built and as-planned models. In his master thesis, van Schaijk (2016) uses the same system to monitor the construction progress of a small apartment unit, the Schependomlaan Project [St16]. The point cloud obtained by frequent UAV surveys and IFC of the as-planned model is fused into a scene and processed by a supervised machine-learning algorithm. The experiment returned accurate progress report confirmed by the site management.

6. Discussion

6.1 Challenges

Physical limitations of aerial robots: As opposed to the immutable ground robotics like laser scanners and total stations, drones possess great overall potential in the construction field as an alternative for working at heights and narrow spaces beyond the reach. Although various types and sizes available depending on the prospective use, drones have limitations regarding the payload capacity. Typical LiDAR weighting around 2 – 2.5 kilograms, surpasses the maximum load allowed on most of the micro aerial vehicles [Ss13]. Weight of the added equipment to small aerial devices introduces the problem of the flight time. Table 2 shows the effect of added battery load on the maximum payload, while Table 3 illustrates the estimated effect of added camera weight to the flight time per single charge [STK20]. Mainstream small size drone can fly up to 30 minutes. Added the weight of the equipment, the instruments that are loaded on the system also draws power from the same battery [STK20]. Overall, energy efficient UAV operation is a challenge with multiple facets. Reduced flight time may cause interruptions while capturing the data, hence produces additional manual labor and reduces the expected work efficiency.

Data artifacts: Point clouds may be generated using a variety of 3d scanning methods. LiDAR and photogrammetry being among the lightest options, suitable to be attached on UAVs, both methods require a trade-off with regards to the depth of measurement, missing objects, and noise [FLR19]. Regardless of the chosen

DJI Drone	Battery Rating (mAh)*count	No-load Flight Time (min)	Maximum Payload (g)
M100	4500*1	22	1245
M100	4500*2	33	645
M100	5700*1	28	1169
M100	5700*2	40	493

Table 2: M100 DJI drone flight time for different battery settings [STK20]

DJI Drone	No-load Flight Time (min)	On-board Camera	Camera Weight (g)	Regression - Predicted UAV flight time (min)	DL - Predicted UAV flight time (min)
M100	22	Zenmuse-X5	526	13.86	9.13
M100	22	Zenmuse-Z30	556	12.20	8.70

Table 3:Estimation of DJI drone flight time with regression and deep learning (DL) methods for 2 different cameras on board [STK20]

method, the point cloud data set is prone to errors caused by device calibration, projected surface and environment characteristics, or registration of point clouds [An13].

Implementing point cloud data in BIM: In general terms, scene understanding using point clouds and BIM has been a main area of research for computer scientists [TB15]. Semantic structuring of the point cloud data for the automatic formation of a building model has been the subject of a number of researches [NSK09], [TB15], however the data complexity and the erroneous nature of the data set has been deemed as major challenges yet to be tackled. Another primary challenge is establishing site-to-BIM automation through leveraging IFC's. In their research, Hamledari (2017) highlighted the lack of semantic information in the IFC exports of existing BIM software, since they cannot make use of the full potential of IFC schema [Ha17].

Legal Aspect: Despite of the growing demand and emergence of potential uses of UAV's, concerns raised with regard to privacy and data security constraints the use of UAV's through legal provisions. UAVs are subject to stringent regulations under different government laws, that limits most UAV operations, causing a major lag in the wide-spread use as well as slowing down research progress [St17]. In the case of Europe, while some defined uses of UAV's are allowed without an operation permit, UAVs above 5 kilogram overall weight are subject to the permission requirement [CCC12]. In addition to the operation permit, the drone pilot must also be certified by the relevant authorities which highlights the need of trained personnel.

6.2 Opportunities for Improvement

Photogrammetry over LiDAR: While there is a strong increase in the popularity of airborne laser scanner systems, passive optical sensors remain as a competition to

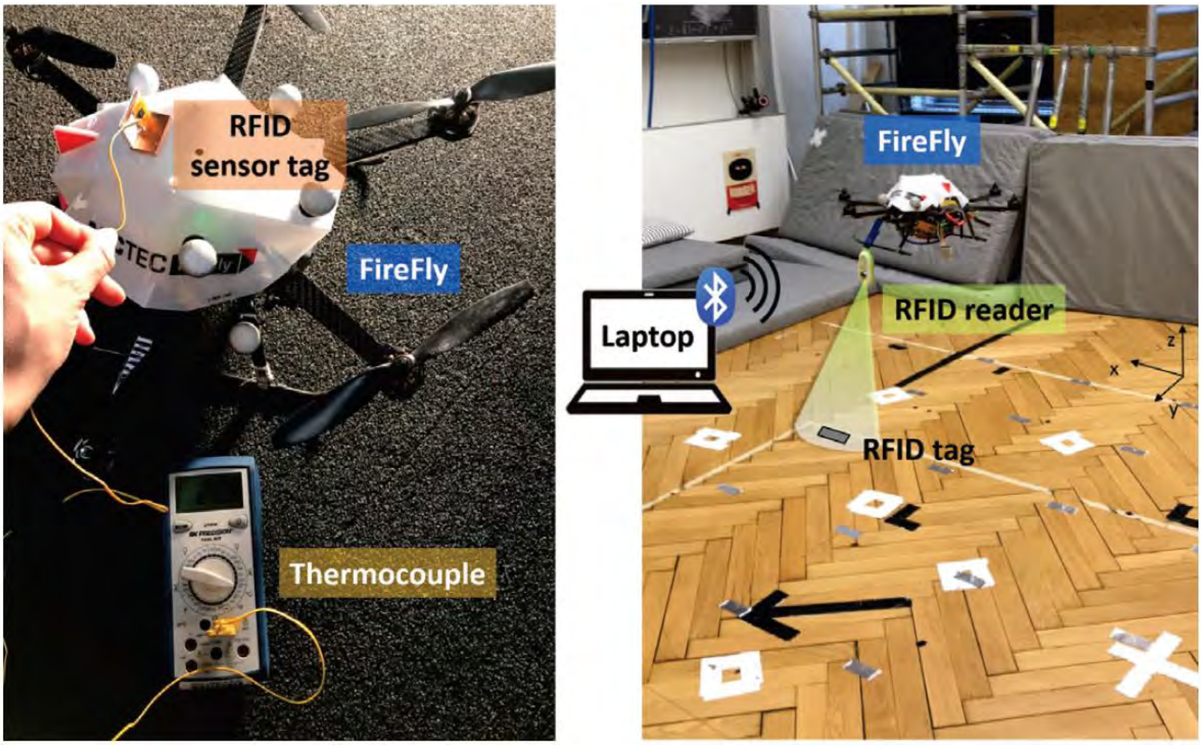

Figure 4: MAV equipped with temperature sensor [LO18]

