Challenges, Tasks, and Opportunities in Teleoperation of Excavator towards Human-in-the-loop Construction Automation

Jin Sol Lee[1], Youngjib Ham, Ph.D.[2], Hangue Park, Ph.D.[3] and Jeonghee Kim, Ph.D.[4]

[1] Ph.D. Student, Department of Construction Science, Texas A&M University, College Station, TX. Email: jinsollee@tamu.edu

[2]Associate Professor, Department of Construction Science, Texas A&M University, College Station, TX. Email: yham@tamu.edu

[3]Assistant Professor, Department of Electrical & Computer Engineering, Texas A&M University, College Station, TX. Email: hangue.park@tamu.edu

[4]Assistant Professor, Department of Engineering Technology & Industrial Distribution and Electrical & Computer Engineering, Texas A&M University, College Station, TX. Email: jeonghee.kim@tamu.edu

Abstract

Teleoperation stands for operating a system, machine, or robot from a distance. Teleoperation has been widely adopted as a promising way to enhance worker safety in extreme and hazardous construction workplaces. Over the years, studies have proposed various approaches to teleoperate construction equipment for excavation, which could bring significant advantages such as declining injury rate and dealing with dangerous on-site tasks. This paper identifies challenges, tasks, and opportunities in teleoperation of excavator through quantitative and qualitative analyses. Prior studies from the past two decades were rigorously reviewed and analyzed through the bibliometric analysis and a systematic review for in-depth discussion. The outcomes provide the future direction of teleoperation in construction workplaces in the following aspects: human operator, interface, operation, and environment. The outcomes indicate that human-centered research that understands and develops systems and technologies from the human point of view is necessary since seamless human-robot interaction is required for teleoperation.

Keywords: excavation, teleoperation, human-in-the-loop

1. Introduction

An excavator is one of the most employed and essential equipment for earthmoving in jobsites. The use of this equipment is not just limited to digging soils to make holes or trenches in earthwork but also used for heavy lifting, soil transformation, and transportation [1,2]. However, the working environment of excavation is known as one of the most hazardous workplaces which has a high probability of fatal injuries of workers and property damages in the event of an accident. Particularly, in the case of underground utility strike during excavation, the repairing cost and its associated societal cost significantly increases as it negatively affects critical infrastructure systems such as gas, electricity, and water supply that is vital to people’s daily lives. Accordingly, the importance of providing a safe earthwork environment for human operator while reducing accidents is essential.

The use of teleoperated excavators has become a promising solution in extreme and hazardous site conditions like disaster areas, underwater, and space [3], and have been studied in various contexts. Teleoperation of excavators indicates manipulating excavators at a distance by a human operator. Since human operators can stay away from dangerous workplaces, teleoperated excavators are expected to be effective for lowering safety accidents. Nonetheless, a study on current status of excavator's usage has observed that the usability and productivity of the excavator teleoperation is often lower than that of traditional operations [4]. The reasons are the current teleoperation sometimes has delay issues of control, and the difficulty for obtaining and understanding the surrounding information such as soil, machines, nearby human workers, and other obstacles, compared to conventional controls [3]. Since teleoperation is in the middle of transition between manual operation and full automation, thanks to the advancement of sensing and control technologies, it is expected that current productivity and safety issues of teleoperated excavators would be resolved toward fully autonomous system of excavator [1]. Despite the advancement of recent technologies (i.e., artificial intelligence, sensing), it could be still challenging to solely rely on full automation of each and every process in jobsites, particularly in case for dynamic and complex excavation tasks having uncertainties in workplaces [5–7]. Rather than relying on a fully autonomous robotic system in which a robot alone senses and performs all task planning and execution [8], teleoperation in which humans can cooperate with the robot system as a commander and take advantages of human-robot interactions, is expected to have wide range of capabilities and potentials as a robotic application for earthmoving tasks [9,10]. As such, robust intervention of human operators for decision-making under uncertainties is still necessary for efficient manipulation of construction robots [10,11]. In this regard, there is a need to carefully examine the relevant studies of excavator teleoperation, one of the areas of human-in-the-loop robotics and automation that will continue to be promising for future construction.

Research on excavator teleoperation has been conducted in multidisciplinary fields such as construction, electrical, and mechanical engineering. Previous studies have conducted literature reviews regarding robotic automation including teleoperation of heavy construction equipment in the field [12–14]. Despite their contribution on highlighting challenges on several types of heavy construction equipment, they are limited to discussing topics and clusters of prior studies since qualitative review was primarily conducted and various equipment were reviewed comprehensively. This paper focuses on an excavator, the most used among construction equipment, in details and examine human operators and teleoperation among different automation levels in a holistic and a systematic view. In this study, prior works are analyzed both quantitatively and qualitatively using the mixed review method to discuss research topics and scopes that need to be explored from a systemic perspective of excavator teleoperation. This mixed method allows to elaborate on research topic clusters based on quantitative data analysis, which complements drawbacks of quantitative reviews that may not enlighten the specific topics with small numbers of the associated papers. Therefore, the objective is to comprehensively review and provide future research directions pertaining to excavator teleoperation by (1) analyzing current research based on keywords through quantitative analysis; and (2) discussing recent research challenges, knowledge gaps, and shedding light on opportunities via in-depth analysis. The scope of the study is peer-reviewed papers related to teleoperation of excavator published in the last two decades.

This paper is organized as follows. The following section examines the terminology used for excavator teleoperation. The methodology section describes the methods and criteria for data collection in this study. The bibliometric analysis and results section discusses the current application of teleoperation for excavators via the text mining for quantitative analysis. In the in-depth discussion with a systematic review, we discuss fundamental components of teleoperations based on in-depth discussion in the following aspects: human operator, interface, operation, and environment. Based on teleoperation applications and components, this section also identifies current challenges, knowledge gaps, and future research directions of excavator teleoperation towards human-in-the-loop construction automation.

2. Taxonomy for excavator teleoperation

Working environments where robots are well applied such as manufacturing are relatively well-controlled, and the tasks of robots are often repetitive. Automation therefore may require little human monitoring or intervention by programming the robot to perform repetitive tasks multiple times with little change between iterations. On the other hand, construction automation is typically obscured by open and changing environments such as dynamic flows of construction works and hard-to-define human-robot cooperation requirements [15]. In specific, work types, site conditions such as weather and soil conditions, and construction equipment characteristics, which vary from site to site, should be considered for earthwork automation. The types and forms of earthwork are inconsistent, not likely repetitive, and the work plans are sometimes modified depending on site work conditions. Topography, geologic features, and further the degree to which underground utilities are buried are different for each jobsite. In particular, in the case of buried utilities, the density or complexity of buried utilities in urban and rural areas are typically different. Of course, before excavation, people try to figure out the topography and geologic features through in-situ sampling and find out the approximate location of underground utilities through the 811 call system, but there are unexpected variables (e.g., mis-location of buried utility, unforeseen rocks, underground water) in the underground that are not visible. In addition, earthworks are not performed by an excavator alone, but mainly in cooperation with a dump truck or other construction equipment, and there are also construction workers who give guides or signals in the vicinity of excavator (e.g., spotter). When excavation needs to be carried out continuously, not just for a single day, the work environment could be volatile because the terrain changes, and people and equipment who perform the task may not be consistent. Thus, automation in earthwork environment often requires human to supervise, collaborate, monitor, and reprogram the robotic system due to its dynamic work environment with uncertainty, which is quite different from other industries where automation of robots have been well adopted. Thus, it is crucial to consider humans as an essential part of the human-in-the-loop system where humans and robots interact consistently.

Teleoperation has been studied as a promising solution in earthwork automation, the intermediate stage between manual operation and full automation, which requires a human-in-the-loop process for operating construction equipment. The definition of teleoperation is operating robots or machines from a distance away by human operators [12,13,15,16]. However, with this definition, there are questions left to look further into teleoperation. One question remains as to how far the human operator can operate remotely. It is a question of whether the word "teleoperation" can be used at a close distance like just in front of an excavator or go with a very long distance. Another question remains as to how much automation or human intervention needs to be done for operating robots and machines at distances. Existing studies show the definitions and types of teleoperations in various ways, and they are commonly defined as one of the steps in the process from manual to full autonomy. Sulaiman et al. [16] stated that a teleoperated excavator was used from some distance away as an intermediate step between a conventional excavator operated directly by a human operator and an unmanned excavator without direct human control. Ha et al. [13] defined teleoperation as one of the five levels of robotic and automation of construction equipment: functional assist, teleoperation, semi-autonomy, full-autonomy, and cooperation. Ha et al. [13] also categorized teleoperation into two groups: remote control or open loop teleoperation. Dadhich et al. [12] considered teleoperation as intermediate processes from manual to full automation: manual, in-sight teleoperation, tele-remote operation, assisted tele-remote operation, and fully autonomous. Building on these, in this paper, we regard teleoperation as an intermediate level between manual operation and full automation. Since full automation cannot be achieved for all at once, and therefore intermediate steps where teleoperation or remote operation is needed are necessary to understand robotic automation in construction and human control toward the ultimate stage of automation maturity [12].

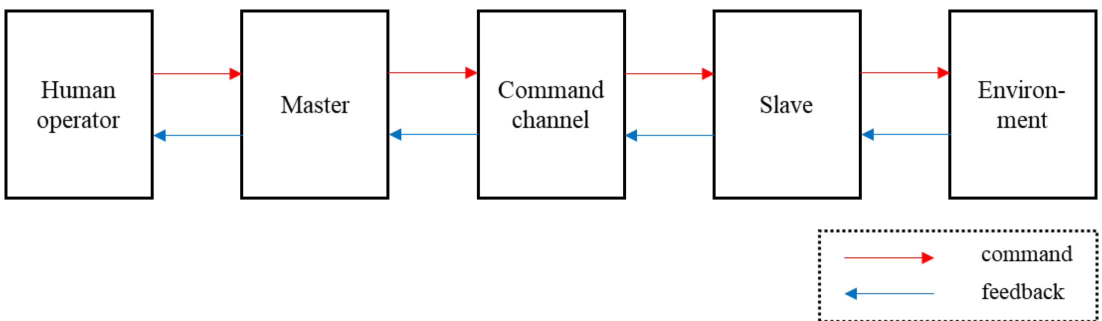


Figure 1. Feedback system of teleoperation.

