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Editors:

Thomas Linner (Dr.-Ing.), Thomas Bock (Prof. Dr.-Ing.)
Chair of Building Realisation and Robotics, Technical University of Munich

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Foreword

CIB Working Commission W119 on Customized Industrial Construction has been established as the successor of former TG57 on Industrialization in Construction and as a joint CIB-IAARC Commission. Prof. Dr.-Ing. Thomas Bock, Technical University of Munich, Germany is the appointed Coordinator of this Working Commission.

W119 embraces a variety of focused task groups that work on the intersection of architecture and construction-related topics with advanced technologies such as ICRT, sensory, automation, robotics and medical technologies. These technologies provide solutions to future social, economic and environmental challenges.

Whereas the yearly workshops of W119 in previous years had a broader scope (e.g. focus on settlements, etc.) regarding the application of automation, robotics technology, and advanced prefabrication solutions in the context of built environment, the 2019 workshop focussed on **Automation and Robotics in Construction**. Robotic solutions along the construction value chain and the major phases of the actual construction process (component production, logistics, prefabrication, on-site construction, maintenance, etc.) are gaining on a worldwide level more momentum. W119, therefore, saw a need to reflect this with the topic of this year's workshop.

The contributions to this year's workshop cover key aspects of future automated and robotic construction such as logistics (***Smart lift control and monitoring for super high-rise building construction project***), building exterior finishing (***Developing a roadmap for implementing on-site construction automation and robotics in Hong Kong***), the analysis of work procedures (***A non-intrusive method for measuring construction workers' muscle***) as well as tools for strategic foresight and requirements engineering (***System boundaries of implementing construction robots for buildings***).

As of late, the development of "hard" physical-mechanical robots and automation systems for the execution of construction tasks are gaining increasing interest. This manifests itself in an increase in academic research activity, joint industry-academia collaboration projects, the emergence of start-ups and a strong and growing interest of large, established organisations. W119 and the contributors to this workshop are dedicated to support further market uptake of such solutions with their research and development activities.

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This workshop proceedings contain the final author versions submitted to the CIB World Building Congress 2019. All articles originally appeared in the official proceedings of the CIB World Building Congress 2019 which can be accessed through www.cibworld.nl.

Smart Lift Control and Monitoring for Super High-rise Building Construction Project

Jihwan Park,
Department of Convergence Engineering for Future City, Sungkyunkwan University
(email: wlghks442@skku.edu)
Joonghwan Shin,
Department of Convergence Engineering for Future City, Sungkyunkwan University
(email: kiwijoa@skku.edu)
Soonwook Kwon,
School of Civil & Architectural Engineering / Dept. of Convergence Engineering for Future City, Sungkyunkwan University
(email: swkwon@skku.edu)
Seojun Lee,
Department of Convergence Engineering for Future City, Sungkyunkwan University
(email: sjlee3003@skku.edu)
Jinwoo Song,
Department of Convergence Engineering for Future City, Sungkyunkwan University
(email: wls171@skku.edu)

Abstract

As the height and size of urban buildings constructed in cities in Korea have recently increased, vertical lift planning and operation is a key factor for the successful project of a tall building. Although many studies have attempted to set up a lift planning system at an early stage, a real-time lift operation control system with respect to the construction stage has yet to be proposed. Therefore, in this study, the sensor module and storage device was used to collect the lift operating data for improvement of lift operation efficiency in order to develop an optimum lift operating analysis system which could perform real-time analysis. Finally, the pattern of operation data of the lift was analyzed and the lift event of the next day was derived. In addition, we verified the efficiency of the proposed optimum vertical zoning simulation system using the expected lift event extracted from the operation history data pattern. In this paper, the proposed system provides more efficient vertical zoning alternatives for the lift manager. This simulation based decision making tool reduces the user's queuing time compared with the previous system. This system is expected to contribute to high-rise building construction of over 400m.

Keywords: Construction lift, High-rise building, Vertical lift zoning, Sensor, Tabu search

Introduction

Over the recent few years, the number of high-rise building constructed worldwide has increased significantly. More than 100 buildings with the height of over 300 m have already been constructed and about 100 projects are under construction. While the standards for defining high-rises differ, the Council on Tall Buildings and Urban Habitat (CTBUH) defines 'super tall' and 'mega tall' buildings as buildings with the heights over 300 m and over 600 m, respectively.