laser scanners. One of the key challenges of aerial laser scanner operation is the heavy payload of LiDAR equipment. Flight planning of aerial laser scanners is usually constrained to physical limitations such as the maximum payload of the flying platform and by extension the flight time of the vehicle with a single charge, or the absence of GPS data. In that regard, photogrammetry stands out as a good alternative to pure LiDAR based options since flight planning has long been studied within the field of photogrammetry, while POS could also be placed on a greater variety of flying platforms [AR20], [Ba99]. Further upsides of the POS can be listed as the vast equipment range already available on the market, high geometric accuracy, low maintenance and longer lifespan. While photogrammetry also comes with many drawbacks such as the need of computational power [Ca20], further advancements in the computer science and hardware is expected to augment the efficiency of photogrammetry applications. By extension, lighter aerial robots can be incorporated into the surveying/monitoring applications on the construction site along with the laser scanners, as low-cost alternatives assisting point cloud generation.

Micro Aerial Vehicles: MAV's are much smaller in size compared to UAV's, which makes them perfect alternatives addressing legal issues related to the use of UAV's in registered aerial fields. Even reaching the maximum payload of MAV's, it is possible to remain under the 5 kilo threshold that is set for the building inspection as per BMVI [CCC12]. The use of MAV on the construction site as a research subject is not as common as larger flying platforms such as UAV's. However, different studies have been conducted on GPS-denied environments for the automated localization of the MAV's [LO18], [Lo18], using light RFID (radio-frequency identification) reader and tags, providing an alternative to GPS with an accuracy at around 0.12 meters. The study by Longhi et al. (2018) used on-board RFID readers/tags attached to MAV's, proving that MAV's are good alternatives for working in tight spaces flexibly while carrying additional load (Fig. 5) [LO18], [Lo18]. The study further suggested that it is possible to achieve autonomy without undertaking expensive computational workload, for which considerable additional weight for a strong processor would be needed.

Automated Construction Monitoring: Many large AEC (architecture, engineering, and construction) companies benefit from visual surveillance systems for field monitoring as well as processing visual data to enrich 3D models. While these means are rich sources of data, construction sites as dynamic worksites require the frequent acquisition of visual data, along with its rapid processing [Ha16]. While the advances in the robotic vision techniques provide a promising outlook towards UAV technology in that regard, use of UAV's are still mostly depending on human guidance. However, in the recent years, there has been many researches proposing autonomous localization methods for UAV's [Ha16], [Ng20], [GJV13], [Ss13]. In their research,

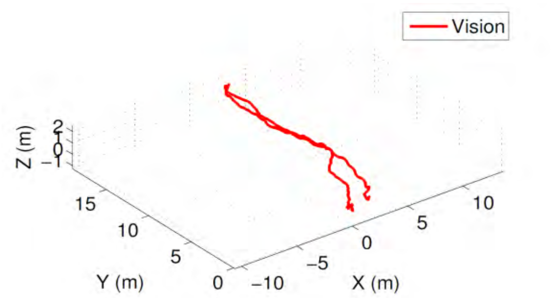

Figure 5: MAV autonomously follows the path and returns to landing platform [Ss13]

Wang et al. developed a system that leveraged BIM to pre-define a flight path around a sample building. The system autonomously evaluated the quality of the as-built construction based on the as-planned model [Wa15]. A team of researchers from TU Berlin has proposed a framework addressing another aspect which is reconstructing BIM autonomously [NSK09]. These studies together provide a promising outlook towards reducing the manual work and overall operational costs to obtain performance and quality control data on construction sites.

7. Conclusion

This research paper provided insights and detailed analysis on how UAV's can be leveraged to perform as-built survey to monitor the progress on construction site. It illustrated current state of the art for progress monitoring using UAV's, with or without using BIM, including high-level challenges and opportunities for development. It further presented different approaches in the research and AEC industry to automate the flight planning and mapping processes, as well as collecting and interpreting data from the operation. It included insights on how BIM can be employed to reduce the computational workload and blend the process of progress monitoring into the overall project workflow.

However, there are many challenges ahead, towards achieving a full systematic monitoring scheme using UAV's. Interdisciplinary collaboration to overcome these challenges can lessen the intensive manual labor exerted to improve monitoring practices.

7.1 Outlook

The following part provides a vision about how UAV`s could be operated and used for construction projects to further enhance productivity and efficiency, and thus reduce the overall projects cost. For drones to become a viable tool for every construction project, the cost for the operation of UAV`s and the cost of the detection equipment attached to the UAV's has to be further reduced. Preprogramming of UAV`s flight path should be simplified to reduce the need to hire drone specialists, which would generate more costs. An idea could be to program a UAV`s flight path so that the drone can regularly fly in a defined schedule. Building information models can be used as a map for flight path determination. With a high flight and monitoring frequency the UAV could provide real time data. This vision suggests that the data delivered by the drone would not only be responsible for progress monitoring and quality control. While monitoring the construction progress the UAV could also monitor the workers movements and therefore ensure their safety while working on the construction site (Fig. 6). With the advancement of technologies like RFID or BLE (Bluetooth low energy) the UAV could also be able to locate important and expensive tools and machinery and track the location of material, extending the progress monitoring to have an even larger impact on improving overall performance indicators of a construction project.