Teleoperation system consists of two parts: the master robot part which is a control module (i.e., interface) to manipulate a slave robot by human operator, the slave robot part which is an execution robot in a remote location. The history of modern teleoperation control began in the late 1940s, when the first master-slave manipulators were developed at the Argonne National Laboratory for handling chemical and nuclear materials. Since then, the evolution of remote operations has been rapid, which has created a sophisticated telepresence system where operators can feel that they are present in sites. As such, the teleoperation system was developed with feedback system to make the operator feel the telepresence that makes them feel as if they are in the field at distance (Figure 1). This system can be largely divided into human operator, master, command channel, slave, and environment [17]. The master is an interface directly controlled by the human operator, and the slave is a robot that moves based on the input command. Since there is a distance between the master and the slave, the communication equipment part, called the communication channel, should deal with the communication and connection of these two robots. Since the operator should control the slave based on the information of the field with a distance, the operator should understand the environment in which the slave is located. In the case of indirect teleoperation, human operators have no choice but to grasp through the master (i.e., interface) to understand the information of the environment and see whether the command and the movement of the slave are performed well. Also, since commands should be transmitted through the master, so the interaction between operator and master is the key to teleoperation. This study is to discuss the state-of-the-art teleoperation systems for excavators. The scope of teleoperation in this review includes both direct teleoperation (i.e., using human eyes to directly observe and perceive the environment) and indirect teleoperation (i.e., the environment cannot be fully observed and perceived with bare eyes, but sensors are needed to understand the environment in a distance). This paper reviews master-slave robot parts as well as key components related to teleoperation as a system toward human-in-the-loop construction automation.

3. Methodology

The purpose of this study is to have an in-depth and comprehensive understanding of challenges, tasks, and opportunities of teleoperation for excavation. The methodology used in this study is based on the mixed review method consisting of quantitative and qualitative approaches (i.e., bibliographic analysis and systematic review). Figure 2 shows an overview of the research framework. Research papers were first retrieved from academic database. Bibliometric analysis was then conducted for generating keyword co-occurrence maps and clusters, based on which key research areas were identified. In-depth discussion in systematic review was conducted based on bibliometric analysis results, to provide comprehensive understanding of research areas with its evolution, and to discuss challenges and opportunities for future research on teleoperation of excavator. The rationale of incorporating both bibliographic analysis and systematic review is to converge and supplement findings from both quantitative and qualitative perspectives, which can deliver convincing insights in case of any inconsistency or contradiction in either analysis [18]. In addition, the conclusions from the two different methods can supplement each other and minimize the subjective interpretation of research trends and opportunities. We first determine which areas should be included and excluded from the study. This study focuses on teleoperation application in construction, especially excavation, and thus the following questions were formulated: What are the current trends of teleoperation in excavation research? What are the current challenges that hinder the adoption of teleoperation in excavation? What are the future directions of teleoperation in excavation research?

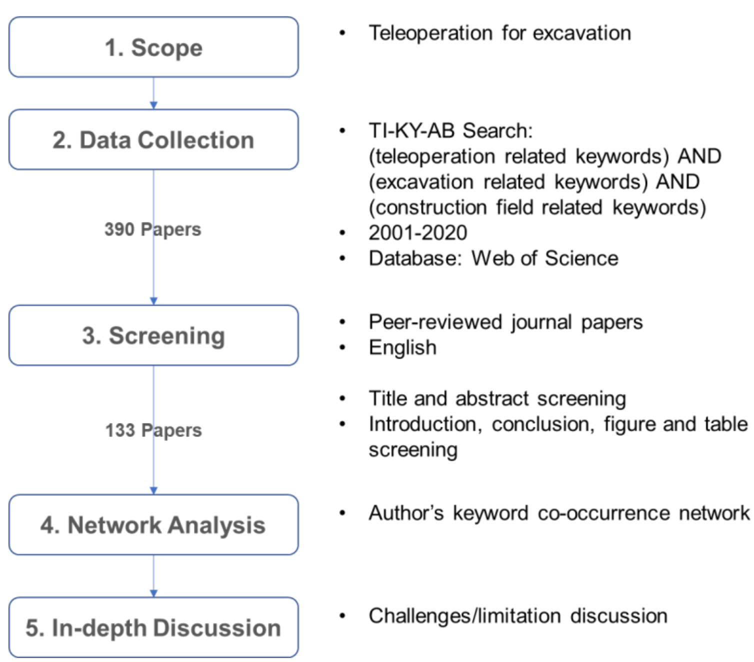


Figure 2. Research Framework.

3.1 Identification of Sources

In this study, Web of Science was selected as the database engine from which to search for and extract studies. The reason for this selection is it comprehensively covers wide range of journal publications and the knowledge domain in comparison with other databases such as Google Scholar [19,20]. Publications from international peer-reviewed journals were considered in this study for quality assurance. Start and end date was specified to identify the latest studies. The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) was leveraged for conducting systematic reviews of research [21].

3.2 Data Collection

The careful acquisition of data related to literature has significant implications in this study, especially in quantitative interpretation of the knowledge domain through the bibliometric analysis. For this reason, we employed three data collection criteria in article selections for our study: 1) contemporary: all articles selected were published between 2001 and 2020, 2) relevance: keywords and abstracts of each article was reviewed manually by authors to ensure their relevance to the targeted research area; 3) quality assurance: only peer-reviewed articles from international journals were included for quantitative review. Compared to non-peer reviewed articles, journal papers typically undergo several rounds of peer reviews, and they typically provide more rigorous information with higher quality. This is a generally accepted method to ensure the high quality and consistency of review [18,22,23]. Existing literature related to teleoperation applications for excavators was first retrieved by searching “Title/Abstract/Keywords”, with the string “TITLE-ABS-KEY ((tele-oper* OR teleoper* OR remote* OR autono* OR automa* OR intelligent OR robot* OR unman*) AND (excavator OR excavation OR earthmoving OR earthwork OR backhoe) AND (construction OR built environment OR architecture OR infrastructure OR building)).” The asterisk character (*) is used to capture any term with spelling variations, such as “teleoperation” and “teleoperated.”

Table 1. Search strategy by combination of search strings.

Theme	Search strings	Boolean operator
Teleoperation related keywords	(tele-oper* OR teleoper* OR remote* OR autono* OR automa* OR intelligent OR robot* OR unman*)	AND
Excavation related keywords	(excavator OR excavation OR earthmoving OR earthwork OR backhoe)	AND
Construction Field related keywords	(construction OR built environment OR architecture OR infrastructure OR building)	

3.3 Screening

This study builds on peer-reviewed journal papers in English published internationally, 390 papers were first extracted with TITLE-ABS-KEY search in Web of Science. Then, we reviewed titles, keywords, and abstracts of all 390 articles and screened out 240 and set aside 150 for the next step. Detailed screen process was conducted within 150 papers by reviewing introduction, conclusion, figures, and tables. This process includes assessing the theoretical background of research questions, methodologies, findings with figures and tables, and contributions. Out of 150 articles, 133 articles were finally remained for a bibliometric and a systematic review in the following section. Excluded papers from the final stage were related to excavation, but these were not included in the study because they mainly examined the associated energy efficiency or construction wastes, which are out of our review scope.

4. Bibliometric analysis and results

The bibliometric analysis is for quantitative review that aims to study, document, and synthesize targeted research trends. This quantitative review enables to draw a picture of the selected research domain through combining information from different categories with a large scale of scientific literature such as citation, impacts, the structure of knowledge, and research evolution [18,24]. In addition, the bibliometric analysis allows linking literature concepts of related articles through the text mining, which enables to explore bibliographic coupling, keyword co-occurrence, and citation analyses. In this paper, bibliometric analyses were conducted with carefully chosen 133 papers. The author keyword co-occurrence analysis was taken to identify essential keywords in research related to teleoperation of excavator to map, cluster, and see the recent trends of the knowledge domain.

4.1 Identified studies

The majority of articles, accounting for around 72%, were published in construction & civil engineering fields such as Automation in Construction, Journal of Computing in Civil Engineering, Journal of Construction Engineering and Management, Computer Aided Civil and Infrastructure Engineering, Construction and Building Materials, and Journal of Civil Engineering and Management (Figure 2). Since teleoperation of excavator is related to robotics and automation as well, some articles were published in journals in electrical or mechanical engineering fields such as Sensors, International Journal of Precision Engineering and Manufacturing, and IEEE Access. Among these journals, Automation in Construction is the most prevalent journal in this research area. The number of articles published in Automation in Construction is 62, which is more than 40% of the total articles, and the number of citations is 1242. A total of 133 peer-reviewed international articles published over past two decades represents a rapidly growing knowledge base on teleoperation of excavator. The articles were distributed by year between 2001 and 2020 in Figure 3. As can be seen, the distribution can be divided into two phases. From year 2001 to 2010, the average number of annual publications was 3, but from year 2011 to 2020, the average of annual publication was 10.3, which is around three times greater than that of 2000s. This is similar to the construction research trends analyzed by Pan and Zhang [25]. This phenomenon seems to be related to the rapid growth of development of artificial intelligence, sensors, telecommunication technology, and computer capacity in the 2010s which had been emerging for various relevant research areas.

Table 2. Identified articles in 2001-2020.