Despite the construction trend, many problems still exist in the planning and execution of high-rise construction. Generally, the problem of high-rise construction is paradoxically caused by the height of a building. Due to the height of the building, the length of the conveyor line increases, causing the overall time for the construction of the project, including structural work and finishing work, to increase exponentially.

A moving plan is established based on the prediction of the lifting load and selects the variable such as the number of lifts, lift specification, and rental period in advance of the project start. On the other hands, movement operation is the management technique used as the number of floors of the building under construction increases. Thus, it is important to carry out lift monitoring of status or operational support based on the sensor network technology when worker and material lifting is performed, along with planning for variables such as the number of cages, installation location, and the time of installation/disassembly. According to the data for the projects involving the construction of seven high-rise buildings in Korea and abroad, lift plans were created based on the criterion of the average lifting frequency of 0.23 ~ 0.28 times/㎡. However, the existing floor area based plan was not obtained for operation management after the beginning of the construction.

For the adjustment of the lift operation plan in the field, where the finishing work process has already started, it is not feasible to modify the selection of the lift, the location of its installation, or the lift rental period. Therefore, an optimization of the control in the limited physical resources environment is the most suitable method for maximizing the efficiency of worker and material lifting.

Research Scope & Method

This study focused on a method for establishing a vertical operating zone based on the monitoring of the operation for a construction lift used to lift the finishing materials for a high-rise building. The lift operation history was created in a database by monitoring the sensor-based lift operation in real time, analyzing the performance data patterns from which they are derived and predicting the next day operation based on the analyzed data.

Values of the expected results of operation derived by the analysis of the pattern of operation performance data were adjusted according to the information obtained after finishing the planning of the process management of the expected lift operation for the following day. On the day after the analysis of the operation performance pattern was performed and after reviewing the finishing work process information, the predicted lifting case data were entered in the simulator. Here, the variables for the vertical operating zone were generated. An alternative for the vertical operation zoning with the obtained values of optimal efficiency (time of performance when performing the least lift operations) was then acquired.

The procedures used in this study were as follows;
1) The current status of vertical lifting was identified by examining previous studies. Furthermore, the

existing analysis used for lift management and its problems were identified.
2) Lift operation performance data patterns based on internally installed lift monitoring were analyzed, and the validity of our approach was verified based on the results of the analysis. These results were used as the predicted results of operation for our vertical operation zoning simulation.
3) Lift operation performance data and methods for the revision of the progress schedule were suggested for the predicted lifting case for the day following the day of the analysis.
4) Vertical operation zoning simulation was implemented based on the suggested method for the predicted lifting case, and the efficiency of this system was verified.