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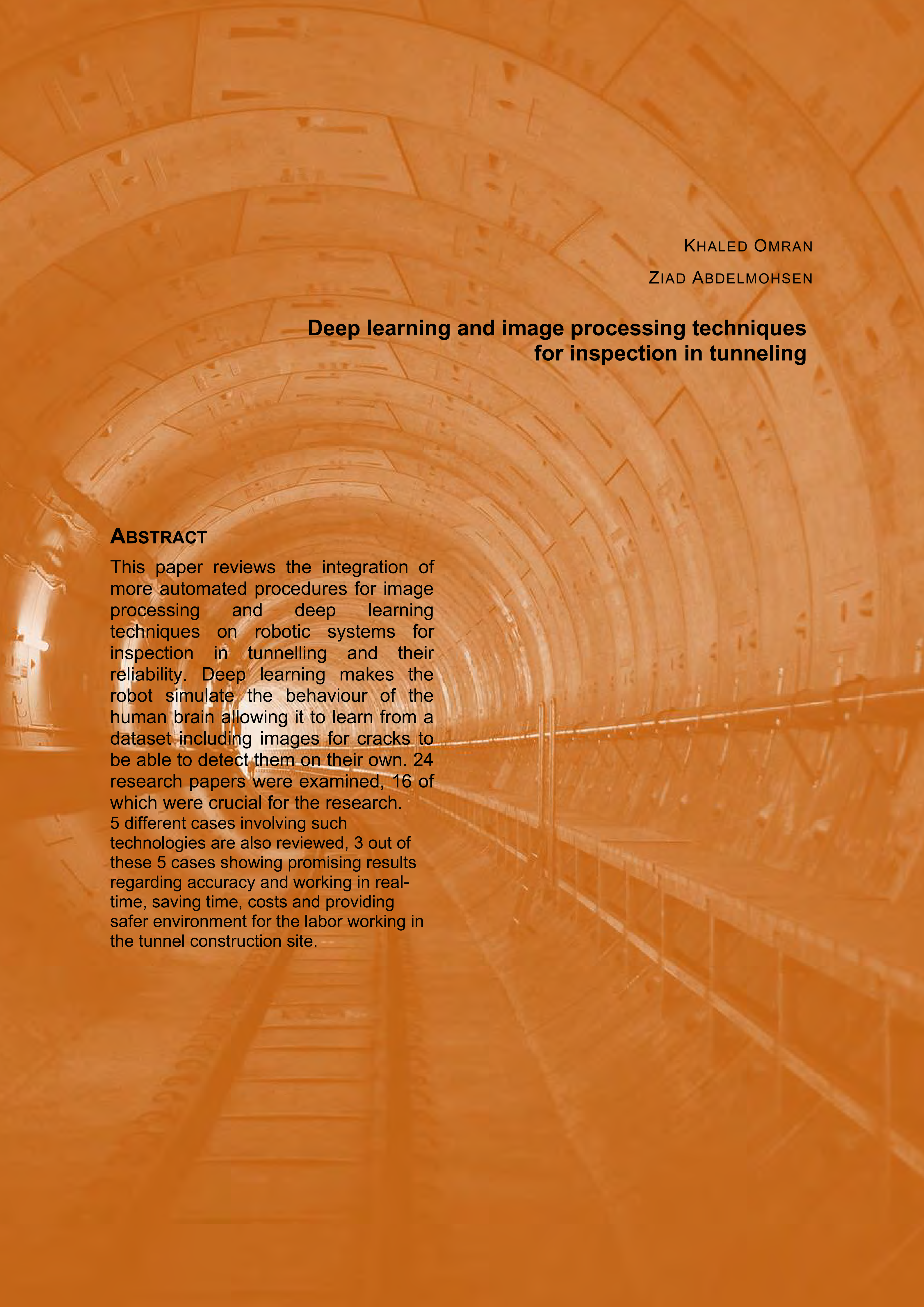


KHALED OMRAN

ZIAD ABDELMOHSEN

Deep learning and image processing techniques for inspection in tunneling

ABSTRACT

This paper reviews the integration of more automated procedures for image processing and deep learning techniques on robotic systems for inspection in tunnelling and their reliability. Deep learning makes the robot simulate the behaviour of the human brain allowing it to learn from a dataset including images for cracks to be able to detect them on their own. 24 research papers were examined, 16 of which were crucial for the research.
5 different cases involving such technologies are also reviewed, 3 out of these 5 cases showing promising results regarding accuracy and working in real-time, saving time, costs and providing safer environment for the labor working in the tunnel construction site.

1. Introduction

Annually, 4700 km of new tunnels are built [TIA19]. Tunnels deteriorate with time as a result of age, environmental variables, increased loading, changes in use, human/natural relevant factors, weak or bad maintenance, and deferred repairs. Therefore, tunnels need constant inspection and maintenance. The vast majority of tunnel inspection activities are now carried out manually. The procedure depends on the workers' perspectives, and the operators must work under settings that are both unpleasant and risky, such as dusty environs, lack of light, or exposure to poisonous substances[MON15].

Makantasis et al. [MAK15] explained that visual limitations due to working hours, lack of continuity of inspectors or inspection methods can reduce the effectiveness of the procedure and confidence in results. Speed and economic reasons; on the one hand, the cost of the engineer on site (especially during night shifts), on the other hand, along with the infrastructure closure are also main factors why manual inspection needs to be replaced. As a result, the demand for automated, cost-effective, and thorough tunnel inspections to prevent catastrophes is growing.

In this paper, the main focus will be on reviewing whether the different image processing and deep learning methods are reliable for automating the inspection process in tunneling, especially in crack detections in the tunnel face.