Academic journals	Number of articles	Number of citations
AUTOMATION IN CONSTRUCTION	62	1242
JOURNAL OF COMPUTING IN CIVIL ENGINEERING	14	280
JOURNAL OF CONSTRUCTION ENGINEERING AND MANAGEMENT	13	186
ADVANCED ENGINEERING INFORMATICS	7	193
SENSORS	7	19
COMPUTER AIDED CIVIL AND INFRASTRUCTURE ENGINEERING	5	60
IEEE ACCESS	6	6
CONSTRUCTION AND BUILDING MATERIALS	4	103
IEEE TRANSACTIONS ON AUTOMATION SCIENCE AND ENGINEERING	4	40
IEEE ASME TRANSACTIONS ON MECHATRONICS	3	32
OTHERS	8	
Total	133	2161

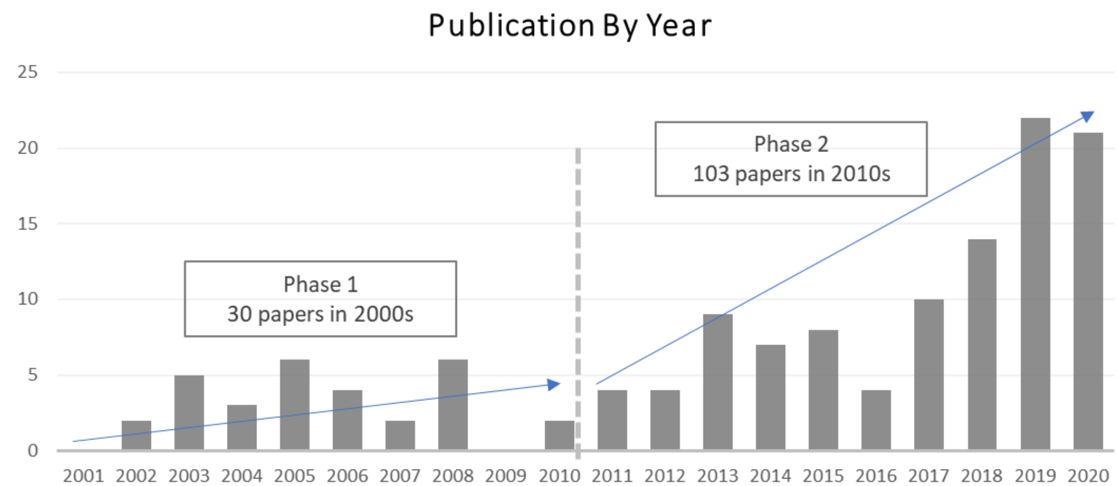
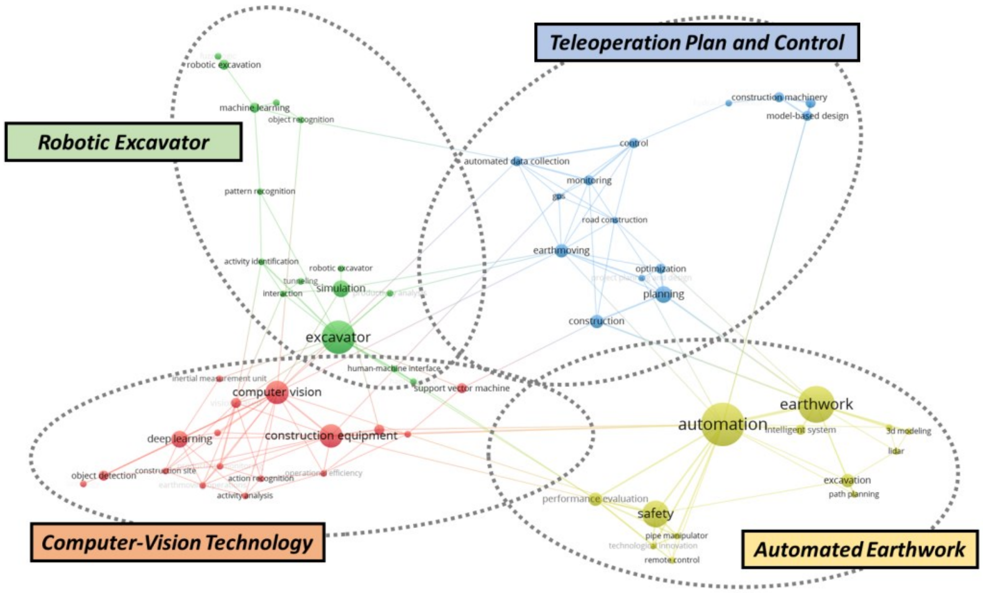
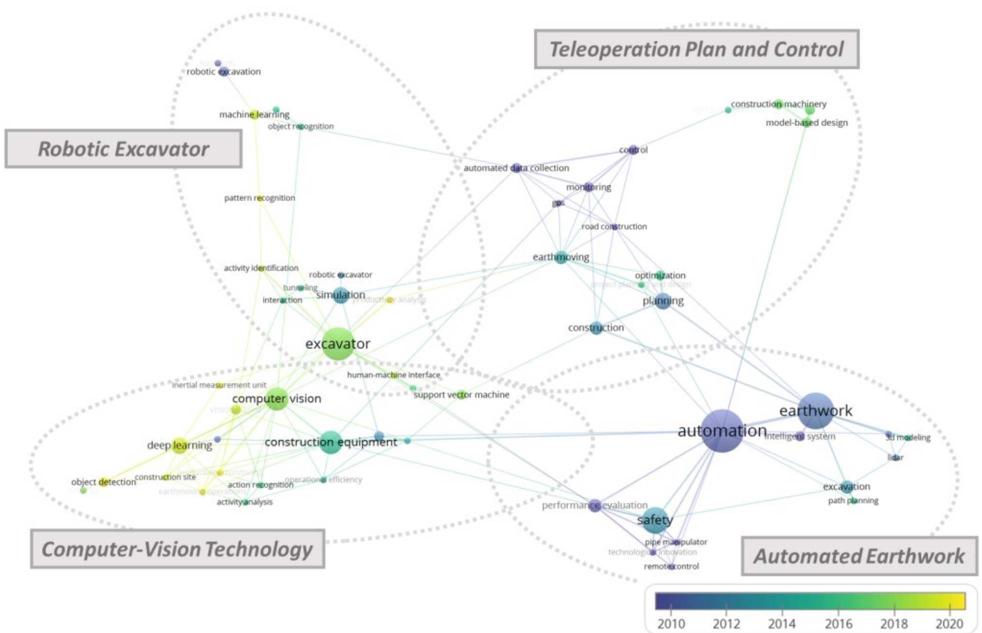


Figure 3. Number of published articles related to excavator teleoperation in 2001-2020.



A) Research cluster with keywords.



B) The trend topics with keywords used from 2010 to 2020.

Figure 4. Author keyword co-occurrence network analysis (min occurrence=2). (a) research clusters with keywords. (b) research topic trends with keywords.

4.2 Keyword analysis

Various topics and themes have been covered in research related to teleoperation of excavators in recent two decades. To overlook those topics and themes, keywords are known as significant elements to understand the trends and descriptive contents of the research articles [26]. Data from the Web of Science and text mining was employed to analyze keyword co-occurrence and visualize the networks between keywords. A keyword co-occurrence analysis was performed through VOSviewer to identify the basic structure and cluster of excavator teleoperation-related research. The degree of co-occurrence is determined by the proximity and similarity of keywords [24,27]. A total of 558 keywords chosen by each journal paper's authors were identified from the literature database. Among them, 70 keywords with a minimum of 2 keyword co-occurrences were used for the co-occurrence network analysis. We could find 4 significant research clusters associated with these identified keywords (Figure 4a), and research topic trends with the keywords (Figure 4b). Building upon from the keyword co-occurrence map (Figure 4a), four research clusters are as follows:

Cluster #1: Robotic Excavator

In order to control excavators by teleoperation, operators need to understand the movement state of excavators from a distance away. Keywords such as pattern recognition, object recognition, and activity identification were observed in the Robotic Excavator cluster based on our quantitative analysis with the VOSviewer. Although these keywords are related with the computer vision technology, it seems that these were categorized in the Robotic Excavator cluster since the articles with those keywords primarily focused on analyzing the activities of robotic excavators and their movement states, rather than vision-based monitoring of work environments (e.g., surrounding conditions while operating an excavator). The keywords of interaction, human-machine interface, and haptic device represent the research on interfaces to recognize the situation of and around teleoperated excavators and to give operators' commands to excavators. This indicates that not only robotic applications for excavators have been studied in the past with conventional keywords such as robotic excavation and simulation, but also extensive research was conducted with technologies such as machine learning and computer vision to understand the activity of the excavator in this research area.

Cluster #2: Computer Vision Technology

Significant advancement of digital technologies has affected research in the construction field. As shown in Figure 4(b), 'Computer Vision' (Occurrence = 7) is a research field that has been receiving a lot of attention recently compared to other clusters. Keywords of vision-based and deep learning along with computer vision are clustered. Over the years, computer vision has gained its attention in various research fields. The architecture, engineering, and construction (AEC) field is one of the most focused areas where vision-based technology has been used to accelerate decision-making processes during construction phase. Construction sites are typically dynamic and complex, so efficient monitoring is often difficult and tedious [28]. With the advancement of machine vision, extensive research related to monitoring excavators via visual sensing and deep learning-based approaches has been conducted. For teleoperation, continuous monitoring of surrounding conditions is required. In the past, people have directly monitored jobsites, but the advancement of technology has shown the possibility that computer vision can replace humans. Computer vision-based monitoring was basically used to monitor the location of people, equipment, and materials at construction sites and to detect the working status or dangerous movement of humans or equipment. In addition, to visually understand the situation of jobsites remotely for decision-making, it is necessary to transmit and analyze a large amount of data, and thus image-based scene understanding and 3D reconstruction also belong to this field. Since understanding environment where distanced excavator is working is crucial for remote operation, sensing technologies based on computer vision seem to be in the spotlight in this research area.

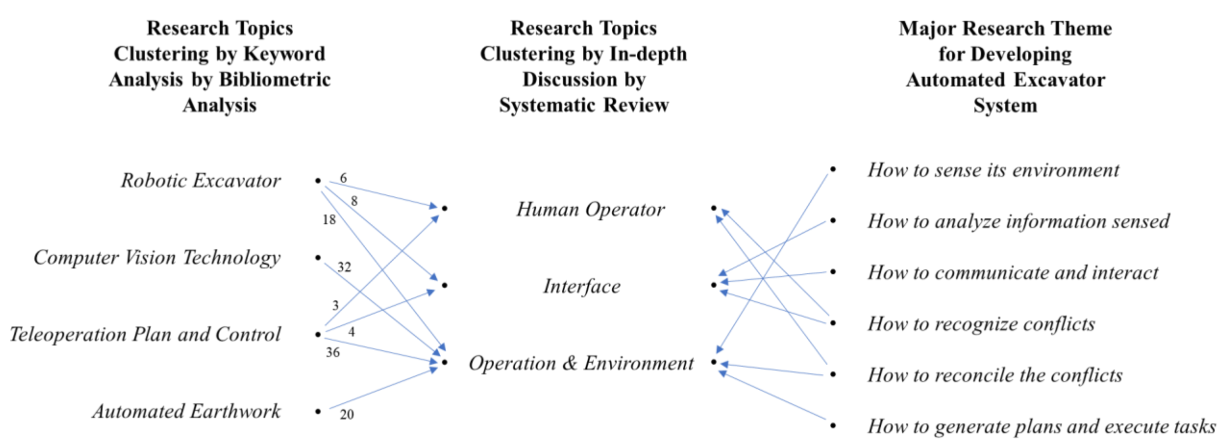
Cluster #3: Teleoperation Plan and Control

Keywords such as monitoring, planning, project planning and design, and model-based design, could be categorized as plan (Occurrence = 5) and control (Occurrence = 3). A successful mission requires a well-organized plan and control to execute tasks based on the plan. This applies to teleoperation as well. Successful remote operation of excavation requires planning and controlling of construction equipment taking account of the as-is situations of workplaces [29,30]. For task planning toward teleoperation, information of the work environment and nearby excavators are prerequisites. Information is often gathered by sensors attached to construction equipment or workplaces. These sensors were also used to help monitor the process of excavation since it is hard to manually monitor the teleoperation. Research on this area encompasses the field of control guidance of excavators that allows remote control for operators who cannot directly recognize the on-site situation and the field of semi-automation where tasks can be partially automated with minimal supervision or command by humans.