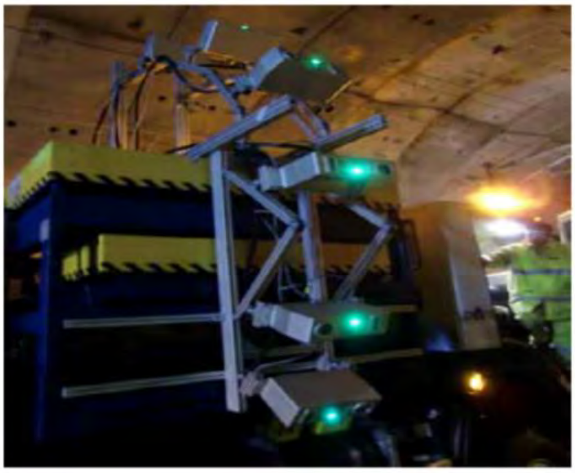
2. State-of-the-art

Figure 1: The Tunnelings system laser sensors and cameras scanning the wall [MON15]

Currently, inspection of cracks in tunneling is widely done using 2 basic techniques. Firstly, the classic "hammer-knocking" inspection method [YAO00] is done manually where a worker physically goes to the face of the tunnel and knocks on susceptible spots where cracks might exist. Moreover, another technique is done by operators measuring cracks in concrete structure by observing cracks with their naked eyes and recording them. [AN04]

A more advanced method is tackled by using computer-assisted technologies for survey operations and data processing that help with on-site inspection. Pre-inspecting the tunnels in the office using previously scanned photos as the foundation for the inspection software cuts down on time spent in the field prioritizing the tunnels based on the severity of the damages and the construction expenses. The owner or operator can then organize financing and intervention schedules. Finally, a maintenance intervention plan for the tunnel (or zone) is developed based on the network's priorities [TIA19].

However, and due to the previously mentioned drawbacks, automation is being researched to be introduced in inspection



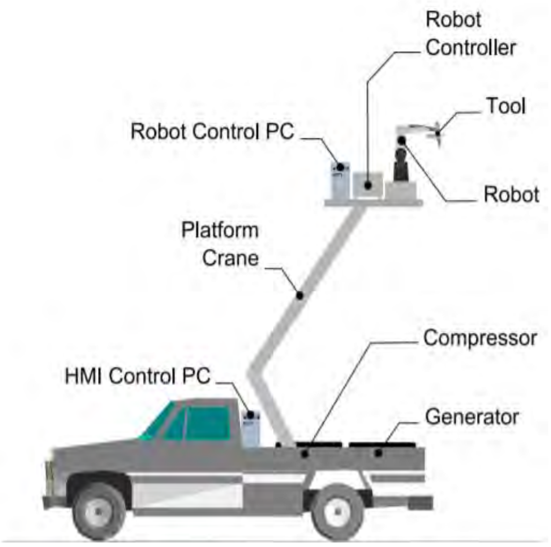


Figure 2: Different components of the TunConstruct system [MON15]

to overcome such problems. Euroconsult and Pavemetrics developed a laser-based method, the Tunnelings system, where cameras and laser sensors, as shown in Fig.1, are used to scan the tunnel's walls and a software is integrated to compare data from 2 different runs and evaluate the results.

However, these systems are tele-operated and eliminate the advantage of remote inspection since some workers need to be around the area of work exposing them to the same aforementioned risks.

Another example is by using robotic systems that can finish inspection with high efficiency and objective outcomes. These systems are designed to avoid cutting the traffic flow and improve safety by completing inspections instead of inspectors in hazardous areas. As a result, manual and visual inspections are being phased out in favor of more precise procedures involving mechanical, electronic, and robotic systems, as well as data from cameras, lasers, sonar, and other sensors. One practical example is the TunConstruct system, a semi-automated EU-funded inspection system shown in Fig.2 designed to detect and apply repairs to cracks.

Figure 3:Wheel drive robot used in inspection [AN04]

The tool is made up of two synchronized systems: one is comprised of mechanical subsystems and actuators, and another for vision and security which consists of camera, laser distance sensor, and security micro-switches. An operator drives the system to the area of inspection then inspection is carried out by a control PC. The operator can steer the robot and select the fracture in the tunnel surface where the system will apply the repair material using the control PC and the photos presented [MON15].

Another more automated method is mentioned in [AN04] where a camera is mounted on a small wheel mobile robot as shown in Fig.3. Using a differential-drive wheel design, the robot maintains a consistent distance from the wall while taking a series of images. To stabilize the images, the camera is mounted on an anti-vibration device. The robot inspects the entire tunnel, but the data is analyzed after all of the photos have been collected. The inspection entails using computer vision algorithms to locate cracks.

After reviewing the different state-of-the-art, it is concluded that neither of the aforementioned systems are fully automated (not tele-operated) or work in real-time. In order to turn into a fully automated robotic system with real time performance, image processing and deep learning techniques are adapted in some practical examples that will be studied in the following sections.

3. Methodology

The research was conducted by searching for topics like inspection on construction sites, inspection in tunneling, image processing tunnel inspection and deep learning in tunneling inspection. Eventually, we came up with 24 research papers and after scanning them, we ended up with 16 research papers that mainly focused on the progress of inspection methods, different semi-automated and fully automated systems in inspection, and crack detection by using deep learning and image processing. In the 16 research papers, the main analysis was based on finding different trends in inspection and understanding the different existing methods. Some are manual, some are automated, some are visual, electrical, laser-based, impulse-based, etc.. Afterwards, ways for the integration of image processing and robotics for inspection by involving different cameras and laser scanners and involving deep learning for cross-referencing results against existing images in a huge database are shown.

Image processing is the field of acquiring images from a scene and analyzing the different features within. Therefore, deep learning and image processing methods for inspection have already been the subject of numerous investigations in the areas of road, rail, and concrete damage detection. [TIA19]

As an example, an automatic detector of cracks in concrete was developed by Yokoyama et al. in 2016 that automatically detects cracks from images of concrete structures using CNN (convolutional neural networks) which is a network type for image processing that is specifically designed to process image pixel data [YOK16]. Another research was conducted by Faghih-Roohi et al. in 2016 in which deep convolutional neural networks are used to analyze image data for automated detection of rail surface defects [FAG16].