Cluster #4: Automated Earthwork

Automation (Occurrence = 13) and earthwork (Occurrence = 11) are also main two keywords in this cluster. As can be seen in Figure 4(b), studies have been conducted to enhance situational awareness of construction sites and surroundings to remotely control robotic excavators since around 2010. Other keywords like ‘3D modeling’, ‘LiDAR’, ‘intelligent system’, and ‘path planning’ are also chosen in this cluster. The studies in this cluster contribute to improving situational awareness of workplaces for excavation in the context of automation or intelligent excavator system. Regarding the keyword ‘safety’ (Occurrence = 8), it was observed that construction safety has been considered in this cluster. During excavation, heavy construction equipment gathers and work simultaneously with human workers, which may cause numerous fatal accidents. In addition, tragic accidents occur during excavation and underground utility installation/maintenance due to the instabilities of trench walls or underground pipe strikes. With keywords in this cluster, we could observe that there have been research efforts toward automated earthwork recently with the advancement of technology while considering construction safety.

5. In-depth discussion with systematic review



* The number on each arrow represents the number of papers associated with the arrow.

Figure 5. Research topic clustering.

5.1 Systematic Review

Although the identified research cluster helps to form the knowledge domain structure of teleoperation for excavators, the quantitative analysis may not be enough to reveal research challenges and inform research requirements. In this regard, a systematic review with in-depth discussion was conducted to supplement the inherent limitation of bibliometric review with quantitative analysis. For example, a small number of research work may be important in a particular field and can have a significant impact on the field of study. However, such a research area could be neglected in quantitative analysis because the number is too small to quantitatively represent the field of study. For this reason, the quantitative analysis may not be able to identify or enlighten the specific research topics with small numbers of published journal papers which have a tremendous effect on the research area. In this context, we conducted the qualitative review to complement the comprehensive overview of the selected research area.

In order to construct the structure and classification for qualitative review of studies regarding teleoperation of excavators in Section 5, we built upon the results of the keyword analysis in Section 4, all papers reviewed for the bibliometric analysis, and relevant further studies (e.g., conference proceedings). In addition, major research questions for developing automated excavator systems were considered to build the research topics for in-depth discussion as well [31]. The classification structure of the research topics was determined through the consensus-based discussion on the qualitative analysis of the research topics. The authors and other faculty members from various disciplines (e.g., Construction Science, Industrial & Systems Engineering, Psychological & Brain Sciences, Electrical & Computer Engineering) had weekly meetings from January to June of 2021. During some weekly meetings, we invited and interviewed a total 15 of construction experts (e.g., excavator operators, superintendents, safety managers, project managers, etc.) with more than 10 years of average construction industry experience to understand the associated current status and challenges in field practices. After meetings to discuss and improve the classification structure of the research topics, all authors agreed and made a consensus on the research topics for qualitative analysis as shown in Figure 5. In Figure 5, the number on each arrow represents the number of papers associated with the arrow. These steps allow to offset the heterogeneity of the findings obtained from both methods, and as far as possible, eliminate potential bias in qualitative reviews. This section focuses on the research needs in teleoperation of excavator to inform future research. Given that excavator teleoperation research have been conducted to develop components or sub-systems of the platform of teleoperation such as communication, kinetic and dynamic movement of excavator, obstacle avoidance, planning, control and navigation [13,32], research topics are clustered into the following for in-depth analysis: human operator, interface, and operation & environment as shown in Figure 6.

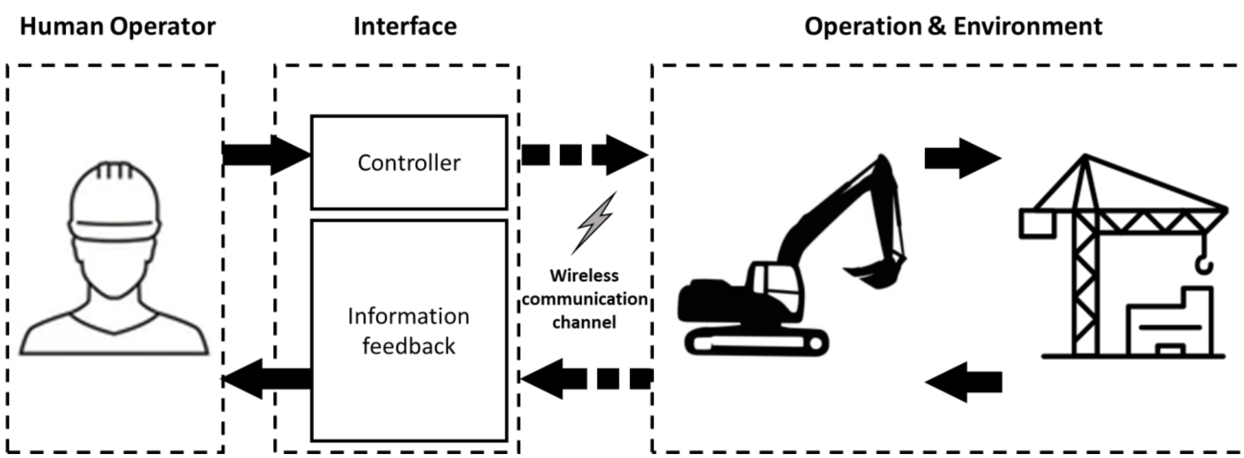


Figure 6. Teleoperation system of excavator.

5.2 Human Operator

5.2.1 Proficiency

As a major part of this system, humans have a significant influence on achieving the system goal. Skilled operators are required for difficult teleoperation tasks to enhance the productivity and the quality of the work. Human operators would plan, make decisions, and take actions through information processing taking account of work contexts and surrounding conditions. The intellectual demands of human operators arise from observation, attention, and memory depending on their capabilities [33]. Though excavator operators have been through similar training, their proficiencies may vary between individuals. These capabilities vary from operator to operator due to a variety of individual factors ranging from age or gender to training and expertise [33]. These differences involve knowledge [34], workspace spatial awareness [34], real-time situation and operation monitoring ability [35], accident detection [36], proximity sensing [37], attention level [38], information processing ability [38,39], or training & experience [40–43].

Compared to other industrial settings where licenses and certifications are used as criteria for assuring work performance and mitigating potential risks caused by unqualified operators (e.g., airplane pilots must be qualified for controlling an airplane), operators in the construction field often do not need a certificate or a license to drive small size of excavators in certain cases. Therefore, in the study relevant to excavator operators, it should also be considered that machines may be controlled by an operator who has little experience. Due to the aging issue and challenging work environments, the supply of skilled operators with high work performance during excavation is typically insufficient in the construction industry, and this situation increases the influx of inexperienced operators into construction jobsites. Many studies have targeted university students or workers who have no or little experience of operating an excavator [42,44–46] while expert operators participated in experiments in some studies including [4,38,46,47]. It was observed that those experts usually had 5 to 10 years of excavator operating experience or similar control interface (e.g., joysticks) experience in the past.

5.2.2 Fatigue and Cognitive Load

The human-in-the-loop approach which sees different aspects of humans (i.e., physiological state, physical state, action, behavior, and intention) should be significantly considered for teleoperation of excavators since it builds on human-machine interactions. The literature indicated that excavator operation is a mentally demanding task, and furthermore, in the case of teleoperation, operators should rely on various technologies compared to conventional operation. Although new technologies have been developed to support the operator's decision making, it should not be disregarded that stress may occur with the adoption of unfamiliar technology depending on the user who uses it in jobsites. It can be difficult to continue remote tasks if physical and cognitive demand of operators keeps high during works. Cognitive overload and fatigue can cause poor decision making, human errors, or underperformance, and this could lead to a dangerous situation for the excavator operators [48]. Therefore, when conducting teleoperation studies, human factors and ergonomics aspects should be measured and assessed physically and mentally.

Among the studies that developed devices or interfaces, human participants were asked to report physical and cognitive loads such as mental demand, temporal demand, physical demand, effort, performance, frustration level, and distraction after the task experiment [45,49]. The survey was primarily based on six subscales of the National Aeronautics and Space Administration (NASA)'s Task Load Index (TLX) subjective workload assessment tool. This evaluation has served as a basis for determining whether a developed device or interface is effective enough for reducing the cognitive load of human operators while enhancing the intuitiveness of using the device. Ergonomic factors, muscle fatigue, wrist, and arm movement were evaluated to validate the suitability of developed control devices in few studies [45,49]. In some studies, the spatial abilities of participants (e.g., Spatial perception Ability (SpA)) which is a critical factor for operator performance also have been primarily examined [42].

5.2.3 Future Directions

Future studies should consider the construction-specific dynamic work environments. For example, operators may differ from day to day even in the same excavation workplace, and the ground of jobsite, which was flat one day, maybe bumpy the next day during the earthwork. It is also possible to perform different tasks each day with the same excavator. The excavator can do trenching for yesterday and loading normal soil into a truck today. In such kind of work environment, the operator's role is significant in the productivity, quality, and safety goal of each excavation task.

Many studies considered either novice or experienced operators for validating their works during experiments. Since both novice and expert operators manipulate excavators in actual construction sites, it is necessary to develop device, controller, and human-machine interface while taking into account both experienced and inexperienced operators. Future human-machine interfaces for excavators should be developed to compensate for bias in previous experience, overconfidence, inattentiveness, and habituated behavior of experienced operators, and to support lack of knowledge and experience for novice operators as well.

Moreover, human factors should be rigorously examined in designing and developing the device or system for teleoperation since human operators are the main decision-makers who receive various information and command to teleoperated excavators. Current works and studies emphasized mainly on technologies and hardware of excavators. Human-centered human-machine interface design is needed for future research. The experience and familiarity of the operator with the design, human data such as their mental load changes, and their fatigue level need to be taken into consideration when making the design. The purpose of the interactive design principle for ensuring communication efficiency between human operators and excavators is to provide easy-to-use interfaces with sufficient and efficient communication between them. These gaps will need to be filled by conducting research through analyzing factors that affect the competence of operators and remote controls of excavators, and by developing adequate training tools to operate excavators via safe and efficient teleoperation. The most appropriate types and amount of information to the operator should be selected, and the associated loads for operators to process it should be evaluated to avoid data/information overload problems in workplaces. In addition, the degree of easy-to-use need to be measured and assessed. Since individuals have different abilities and degrees to feel each type of information, evaluating such degrees with subjects who can represent the demographic of excavator operators is crucial in experiments. For this purpose, there are metrics for evaluation such as response rate, task accuracy with trajectory, or work efficiency with time. Survey such as the NASA TLX has been adopted to measure physical/cognitive load, fatigue, intuitiveness, and stress of operators in studies. However, since these traditional surveys are obtained through the participants' responses before or after the experiment, the results of the experiment may not be reliable if the participants do not report properly. Therefore, in future work, it is expected that human sensor data with physiological measurement devices such as electroencephalograph (EEG) or electromyography (EMG) has the potential to give more objective information during excavation tasks for further behavior analysis and supplement the drawbacks of conventional survey methods.

5.3 Interface

5.3.1 Interface as assisting information feedback

Typically, a teleoperation system consists of a master robot part and a slave robot part. A master robot part is where the human operator commands, and a slave robot part is a robot or a machine that receives an operator’s command and performs tasks. Since the master part and the slave part are separated from each other in teleoperation, humans cannot directly recognize the environment where the slave part interacts with. Known that operators' situational awareness is significant for robust control decision making for ensuring safety and productivity during teleoperation, operators should rely on interfaces to understand the environment where the machine interacts with during tasks. Therefore, one of keys to perform the successful teleoperation is an intuitive interface that can support strong situational awareness. Reinforced situational awareness with intuitive interfaces can provide a work environment in which human operators can work in good health by enhancing the understanding of site conditions and machines because operators would get telepresence feeling like onboarding the machine in the field [15]. Various interfaces such as visual, haptic, or auditory cues have been designed and developed in responding to on-site demands for enhanced situational awareness.

Visual interface (2D/3D/Visual Annotation) - Most visual interfaces of teleoperation systems rely on providing image or video data. When multiple cameras are installed for monitoring, changing visual scenes on an interface or viewing scenes on multiple views is needed. In this case, operators need to pay attention to multiple scenes simultaneously, which may increase cognitive loads for information processing and thus likely lower work productivity [15]. To overcome limitations of conventional visual interface, research has been conducted to improve spatial understanding in teleoperation through dedicated remote sensors other than common video cameras. For example, environmental scanning techniques such as LiDAR have been introduced to gather the 3D point cloud data of given scenes [50]. The virtual reality (VR) has been tested as an intuitive user interface to explore the virtual scene in construction [15]. With the recent advancement of VR, increasingly reproduced information has been positioned into the interface that would enhance the situational awareness of operators. However, if excessive visual information is provided, human operators often cannot digest all information and feel cognitive load or fatigue. Visual annotation (VA) would be a promising solution to supplement visual perception loss because of large amounts of visual information in a short time. For example, hazardous obstacles have been highlighted so that operators can recognize obstacles or set up a radar map indicating the position of obstacles in the corner of the screen [42]. However, since the VA only gives information about visible obstacles, there is still a limitation in cases where it is necessary to perform excavation tasks with uncertainties regarding invisible obstacles (e.g., buried underground utilities).

Tactile interface - For teleoperation in construction, a tactile feedback has been proposed in an interface system such as [51]. Providing information about collisions by tactile sense (e.g., high-frequency vibration) showed the potential in raising situational awareness because it can help improve realistic understanding of situations. Since humans can recognize the physical environment through tactile sense, transmitting tactile signals to operators when contacting objects can improve the sense of reality and understanding of field situations [4]. For example, Okamura et al. [52] showed that the sense of touch reflecting the characteristics of different physical environments helps operators perceive and recognize objects with different characteristics. As such, the use of tactile sensation to enhance operators' understanding of jobsite conditions has been applied in the construction field [4]. Regarding the construction machinery to which teleoperation is applied, it is expected that tactile information will be able to play a crucial role in alerting operators of field situations on construction sites. However, the tactile feedback has challenges, such that environmental stimuli, such as other mechanical vibrations caused by other proximal equipment, could mask tactile displays.

Auditory interface - The auditory interface can help give alarms to operators. A visual interface may cause a cognitive load problem because human operators need to process multiple pieces of visual information at once. Since the auditory interface uses a different sensory channel (i.e., hearing) as opposed to the sight, it would be an appropriate interface for alarming when it is in a visually demanding situation. However, when information related to the danger can be visually transmitted to operators in an appropriate manner, the auditory interface may duplicate the associated information, which should be carefully considered for designing auditory interface [2]. Bhalerao et al. [53] and Mavridis et al. [54] showed that participants trained with verbal-audio or audio stimuli performed better in the training than those who are trained without such stimuli. Meanwhile, the auditory channel may be less-available due to the presence of high-decibel workplace noise, and often also the need to wear protective hearing equipment.

5.3.2 Interface as controller

The interface as a controller is supposed to deliver commands by the operator to the machine from a distance. Therefore, the major goal of relevant studies is to develop an intuitive, ease-to-use, and efficient-to-use controller.

Joystick – Shin et al. [55] developed joysticks for remote control by installing a device on existing levers and pedals in the cockpit to control excavators at a distance. But the conventional controller interface (e.g., joystick) is often known as counter-intuitive to some excavator operators. Since the operator has to control two joysticks to manipulate excavator attachment with three components (e.g., bucket, arm, and boom), it is quite difficult and confusing. This may cause a lot of cognitive loads to operators especially novice operators. Although joystick allows operators to control the end effector of the slave robot arm by means of trajectory-related methods, it requires training for operators to be familiar with the mechanism. It should be noted that even professional operators are prone to make error under excessive working pressure and high perceived load when remotely operating robot systems in an unstructured environment with uncertainties (e.g., obstacles such as underground utility strike).

Haptic & Graphic User Interface – Kim et al. [44] and Gong et al. [56] proposed haptic-based methods to control the excavator attachment by the human arm since the kinetic mechanism of the human arm is much more similar to that of the excavator arm and bucket compared to the joystick. However, these studies posed challenges in that excessive physical load may be required for workers if the arm is manipulated for long periods of time compared to finger-moving joysticks. Okishiba et al. [45] developed a graphical user interface (GUI) for control via human factors analysis taking account of the cognitive load of human information processing among different interface types. Compared to a joystick that takes time to get used to and adapt to, the GUI based on a mobile device was developed so that unskilled workers can more easily control excavators remotely.

5.3.3 Future Directions

There is a contradiction in designing interactive interface (i.e., delivering sufficient information with less cognitive load to operators). If too much information is provided visually, it may not be able to be digested during tasks and likely lowers concentration and work efficiency. In this context, research on how to optimally deliver information feedback via robust interfaces should be conducted in terms of the contents of visual presentation, information format, and the relationship with other sensory feedback. As well as the operator's cognitive load, the load of computer and communication channel should be also considered. Since the size of visual data is often large, it is necessary to consider the format, space, and transmission type to efficiently store and process the data. While the interface for remote operation is primarily focused on visual feedback, it should not be overlooked that tactile and/or audio feedback can be used to tele-operate the excavator. Audio feedback has been used to intuitively transmit warning to operators, and tactile feedback has been used to recognize the characteristic of physical environments. As such, in order to reduce cognitive loads due to excessive visual feedback, leveraging other sensory channels would be a promising solution in the future research. The interface for excavator is crucial for effective interaction between human and excavator.

Another research gap is that the control of validity of experimental environments during the use of simulators is not specifically defined. Prior studies mentioned that the simulator was used for the experiments, but there are differences between the virtual environments in simulators and the real-life environment. If the environment control is too high in the virtual environment, the performance of the interface design is likely to be different in a sub-ideal (real-life) environment. Though it is convenient and cost-efficient to use a simulator for experiments, more attention to the balance between environment control and validity is needed from the experimenters.

Lastly, it should not be neglected that the ultimate goal for effective communication is to perform and assist excavation tasks effectively (e.g., digging, dumping, driving, lifting). For future studies, it is essential to conduct the task analysis for human operator and excavator, regarding operators' behaviors as well as kinetic movement of excavator while executing given tasks to check its usability. It is necessary to identify information processing or decision-making process of operators when performing tasks with excavators (especially, complex tasks that require much caution) and taking account of users' perspective in the design process when developing an effective interface.

5.4 Operation & Environment

5.4.1 Data Communication Efficiency

To teleoperate excavators, hardware such as machines, sensors, computers, and interfaces need to send and receive data (e.g., image/video data, 3D spatial data, excavator motion data) and associated information wirelessly in real time. Exchanging such different types of data and vast amounts of information in real time may cause the deterioration of wireless communication performance. If communication performance deteriorates, errors including compatibility problems may occur in collecting and transmitting information due to data interference or transmission errors between platforms. In addition, it takes a long time to process data, and there may be a time delay in the operation (i.e., latency). Communication errors or delay problems affect safety, work efficiency, and accuracy in performing teleoperation tasks [57]. Therefore, establishing an efficient communication channel is important for the teleoperation of excavators.

Likewise, Dadhich et al. [12] emphasized the reliable wireless network of remote communication for different types of information to be used as feedback and to transmit control commands. Wireless networks often have traffic problems because they are not only for teleoperation but also for other purposes in jobsite management (e.g., security cameras, UAVs) and thus using dedicated methods such as wireless local area networks (WLANs) need to be considered. In addition, advancement of wireless communication technology, where it moves from 3G to 4G LTE, now 5G is commercialized to complement slow speed of WLANs, and 6G is coming, thus we may envision ultra-low latency in teleoperation. Latency lowers the transmission rate due to data interference, error, and compatibility issues based on data types in addition to the communication network and speed [12]. In this regard, effective data management has been studied. Kim et al. [29] conducted a study on how to reduce the high data traffic load caused by high volume and frequency when operating excavators remotely. Kim et al. [29] developed the Data Communication Manager (DCM), a middleware interface system, for efficient communication between control station and data from sensors and controllers of intelligent excavators. Lee et al. [58] developed a GPS-based fleet telematics system that can monitor health conditions or performance of operators based on data such as location, speed, distance, and utilization time of heavy earthwork equipment in real time. Despite the significance of this field in remote operation, relatively few studies have been conducted compared with other topics in excavator teleoperation. In this regard, there is still a need for research related to wireless communication system for teleoperating excavators to achieve low latency and minimizing data loss for efficient data communication during teleoperation.