4. Results

4.1 Automatic Defect Detection of Metro Tunnel Surfaces Using a Vision-based Inspection System

Inadequate illumination, and a short examination window are problems faced through traditional inspection. To solve these issues, an autonomous Metro Tunnel Surface Inspection System (MTSIS) was created for efficient and accurate defect identification as shown in Fig.4, which includes the design of both hardware and

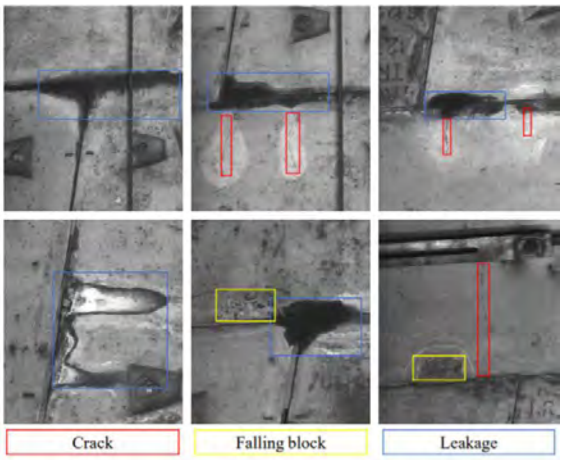


Figure 4: Examples of metro tunnel surface defects, collected and analyzed using MTSIS. [LI21]

software components, Fig.5.

The components of the metro tunnel

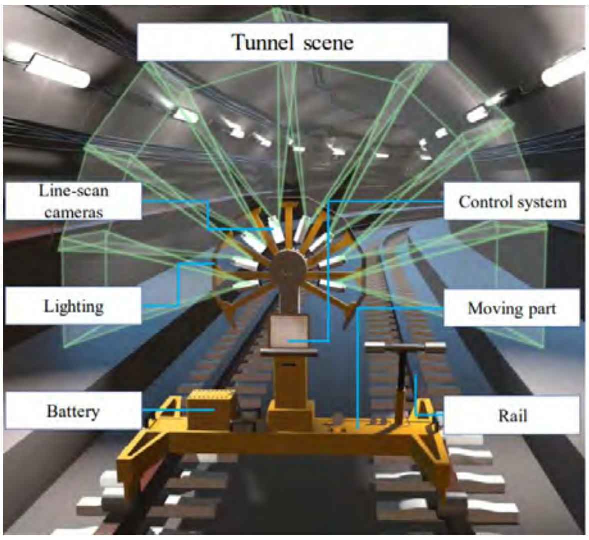


Figure 5: MTSIS Configuration [LI21]

surface inspection system (MTSIS) are divided into hardware and software. The system's pipeline consists of three steps. The first stage is collecting metro tunnel photographs; the second stage is pre-processing collected raw photos; and the last step is defects detection.

To satisfy the urgent need for an efficient and effective technique of inspecting metro tunnel surfaces, an autonomous MTSIS that combines a data gathering module and a fault identification module was designed. A vision-based metro tunnel surface data collecting equipment was created for the data collection module to achieve picture gathering with a high frequency throughout a limited time window. Picture pre-processing and defect detection methods are used in the data processing module to increase image quality and detect faults, respectively.

Based on the picture data, a convolutional neural network for metro tunnel surface defect identification is suggested for use. However, this approach has several defects such as working in non-real-time and has low accuracy regarding defect segmentation. [LI21].

4.2 Deep Convolutional Neural Networks for Efficient Vision Based Tunnel Inspection

In this case, a fully automated tunnel inspection approach based on hierarchically creating complex features from the raw input data from a single monocular camera is discussed. This approach helps in turning the procedure into a real-time one. The information gathered is utilized to train a defect detector, specifically using Convolutional Neural Network to construct high level features because of its global function approximation properties as displayed in Fig.6, a Multi-Layer Perceptron, which is a class of neural networks (deep learning algorithms), was chosen to create high level features and as a detector. Due to the feedforward nature of Convolutional Neural Networks (CNN) and MultiLayer Perceptrons (MLP), where information moves only forward in the network and never goes back, such a technique provides incredibly quick predictions which can be summed in three main parts; adaptability to the defect types, feature extraction and that it does not need a special camera for image acquisition.

The method of encoding visual information is known as visual information modelling for tunnel inspection. Low-level feature extraction methods are used in this procedure. Following the extraction of low-level features, pixels' visual information is defined by their responses to various feature extraction techniques. these features are used to create feature vectors, and then start to deal with scale invariance. These methods are ordered as shown in Fig.7:

A. Edges: taking care of getting them more accurately and saving the magnitude using special operators.

B. Frequency: Clarifying regions of high frequency in the image and suppressing low frequency regions.

C. Image entropy: Measures how much information is encoded in an image. Photos with huge uniform sections have little entropy, whereas images with a lot of texture have a lot of entropy. Therefore, entropy can be used to suppress homogeneous image regions and highlight possible fault areas, which are likely to be strongly textured.

D. Texture: Use a separate texture detector capable of distinguishing distinct texture forms since fault zones are likely to be highly textured. Special filters are used for that.

E. Histogram of Oriented Gradients (HOG): used for object detection.

F. Scale Invariance: since the defects have different sizes

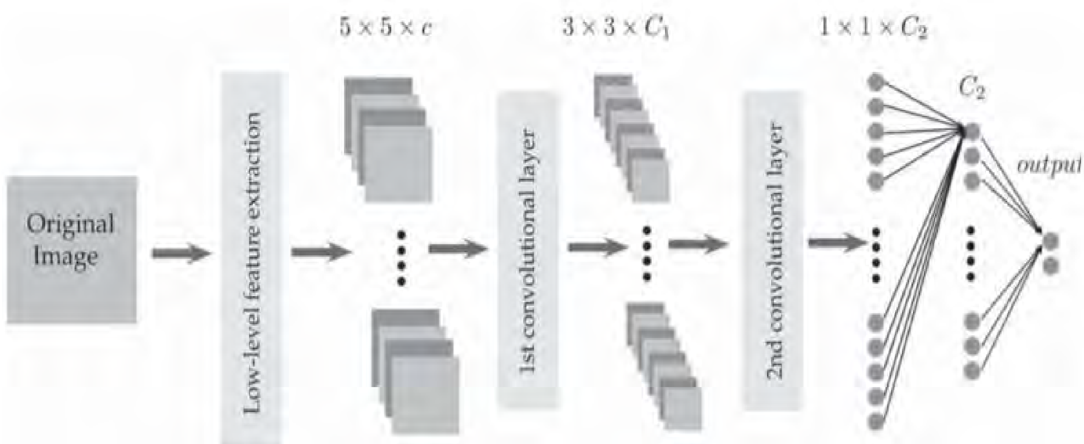


Figure 6: Deep learning model architecture. [MAK15]