5.4.2 Environment Awareness

People have expectations that remote control of construction equipment for excavation could improve productivity and safety. However, unlike the manufacturing industry where workplaces are typically structured, there could be more risks and uncertainties associated with remote control in construction sites. Coping with an unexpected environment through real-time monitoring is crucial for earthwork involving uncertainties. Therefore, reliable information along with continuous and real-time monitoring of workplaces is essential for remote operation of excavators in a safe and successful manner [59]. Technologies aided by computer vision can contribute to robust machine vision-based inspection, which increasingly replaces error-prone, time-consuming, labor-intensive, and dangerous manual observation [25]. In teleoperation, since human operators may not be able to see and feel sites directly, providing reliable spatial information is essential for robust control. In addition to monitoring the kinetic movement of excavators, operators should be aware of the work environment to perform teleoperation tasks well. Environment awareness should be able to understand information related to safety as well as task productivity in real time, which is based on recognizing surroundings and obstacles that may affect or interfere with works.

Environment awareness in the context of excavation can be divided into two categories; one is site monitoring for objects above ground [60–79], and the other is monitoring for terrain conditions and underground objects [80–84]. There are many obstacles for excavation because the workplace is often not well-organized, and the ground level is not typically consistent. Therefore, in order to remotely operate excavators safely without colliding with obstacles above ground, it is necessary to be aware of the surrounding situation. In this regard, studies on 3D mapping of construction sites (e.g., in the form of 3D point cloud data) have been conducted [6,85]. In unstructured surface conditions of jobsites for earthwork, at least obstacles are visible, but underground situations are invisible, and thus the associated uncertainty is greater than the ground surface, which likely leads major safety issues.

In case of buried utilities, one of the main obstacles for excavation, it is not easy to pinpoint the exact location of underground utility because the reference (e.g., as-built drawings) may misrepresent the location of utility and may not be updated, or the human error of the locator may provide misinformation to excavation workers. Therefore, it is important to know the actual location/depth while performing excavation tasks. Studies have been conducted to ensure the excavation safety and have used technologies for locating and mapping underground utilities to prevent accidents [86]. Wei et al. [84] and Cai et al. [87] proposed ways to improve the accuracy of utility mappings by integrating detectable and undetectable data. The methodology included identifying utility presence and estimating utility location using spatial data from GPR, previous records of buried utility, and specifications. Li et al. [88] has developed a framework that integrates spatial reasoning and natural language processing (NLP) for utility compliance automation.

5.4.3 Future Directions

Teleoperation requires telepresence that allows human operators to feel realism even from a distance. Toward such telepresence, the information about excavators and the surroundings needs to be robustly delivered to human operators, which requires seamless data transmission and reception of various types and large amounts of data and information. Accordingly, reliable information on the work environment and multicast communication is necessary. Real-time modeling of construction workplaces and efficient data management systems are essential for teleoperation, but relevant technical limitations still exist. With the current communication technology, latency may not be a problem in a short distance, but in the case of controlling from a long distance, there is a need for robust ways to overcome latency issues for accurate control.

Regarding environment awareness of construction workplaces, although studies have been conducted on 3D mapping of jobsites, there is still a question as to whether this can take account of cognitive overload issues due to excessive information to operators and the latency issue of data transmission when operators teleoperate excavators. Therefore, in future studies, it is necessary to conduct experiments to confirm whether 3D mapping is practical in teleoperation of excavators in jobsites. The hybrid GPR/GPS systems have shown promising results, but they may not be ideal solutions for taking account of underground utilities under each and every site condition. GPR surveys take time for analyzing data and often have limitation on catching utilities depending on soil conditions. In this context, there is a need for further studies on underground utility detection and localization to gather complete site information. Although accurate site information is important to prevent potential accidents, when looking at the root cause of an accident such as a buried utility strike, many cases are still caused by excavator operators' inattentive operation. Therefore, it would be a good way to reduce fatal accidents via guidance systems that can support inattentive excavator operators to work safely along with accurate spatial information of obstacles (e.g., buried utilities).

5.5 Opportunities in teleoperation of excavators

Although Occupational Safety and Health Administration (OSHA) safety trainings and various regulations are required in many jobsites before excavation tasks, fatal accidents still occur. Physically removing human operators from dynamic and dangerous excavation sites could be a fundamental way to reduce deadly accidents. Therefore, when the technology related to teleoperation is further developed and supported, its application to excavators is expected to bring us many opportunities in the future since it allows operators to manipulate excavators from a safe distance. In particular, this is essential in extremely challenging situations such as disaster areas caused by earthquakes, floods, or tsunamis, which are dangerous or harmful for humans to work on site.

After quantitative reviews with keyword analysis, we have conducted a qualitative review and in-depth discussion of studies related to the teleoperation of excavators in three aspects (i.e., human operator, interface, operation & environment). In-depth analysis was performed by selecting a total of 9 papers in the Human operator section, 12 papers in the Interface section, and 106 papers in the Operation & Environment section. As such, we could observe that the Human Operator cluster and the Interface cluster have a relatively small amount of research conducted compared to the Operation & Environment cluster. Since the dynamic field environment (e.g., the movement and interaction of heavy equipment and laborers on bumpy, rough, and uneven ground condition) is one of the most challenging parts, it makes sense that there have been many studies conducted in the Operation & Environment cluster among others. However, it should not be neglected that the subject that operates an excavator is human. Although higher levels of automation could reduce the dependence of the human operator on decision-making, human intervention is still required in certain task situations (e.g., non-pre-programmed and error-prone situations). In this regard, human-centered research (e.g., physical and psychological stress, ability of human operator, human-robot interface) needs to be more conducted by future researchers.

6. Conclusion

There has been increasing interest of the automation in hazardous construction workplaces. Given the currently developed technologies, achieving full autonomy for each and every construction task needs more time because of dynamic, complex, and uncertain nature of construction workplaces. In this context, there have been research efforts on emerging teleoperation technologies for human-in-the-loop construction automation. Among various type of construction robots, this paper focuses on excavators which are the most widely employed and representative construction robot at jobsites while the largest proportion of fatal accidents in construction is related to excavation. This paper explores challenges, tasks, and opportunities of excavator teleoperation by examining related studies in the past two decades using the mixed review method, both quantitative (i.e., bibliometric analysis) and qualitative (i.e., systematic review) approaches. Total 133 peer-reviewed papers were systematically and rigorously reviewed. Through the bibliometric analysis with the VOSviewer, research clusters were identified: excavator, computer vision technology, teleoperation plan and control, and automated earthwork. The number of studies related to excavator teleoperation in the 2010s was more than three times higher than that in the 2000s. The research clusters identified from the bibliographic analysis are synthesized through the consensus-based discussion to develop the classification structure of the retrieved publications. The classification structure is used to conduct the qualitative review and the comprehensive discussion of excavator teleoperation related research challenges, knowledge gaps, and potentials. Through the in-depth discussion for the qualitative reviews, research directions in terms of human operator, interface, and operation & environment were identified, which clarifies the essential roles of each area in the overall system of teleoperation for excavation. Since teleoperation always involves human operators, excavator research needs to be conducted from human perspectives and represent the demographic of excavator operators. For developing robust human-machine interfaces, research should be conducted in the aspect of enhancing task performance while delivering sufficient information with less cognitive load to operators. And when it comes to various tasks of excavation to be performed remotely, it is necessary that operators robustly sense situational awareness taking account of uncertainties in jobsites for preventing safety accidents, and simultaneously there is a need for technologies for efficiently transmitting vast amounts of heterogeneous data. As such, there are still challenges that need to be addressed, and this paper could shed light on this field by reviewing relevant studies, analyzing knowledge gaps, and suggesting the direction of future research. If successful in filling the gaps for teleoperation, it is anticipated that human-in-the-loop automation can make construction work safer and more efficient.

Acknowledgement

This material is based upon work supported by the National Science Foundation under Grant No. 2026574. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

Reference

[1] J. Kim, D. Lee, J. Seo, Task planning strategy and path similarity analysis for an autonomous excavator, Automation in Construction. 112 (2020) 103108. https://doi.org/10.1016/j.autcon.2020.103108.

[2] F. Morosi, M. Rossoni, G. Caruso, Coordinated control paradigm for hydraulic excavator with haptic device, Automation in Construction. 105 (2019) 102848. https://doi.org/10.1016/j.autcon.2019.102848.

[3] M. Ito, C. Raima, S. Saiki, Y. Yamazaki, Y. Kurita, Effects of Machine Instability Feedback on Safety During Digging Operation in Teleoperated Excavators, IEEE Access. 9 (2021) pp.28987-28998. https://doi.org/10.1109/ACCESS.2021.3059710.

[4] H. Nagano, H. Takenouchi, N. Cao, M. Konyo, S. Tadokoro, Tactile feedback system of high-frequency vibration signals for supporting delicate teleoperation of construction robots, Advanced Robotics. 34 (2020) pp.730-743. https://doi.org/10.1080/01691864.2020.1769725.

[5] A. Dubois, L.-E. Gadde, The construction industry as a loosely coupled system: implications for productivity and innovation, Construction Management and Economics. 20 (2002) pp.621-631. https://doi.org/10.1080/01446190210163543.

[6] D. Moon, S. Chung, S. Kwon, J. Seo, J. Shin, Comparison and utilization of point cloud generated from photogrammetry and laser scanning: 3D world model for smart heavy equipment planning, Automation in Construction. 98 (2019) pp.322-331. https://doi.org/10.1016/j.autcon.2018.07.020.

[7] A. Stroupe, T. Huntsberger, A. Okon, H. Aghazarian, M. Robinson, Behavior-based multi-robot collaboration for autonomous construction tasks, in: 2005 IEEE/RSJ International Conference on Intelligent Robots and Systems, 2005: pp. 1495–1500. https://doi.org/10.1109/IROS.2005.1545269.

[8] G. Hitz, A. Gotovos, F. Pomerleau, M. Garneau, C. Pradalier, A. Krause, R.Y. Siegwart, Fully autonomous focused exploration for robotic environmental monitoring, in: 2014 IEEE International Conference on Robotics and Automation (ICRA), 2014: pp. 2658–2664. https://doi.org/10.1109/ICRA.2014.6907240.

[9] S. Hirche, M. Buss, Human-Oriented Control for Haptic Teleoperation, Proceedings of the IEEE. 100 (2012) pp.623-647. https://doi.org/10.1109/JPROC.2011.2175150.

[10] Q. Zhu, J. Du, Y. Shi, P. Wei, Neurobehavioral assessment of force feedback simulation in industrial robotic teleoperation, Automation in Construction. 126 (2021) 103674. https://doi.org/10.1016/j.autcon.2021.103674.