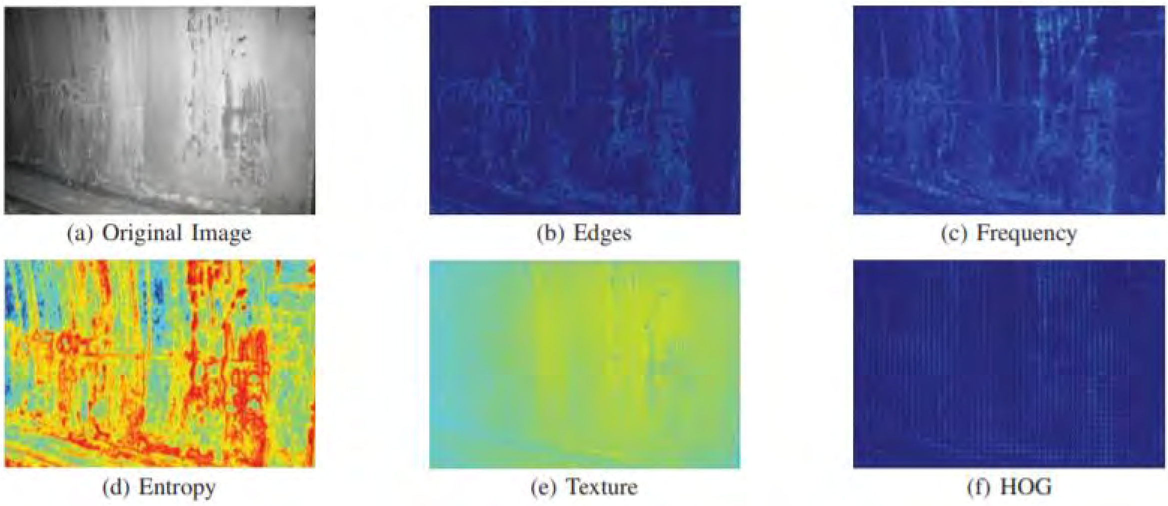


Figure 7: Low-level feature maps are depicted. The color scale depicts the pixel responses to various feature extraction algorithms. The colors blue and red denote low and high magnitude. [MAK15]

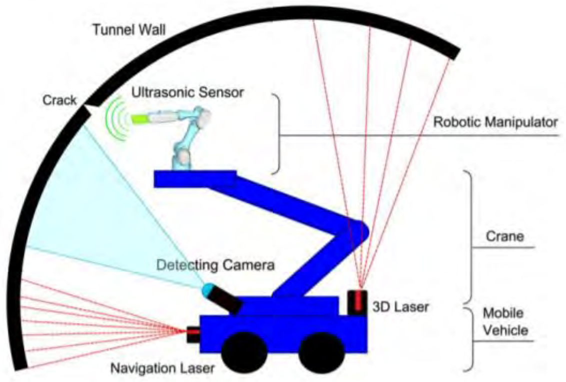


Figure 8: ROBINSPECT schematic representation [MON15]

Figure 9: Defect pixels are colored blue, but non-defect pixels are opaque. [MAK15]

All of the photos were gathered as part of the ROBINSPECT European FP7 project, Fig.8. They originate at Greece's Metsovo highway tunnel. A hand-held DSLR (digital single-lens reflex) camera was used to acquire image data at this section of the tunnel. There was no particular setup for picture acquisition; photos were captured from any angle and distance from the tunnel surface [MAK15].

Various cameras with artificial vision algorithms for crack detection and an ultrasonic system for crack characterization make up the two sensor subsystems. In terms of the inspection operation, the vehicle aligns itself at a consistent distance from the tunnel wall (using navigation laser sensors) and then moves parallel to the tunnel wall at a constant speed while the examination is carried out. The first stage of examination is based on visual identification utilizing photos from a DSLR camera. Depending on the type of the defect detected, the system either saves the position and kind of defect and continues moving, or stops to take more measurements [MON15].

Over 100000 samples were included in the final dataset. With an 8:1:1 split ratio, dividing the dataset into three sets: training, validation, and testing data. That is, 80 percent of samples were chosen at random for the training set, 10% for the validation and 10% for the testing sets [Deep Convolutional Neural Networks for efficient vision based tunnel inspection].

The system can detect over 90% of flaws as shown in Fig.9 while also having the lowest false negative rate (FNR), without reducing classification accuracy for the non-defect class. Finally, because CNN and MLP are feed forward, the suggested approach can evaluate 1000 pixels in 0.18 seconds which shows that the deep learning technique has the potential for accurate and reliable tunnel inspection. However, this approach has several disadvantages such as lack of accurate information about the shape of the crack and its location.

4.3 Image-based concrete crack detection in tunnels using deep fully convolutional networks

Inspired by the drawbacks mentioned at the end of 4.2, this 3rd study was conducted with the aim of increasing the accuracy of crack detection.

Image-based crack segmentation is a reliable way for detecting cracks in tunnels. The advancement of deep learning techniques, particularly the creation of image segmentation based on convolutional neural networks, has opened up new crack detection possibilities. CrackSegNet, an upgraded deep fully

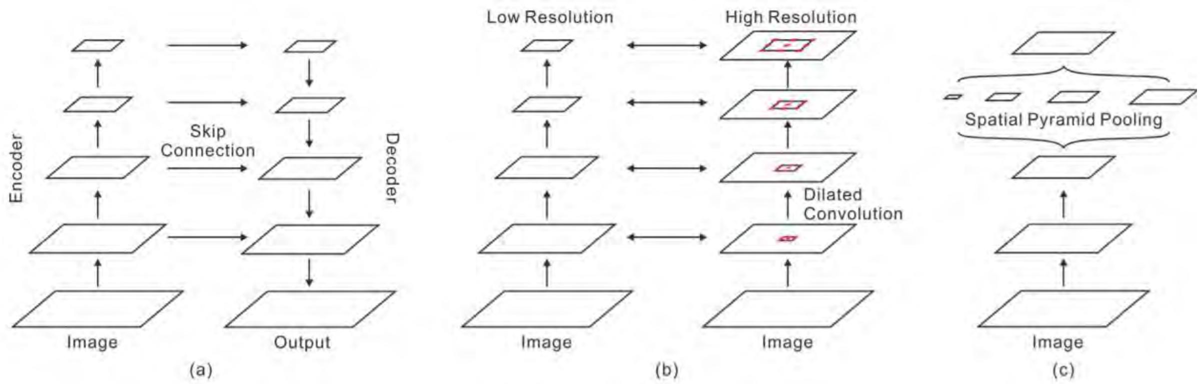


Figure 10: (a) U-net, (b) dilated convolutions, and (c) spatial pyramid pooling [REN20]

convolutional neural network, is proposed in this article for dense pixel-wise crack segmentation.

Fully Convolutional Networks (FCNs) are CNN extensions to allow for intense prediction without the use of a fully connected layer. The segmentation map's structure allows it to generate images of any size and has a faster processing speed than the image block classification approach. Following this successful demonstration, the FCN structure was used by practically all semantic segmentation investigations.

This method comprises of a backbone network, dilated convolution, spatial pyramid pooling, and skip connection modules. These modules can be utilised for multiscale feature extraction, aggregation, and resolution reconstruction, considerably improving the network's overall crack segmentation performance.

To solve the problem of class imbalance, an optimized loss function is used. This method uses modular design approaches to retain the benefits of FCN, U-net, and PSPNet while also improving on crack dataset properties, making it more robust, efficient, and generalizable. With this improved model, photos captured by cameras in tunnels can be used to do long-term crack inspection and monitoring, allowing for more effective segmentation of concrete fractures.

The resulting technique has strong generalisation and minimal data requirements, and it may be improved by adding more powerful architectures or more labelled picture training. The proposed crack segmentation method outperforms the existing method in terms of accuracy and speed. CrackSegNet also outperforms other fully convolutional network topologies like U-net in terms of accuracy. The viability of CNN-based crack detection during tunnel inspection and other SHM-related tasks would lead to a safer, more efficient, and less cost civil infrastructure condition assessment, with the possibility of automation in the future [REN20].

4.4 Automatic crack detection for tunnel inspection using deep learning and heuristic image post-processing

The 4th study was aimed at filtering out noise from the gathered pictures.

The robotic platform inspects a tunnel on the Egnatia Motorway. The described computer vision component is responsible for crack detection using the Robo-Spect, Fig.11, as well as a combinatory deep

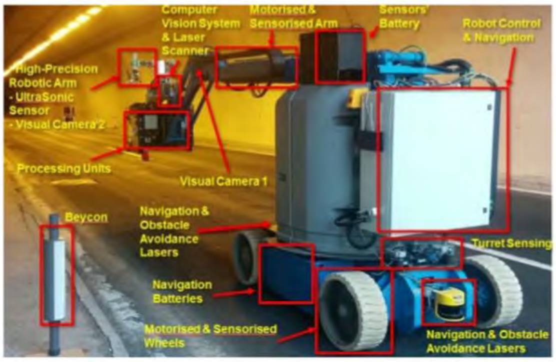


Figure 11: ROBO-SPECT robotic platform's components. The computer vision module is given in this publication. [PRO19]

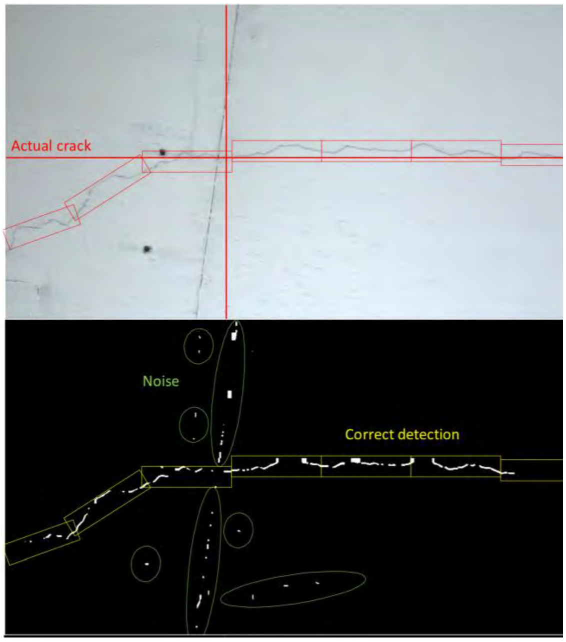


Figure 12: Given an RGB image (top), the CNN classifier annotates it (middle) and the post processing technique (bottom) eliminates the noisy area [PRO19]

learning heuristic post-processing technique that fixes the problem in a faster and more efficient manner. Crack detection given an RGB picture is conducted in two steps as shown in Fig.12: i) CNN-based classifier is used to annotate the picture, and ii) a postprocessing heuristics-based technique is used to remove noise from the annotated picture.

The findings show that the proposed CNN and heuristics-based approach outperforms existing crack detection algorithms in terms of detection performance and computational cost, Test F1 scores by classifier (with 95 percent confidence intervals) [PRO19].

4.5 Tunnel Inspection with Artificial Intelligence

Amberg Technologies and Amberg Engineering, both subsidiaries of the Swiss Amberg Group, have created a cloud-based platform for automated damage detection that employs artificial intelligence. The new Amberg Inspection Cloud processes inspection data with the long-term goal of constructing a digital twin of the examined tunnel. This technique is meant to cut inspection costs while also improving infrastructure sustainability.