[11] P.F. Hokayem, M.W. Spong, Bilateral teleoperation: An historical survey, Automatica. 42 (2006) pp.2035-2057. https://doi.org/10.1016/j.automatica.2006.06.027.

[12] S. Dadhich, U. Bodin, U. Andersson, Key challenges in automation of earth-moving machines, Automation in Construction. 68 (2016) pp.212-222. https://doi.org/10.1016/j.autcon.2016.05.009.
[13] Q.P. Ha, L. Yen, C. Balaguer, Robotic autonomous systems for earthmoving in military applications, Automation in Construction. 107 (2019) 102934. https://doi.org/10.1016/j.autcon.2019.102934.
[14] N. Melenbrink, J. Werfel, A. Menges, On-site autonomous construction robots: Towards unsupervised building, Automation in Construction. 119 (2020) 103312. https://doi.org/10.1016/j.autcon.2020.103312.
[15] T. Zhou, Q. Zhu, J. Du, Intuitive robot teleoperation for civil engineering operations with virtual reality and deep learning scene reconstruction, Advanced Engineering Informatics. 46 (2020) 101170. https://doi.org/10.1016/j.aei.2020.101170.
[16] H. Sulaiman, M. Saadun, A. Yusof, Modern manned, unmanned and teleoperated excavator system, Journal of Mechanical Engineering and Technology. 7 (2015). https://journal.utem.edu.my/index.php/jmet/article/view/539.
[17] L. Basañez, R. Suárez, Teleoperation, in: Nof S. (Eds) Springer Handbook of Automation, Springer, 2009: pp. 449–468. https://doi.org/10.1007/978-3-540-78831-7_27.
[18] Y. Zhang, H. Liu, S.-C. Kang, M. Al-Hussein, Virtual reality applications for the built environment: Research trends and opportunities, Automation in Construction. 118 (2020) 103311. https://doi.org/10.1016/j.autcon.2020.103311.
[19] P. Hallinger, J. Kovačević, A bibliometric review of research on educational administration: Science mapping the literature, 1960 to 2018, Review of Educational Research. 89 (2019) pp.335-369. https://doi.org/10.3102/0034654319830380.
[20] P. Mongeon, A. Paul-Hus, The journal coverage of Web of Science and Scopus: a comparative analysis, Scientometrics. 106 (2016) pp.213-228. https://doi.org/10.1007/s11192-015-1765-5.
[21] D. Moher, A. Liberati, J. Tetzlaff, D.G. Altman, Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement, International Journal of Surgery. 8 (2010) pp.336-341. https://doi.org/10.1016/j.ijsu.2010.02.007.
[22] M.R. Hosseini, I. Martek, E.K. Zavadskas, A.A. Aibinu, M. Arashpour, N. Chileshe, Critical evaluation of off-site construction research: A Scientometric analysis, Automation in Construction. 87 (2018) pp.235-247. https://doi.org/10.1016/j.autcon.2017.12.002.
[23] M. Oraee, M.R. Hosseini, E. Papadonikolaki, R. Palliyaguru, M. Arashpour, Collaboration in BIM-based construction networks: A bibliometric-qualitative literature review, International Journal of Project Management. 35 (2017) pp.1288-1301. https://doi.org/10.1016/j.ijproman.2017.07.001.
[24] N.J. van Eck, L. Waltman, R. Dekker, J. van den Berg, A comparison of two techniques for bibliometric mapping: Multidimensional scaling and VOS, Journal of the American Society for Information Science and Technology. 61 (2010) pp.2405-2416. https://doi.org/10.1002/asi.21421.
[25] Y. Pan, L. Zhang, Roles of artificial intelligence in construction engineering and management: A critical review and future trends, Automation in Construction. 122 (2021) 103517. https://doi.org/10.1016/j.autcon.2020.103517.
[26] M. Akinlolu, T.C. Haupt, D.J. Edwards, F. Simpeh, A bibliometric review of the status and emerging research trends in construction safety management technologies, International Journal of Construction Management. (2020) pp.1-13.

https://doi.org/10.1080/15623599.2020.1819584.

[27] N.J. van Eck, L. Waltman, Visualizing Bibliometric Networks. In: Ding Y., Rousseau R., Wolfram D. (eds) Measuring Scholarly Impact, Springer International Publishing, 2014. http://link.springer.com/10.1007/978-3-319-10377-8 (accessed September 27, 2021).

[28] S. Xu, J. Wang, W. Shou, T. Ngo, A.-M. Sadick, X. Wang, Computer Vision Techniques in Construction: A Critical Review, Archives of Computational Methods in Engineering. 28 (2021) pp.3383-3397. https://doi.org/10.1007/s11831-020-09504-3.

[29] J. Kim, S.S. Lee, J. Seo, V.R. Kamat, Modular data communication methods for a robotic excavator, Automation in Construction. 90 (2018) pp.166-177. https://doi.org/10.1016/j.autcon.2018.02.007.

[30] T. Tanimoto, K. Shinohara, H. Yoshinada, Research on effective teleoperation of construction machinery fusing manual and automatic operation, Robomech Journal. 4 (2017) pp.1-12. https://doi.org/10.1186/s40648-017-0083-5.

[31] S.-K. Kim, J.S. Russell, Framework for an intelligent earthwork system: Part II. Task identification/scheduling and resource allocation methodology, Automation in Construction. 12 (2003) pp.15-27. https://doi.org/10.1016/S0926-5805(02)00033-X.

[32] Q. Ha, M. Santos, Q. Nguyen, D. Rye, H. Durrant-Whyte, Robotic excavation in construction automation, IEEE Robotics & Automation Magazine. 9 (2002) pp.20-28. https://doi.org/10.1109/100.993151.

[33] K.K. Hughes, Integration Of Cognitive And Physical Factors To Model Human Performance In Fluid Power Systems, Dissertations. (2011) 279. https://digital.library.ncat.edu/dissertations/11/ (accessed September 27, 2021).

[34] X. Su, S. Talmaki, H. Cai, V.R. Kamat, Uncertainty-aware visualization and proximity monitoring in urban excavation: a geospatial augmented reality approach, Visualization in Engineering. 1 (2013) pp.1-13. https://doi.org/10.1186/2213-7459-1-2.

[35] S. Talmaki, V.R. Kamat, H. Cai, Geometric modeling of geospatial data for visualization-assisted excavation, Advanced Engineering Informatics. 27 (2013) pp.283-298. https://doi.org/10.1016/j.aei.2013.01.004.

[36] J. Akyeampong, S.J. Udoka, E.H. Park, A Hydraulic Excavator Augmented Reality Simulator for Operator Training, in: Proceedings of the 2012 International Conference on Industrial Engineering and Operations Management, 2012: pp. 1511–1518.

[37] X. Chen, F. Chen, J. Zhou, L. Li, Y. Zhang, Cushioning structure optimization of excavator arm cylinder, Automation in Construction. 53 (2015) pp.120-130. https://doi.org/10.1016/j.autcon.2015.03.012.

[38] M. Wallmyr, T.A. Sitompul, T. Holstein, R. Lindell, Evaluating Mixed Reality Notifications to Support Excavator Operator Awareness, in: D. Lamas, F. Loizides, L. Nacke, H. Petrie, M. Winckler, P. Zaphiris (Eds.), Human-Computer Interaction – INTERACT 2019, Springer International Publishing, Cham, 2019: pp. 743–762. https://doi.org/10.1007/978-3-030-29381-9_44.

[39] Q. Xiang, X. Luo, G. Ye, X. Gong, J. Ke, A Methodology for Analyzing Information Needs in Construction, in: Construction Research Congress 2020, American Society of Civil Engineers, Tempe, Arizona, 2020: pp. 157–164. https://doi.org/10.1061/9780784482872.018.

[40] Y. Du, M.C. Dorneich, B. Steward, Virtual operator modeling method for excavator trenching, Automation in Construction. 70 (2016) pp.14-25. https://doi.org/10.1016/j.autcon.2016.06.013.

[41] P.S. Dunston, R.W. Proctor, X. Wang, Challenges in evaluating skill transfer from

construction equipment simulators, Theoretical Issues in Ergonomics Science. 15 (2014) pp.354-375. https://doi.org/10.1080/1463922X.2011.624647.
[42] Z. Hong, Q. Zhang, X. Su, H. Zhang, Effect of virtual annotation on performance of construction equipment teleoperation under adverse visual conditions, Automation in Construction. 118 (2020) 103296. https://doi.org/10.1016/j.autcon.2020.103296.
[43] S. Talmaki, V.R. Kamat, Real-Time Hybrid Virtuality for Prevention of Excavation Related Utility Strikes, Journal of Computing in Civil Engineering. 28 (2014) 04014001. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000269.
[44] D. Kim, J. Kim, K. Lee, C. Park, J. Song, D. Kang, Excavator tele-operation system using a human arm, Automation in Construction. 18 (2009) pp.173-182. https://doi.org/10.1016/j.autcon.2008.07.002.
[45] S. Okishiba, R. Fukui, M. Takagi, H. Azumi, S. Warisawa, R. Togashi, H. Kitaoka, T. Ooi, Tablet interface for direct vision teleoperation of an excavator for urban construction work, Automation in Construction. 102 (2019) pp.17-26. https://doi.org/10.1016/j.autcon.2019.02.003.
[46] L. Scalera, S. Seriani, P. Gallina, M. Di Luca, A. Gasparetto, Experimental Evaluation of Vibrotactile Training Mappings for Dual-Joystick Directional Guidance, in: D. Prattichizzo, H. Shinoda, H.Z. Tan, E. Ruffaldi, A. Frisoli (Eds.), Haptics: Science, Technology, and Applications, Springer International Publishing, Cham, 2018: pp. 575–586. https://doi.org/10.1007/978-3-319-93399-3_49.
[47] Y. Du, M.C. Dorneich, B. Steward, Modeling expertise and adaptability in virtual operator models, Automation in Construction. 90 (2018) pp.223-234. https://doi.org/10.1016/j.autcon.2018.02.030.
[48] Y. Desai, D. Davis, S. Jiang, A. Ward, The Effect of Auditory Cues on Haptic-Controlled Excavator Operator Performance, IIE Annual Conference. Proceedings. (2014) pp.825-832. https://www.proquest.com/docview/1622299272/abstract/9DB507386F784741PQ/1 (accessed September 28, 2021).
[49] J. Akyeampong, S. Udoka, G. Caruso, M. Bordegoni, Evaluation of hydraulic excavator Human–Machine Interface concepts using NASA TLX, International Journal of Industrial Ergonomics. 44 (2014) pp.374-382. https://doi.org/10.1016/j.ergon.2013.12.002.
[50] M.J. Chae, G.W. Lee, J.Y. Kim, J.W. Park, M.Y. Cho, A 3D surface modeling system for intelligent excavation system, Automation in Construction. 20 (2011) pp.808-817. https://doi.org/10.1016/j.autcon.2011.02.003.
[51] T. Hirabayashi, J. Akizono, T. Yamamoto, H. Sakai, H. Yano, Teleoperation of construction machines with haptic information for underwater applications, Automation in Construction. 15 (2006) pp.563-570. https://doi.org/10.1016/j.autcon.2005.07.008.
[52] A.M. Okamura, M.R. Cutkosky, J.T. Dennerlein, Reality-based models for vibration feedback in virtual environments, IEEE/ASME Transactions on Mechatronics. 6 (2001) pp.245-252. https://doi.org/10.1109/3516.951362.
[53] B.N. Bhalerao, P.S. Dunston, R.W. Proctor, Use of PC-based Simulators to Train Basic Control Functions of a Hydraulic Excavator: Audiovisual Instruction Contrasted with Hands-On Exploration, International Journal of Human–Computer Interaction. 33 (2017) pp.66-74. https://doi.org/10.1080/10447318.2016.1232230.
[54] N. Mavridis, G. Pierris, P. Gallina, Z. Papamitsiou, U. Saad, On the subjective difficulty of Joystick-based robot arm teleoperation with auditory feedback, in: 2015 IEEE 8th GCC Conference Exhibition, 2015: pp. 1–6. https://doi.org/10.1109/IEEEGCC.2015.7060097.

[55] D. Shin, M. Kang, S. Lee, C. Han, Development of remote controlled manipulation device for a conventional excavator without renovation, in: 2012 IEEE/SICE International Symposium on System Integration (SII), 2012: pp. 546–551. https://doi.org/10.1109/SII.2012.6427299.
[56] D. Gong, Y. Wang, J. Yu, G. Zuo, Motion Mapping from a Human Arm to a Heterogeneous Excavator-like Robotic Arm for Intuitive Teleoperation, in: 2019 IEEE International Conference on Real-Time Computing and Robotics (RCAR), 2019: pp. 493–498. https://doi.org/10.1109/RCAR47638.2019.9044131.
[57] Y. Okawa, M. Ito, R. Sekizuka, S. Saiki, Y. Yamazaki, Y. Kurita, An Assistive Interface of a Teleoperation System of an Excavator by Overlapping the Predicted Position of the Arm, in: Kitakyushu, Japan, 2020. https://doi.org/10.22260/ISARC2020/0012.
[58] S.S. Lee, S. Park, J. Seo, Utilization analysis methodology for fleet telematics of heavy earthwork equipment, Automation in Construction. 92 (2018) pp.59-67. https://doi.org/10.1016/j.autcon.2018.02.035.
[59] R.K. Shah, A new approach for automation of location-based earthwork scheduling in road construction projects, Automation in Construction. 43 (2014) pp.156-169. https://doi.org/10.1016/j.autcon.2014.03.003.
[60] E.R. Azar, B. McCabe, Part based model and spatial–temporal reasoning to recognize hydraulic excavators in construction images and videos, Automation in Construction. 24 (2012) pp.194-202. https://doi.org/10.1016/j.autcon.2012.03.003.
[61] E.R. Azar, B. McCabe, Automated Visual Recognition of Dump Trucks in Construction Videos, Journal of Computing in Civil Engineering. 26 (2012) pp.769-781. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000179.
[62] C. Chen, Z. Zhu, A. Hammad, Automated excavators activity recognition and productivity analysis from construction site surveillance videos, Automation in Construction. 110 (2020) 103045. https://doi.org/10.1016/j.autcon.2019.103045.
[63] J. Chen, Y. Fang, Y.K. Cho, C. Kim, Principal Axes Descriptor for Automated Construction-Equipment Classification from Point Clouds, Journal of Computing in Civil Engineering. 31 (2017) 04016058. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000628.
[64] W. Fang, L. Ding, B. Zhong, P.E.D. Love, H. Luo, Automated detection of workers and heavy equipment on construction sites: A convolutional neural network approach, Advanced Engineering Informatics. 37 (2018) pp.139-149. https://doi.org/10.1016/j.aei.2018.05.003.
[65] M. Golparvar-Fard, A. Heydarian, J.C. Niebles, Vision-based action recognition of earthmoving equipment using spatio-temporal features and support vector machine classifiers, Advanced Engineering Informatics. 27 (2013) pp.652-663. https://doi.org/10.1016/j.aei.2013.09.001.
[66] Y. Guo, Y. Xu, S. Li, Dense construction vehicle detection based on orientation-aware feature fusion convolutional neural network, Automation in Construction. 112 (2020) 103124. https://doi.org/10.1016/j.autcon.2020.103124.
[67] Q. Hu, Y. Bai, L. He, Q. Cai, S. Tang, G. Ma, J. Tan, B. Liang, Intelligent Framework for Worker-Machine Safety Assessment, Journal of Construction Engineering and Management. 146 (2020) 04020045. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001801.
[68] V.R. Kamat, J.C. Martinez, Dynamic 3D Visualization of Articulated Construction Equipment, Journal of Computing in Civil Engineering. 19 (2005) pp.356-368. https://doi.org/10.1061/(ASCE)0887-3801(2005)19:4(356).
[69] H. Kim, Y. Ham, W. Kim, S. Park, H. Kim, Vision-based nonintrusive context documentation

for earthmoving productivity simulation, Automation in Construction. 102 (2019) pp.135-147. https://doi.org/10.1016/j.autcon.2019.02.006.

[70] J. Kim, S. Chi, J. Seo, Interaction analysis for vision-based activity identification of earthmoving excavators and dump trucks, Automation in Construction. 87 (2018) pp.297-308. https://doi.org/10.1016/j.autcon.2017.12.016.

[71] J. Kim, S. Chi, Multi-camera vision-based productivity monitoring of earthmoving operations, Automation in Construction. 112 (2020) 103121. https://doi.org/10.1016/j.autcon.2020.103121.

[72] H. Luo, M. Wang, P.K.-Y. Wong, J.C.P. Cheng, Full body pose estimation of construction equipment using computer vision and deep learning techniques, Automation in Construction. 110 (2020) 103016. https://doi.org/10.1016/j.autcon.2019.103016.

[73] M. Memarzadeh, M. Golparvar-Fard, J.C. Niebles, Automated 2D detection of construction equipment and workers from site video streams using histograms of oriented gradients and colors, Automation in Construction. 32 (2013) pp.24-37. https://doi.org/10.1016/j.autcon.2012.12.002.

[74] C. Sabillon, A. Rashidi, B. Samanta, M.A. Davenport, D.V. Anderson, Audio-Based Bayesian Model for Productivity Estimation of Cyclic Construction Activities, Journal of Computing in Civil Engineering. 34 (2020) 04019048. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000863.

[75] X. Shen, E. Marks, N. Pradhananga, T. Cheng, Hazardous Proximity Zone Design for Heavy Construction Excavation Equipment, Journal of Construction Engineering and Management. 142 (2016) 05016001. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001108.

[76] Y. Shi, Y. Xia, Y. Zhang, Z. Yao, Intelligent identification for working-cycle stages of excavator based on main pump pressure, Automation in Construction. 109 (2020) 102991. https://doi.org/10.1016/j.autcon.2019.102991.

[77] H. Tajeen, Z. Zhu, Image dataset development for measuring construction equipment recognition performance, Automation in Construction. 48 (2014) pp.1-10. https://doi.org/10.1016/j.autcon.2014.07.006.

[78] S. Tang, D. Roberts, M. Golparvar-Fard, Human-object interaction recognition for automatic construction site safety inspection, Automation in Construction. 120 (2020) 103356. https://doi.org/10.1016/j.autcon.2020.103356.

[79] J. Zou, H. Kim, Using Hue, Saturation, and Value Color Space for Hydraulic Excavator Idle Time Analysis, Journal of Computing in Civil Engineering. 21 (2007) pp.238-246. https://doi.org/10.1061/(ASCE)0887-3801(2007)21:4(238).

[80] H. Fernando, J. Marshall, What lies beneath: Material classification for autonomous excavators using proprioceptive force sensing and machine learning, Automation in Construction. 119 (2020) 103374. https://doi.org/10.1016/j.autcon.2020.103374.

[81] K.-T. Kim, L.E. Bernold, A comparison of two innovative technologies for safe pipe installation — "Pipeman" and the Stewart–Gough platform-based pipe manipulator, Automation in Construction. 17 (2008) pp.322-332. https://doi.org/10.1016/j.autcon.2007.04.004.

[82] B.T. Kolera, L.E. Bernold, Intelligent Utility Locating Tool for Excavators, Journal of Construction Engineering and Management. 132 (2006) pp.919-927. https://doi.org/10.1061/(ASCE)0733-9364(2006)132:9(919).

[83] C.P. Tan, Y.H. Zweiri, K. Althoefer, L.D. Seneviratne, Online soil parameter estimation scheme based on Newton-Raphson method for autonomous excavation, IEEE/ASME

Transactions on Mechatronics. 10 (2005) pp.221-229. https://doi.org/10.1109/TMECH.2005.844706.
[84] L. Wei, D.R. Magee, A.G. Cohn, An anomalous event detection and tracking method for a tunnel look-ahead ground prediction system, Automation in Construction. 91 (2018) pp.216-225. https://doi.org/10.1016/j.autcon.2018.03.002.
[85] S. Siebert, J. Teizer, Mobile 3D mapping for surveying earthwork projects using an Unmanned Aerial Vehicle (UAV) system, Automation in Construction. 41 (2014) pp.1-14. https://doi.org/10.1016/j.autcon.2014.01.004.
[86] W.A. Tanoli, A. Sharafat, J. Park, J.W. Seo, Damage Prevention for underground utilities using machine guidance, Automation in Construction. 107 (2019) 102893. https://doi.org/10.1016/j.autcon.2019.102893.
[87] J. Cai, J. Jeon, H. Cai, S. Li, Fusing Heterogeneous Information for Underground Utility Map Generation Based on Dempster-Shafer Theory, Journal of Computing in Civil Engineering. 34 (2020) 04020013. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000892.
[88] S. Li, H. Cai, V.R. Kamat, Integrating Natural Language Processing and Spatial Reasoning for Utility Compliance Checking, Journal of Construction Engineering and Management. 142 (2016) 04016074. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001199.