Laser scanning is the most prevalent form of data capture. The quality of these findings is unaffected by light circumstances, but the color information is lost. Photogrammetry has the opposite qualities. It requires light to produce good color photos, but the entire process takes a long time. In the tunnel, measurement equipment is transported in a variety of ways, as manually driven trolleys, trains, remote-controlled tiny robots, drones, and vehicles. But in this research paper they used the Amberg MISS (Mobile Infrastructure Scanning System) at Switzerland's Ceneri Base Tunnel for the study.

TunnelMap is a program that includes tools for creating a database of feature drawings. However, the program has limits. That is why a new platform has been developed called Amberg Inspection cloud. Its focus is to apply data analysis and data processing to save time and be more cost effective. Artificial intelligence and machine learning have been evolving since the mid-twentieth century. Recent advances in this

Case\ Attribute	4.1	4.2	4.3	4.4	4.5
False -ve rate	High	Low	Low	Low	High
Evaluation speed / Acquired speed	No real time evaluation (27,780 pixel/sec)	High (5555 pixel/sec)	high	-	-
Precision	-	-	70%	66.7%	-
Accuracy	90%	90%	-	76%	-

Figure 13: Matrix comparing different findings and results of mentioned case

discipline, along with powerful technology, allowed the methodology to transition from an academic to a commercial use.

Once completed, the analysis may be accessed instantly online in the Inspection Cloud. This includes comparing tunnel conditions from different years, visualizing damage along the tunnel, and exporting standard DXF files. Automatic feature drawing will be added in the future. Once Amberg Inspection Cloud has been fully built, the inspection engineer merely needs to examine the automatic drawings and make small modifications if necessary. When compared to traditional hand drawing, this will save a significant amount of time.

Data transmission and business engineering both take time. In this area, the objective is to be completely Building Information Modelling (BIM) compliant. Currently, this growth is hampered by the lack of a BIM standard for tunnels. The Inspection Cloud combines 3D location data, 1D feature data, 1D time data, and effective data analysis. The chain is missing a BIM format that enables for easy transfer to other systems.

First test projects have revealed that compared to a typical inspection, time savings of up to 60% are attainable. Savings of up to 30% are feasible with the current level of the program [TIA19].Decision matrix

5. Discussion

The 4.1 study was conducted in a non-real time manner where tunnel photos are firstly collected then pre-processing takes place with defect detection happening after. Although this method overcomes illumination problems and short examination problems, it has bad defect grade evaluation and low accuracy defect segmentation. Therefore, CNNs are suggested for such experiments which is considered in previously mentioned cases for better accuracy and speed.

In the 4.2 study, deep learning modules such as CNN and MLP have the potential for accurate and reliable tunnel inspection. CNN-based crack image classification and detection methods infer image-based labels such as crack or lack of a crack but have drawbacks such as lack of precise information about the crack shape and location. Therefore, developing a dense pixel-level crack segmentation method needs to be researched to get information more precisely and more high-level features of cracks in the image like path, location, length, width, and density. This was conducted in case 4.3.

In 4.3, FCNs were used for creation of image segmentation that could generate images in any size and have faster processing speed allowing for long-term crack inspection with better accuracy.

In 4.4, a classical computer vision algorithm was used for crack detection along with deep learning heuristic post-processing technique to remove noise. This experiment showed lower accuracy than 4.2 and 4.3.

Finally, the 4.5 case has a cloud-based platform developed for automated damage detection that uses AI to save time and cost as compared with traditional inspection methods. Measurement equipment are transported on the system through the tunnel for inspection. However, lack of BIM standards for tunnels makes the cloud not BIM compliant for easy transfer to other systems.

Accordingly, and as per the results discussed in section 4, deep learning modules as CNNs and MLP along with image processing techniques show better accuracy, speed and less false negative detections working in real time, therefore it is recommended to further research in such direction that has a greater potential.

Thinking of the future, in terms of complicated and unstructured surroundings, the vast majority of big inspection systems cannot or have difficulty functioning efficiently due to the usage of wheeled platforms. One possible approach would be to utilize legged robots with insect-like legs, such as John Deere's proof-of-concept robotic harvest system or Boston Dynamics' quadruped robot, that can navigate easily through unexpected obstacles. Furthermore, and with extended

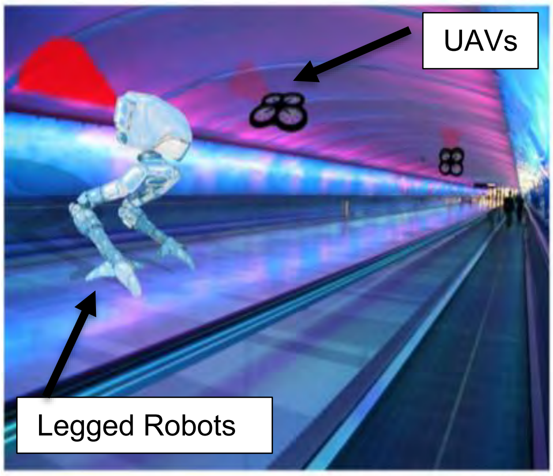


Figure 14: Conceptual image of a future tunnel inspection process by using legged robots and UAVs [MON15]

research in the fields of robot walking gait generation and overcoming stability concerns, humanoids can also be used for inspection.

Unmanned Aerial Vehicle (UAV) innovations are another technology suitable to future tunnel inspection processes that circumvent mobility limits. One advantage is that these robots may be made at a low cost and operated concurrently because they do not disrupt traffic. A swarm of robots with decreased size might be employed to undertake the inspection procedure more quickly and thoroughly while simultaneously collecting significant amounts of data.

6. Conclusion

Deep learning is not a new concept, but the ability to leverage powerful processing engines has radically revolutionized how these technologies are used. The aim of this paper is to question the reliability of deep learning architectures for the tunnel defect inspection. Going through the state-of-the-art studies it showed that automatizing the tunnel inspection is promising and showing good results to go more in deep in technology in this area. After that, more studies using deep learning and image processing techniques were tackled showing 30-90% more efficient result saving time, costs and providing safer environment for the labor working in the tunnel construction site. The deep learning approach outperformed all other techniques, showcasing that such a method has potential for accurate tunnel inspection

Finally, further research into crack characteristics is required, and the algorithm must progress toward total automation.

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