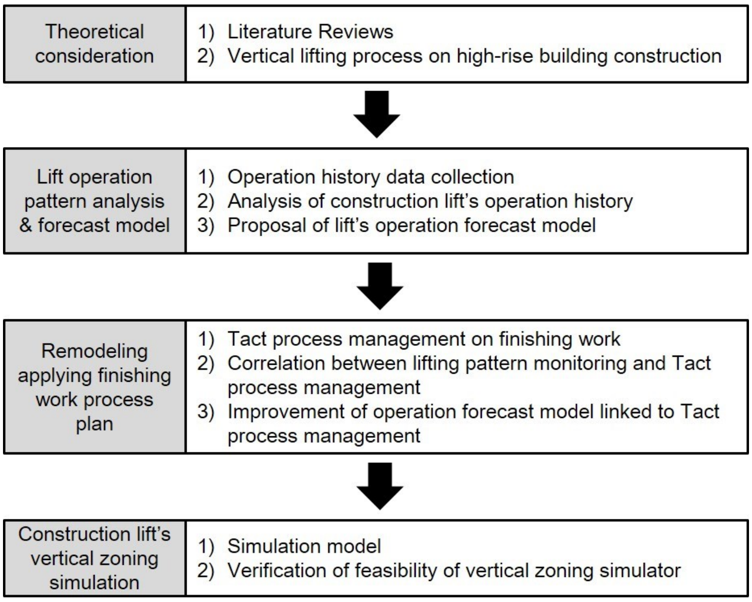


Figure 1: Research method

Literature Review

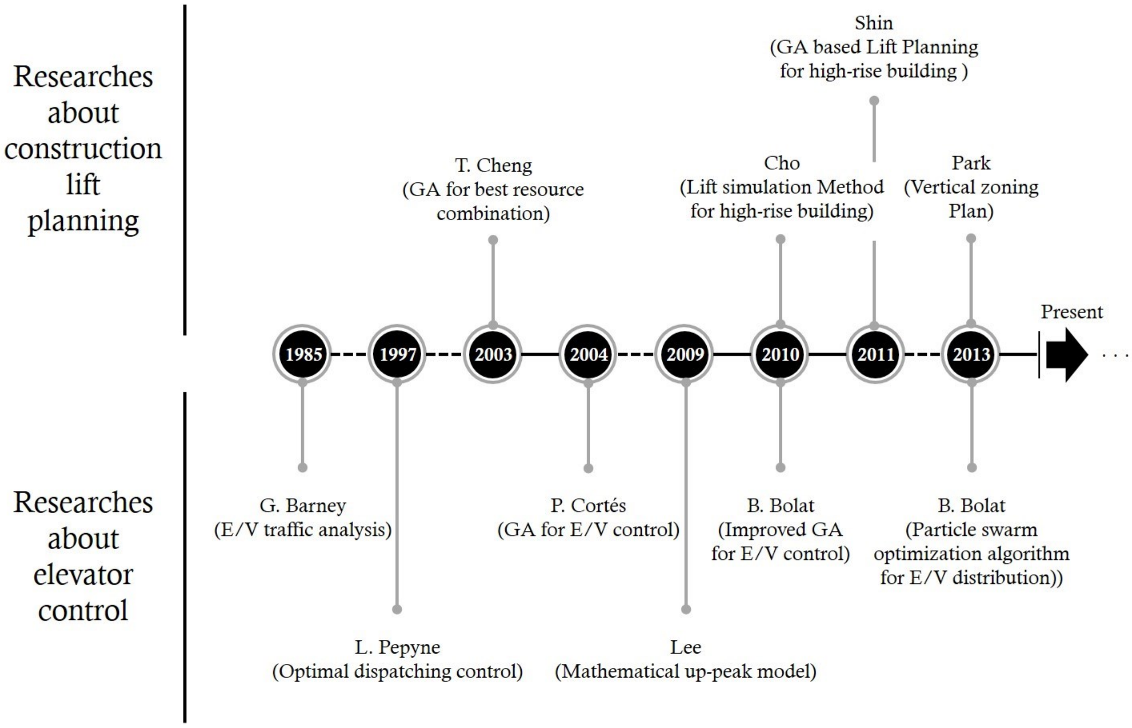


Figure 2: Research history related to vertical lifting

Figure 2-1 shows the main research flows related to vertical lifting. The history of studies on elevator control techniques and studies on construction lift management are very deeply related. The mathematical computation and optimization techniques used in elevator control system have been steadily expanding into the construction lift area for the past 30 years. Recently, there is a growing research on construction lift management technique using mathematical algorithms as buildings have been getting high and larger.

As super high-rise construction has become more popular in Korea, there has been a growing need for systematic construction planning and site management. The government and private corporations are actively undertaking studies on the operation planning for construction hoists and tower crane lifting. Kim et al. studied the methods for calculating the number of the construction hoists required at a super high-rise construction site (2008), and Shin et al. (2010) proposed a construction hoist movement planning model for super high-rise construction. Cho et al. (2011) proposed an algorithm that calculates the lifting time by considering the acceleration and deceleration capability of the construction hoists (2011). While many studies of the construction hoist planning have been reported, few studies have been conducted on the system, management and algorithm of construction hoist operation, and in particular, no empirical analysis has been reported.

In an investigation of the vertical zoning of the construction lift used for a high-rise building, Park (2013) suggested a zoning method for lift operation using genetic algorithm and insisted that the lifting efficiency could be improved by establishing a lift operation zone at the high-rise building construction project. Similar to Park's work (2013), Moon (2013) described a transfer lift operation system based on discrete event simulation. Both meta-heuristic and simulation-based advanced vertical zoning methods showed that the zoning system can positively affect the time and budget required for high-rise construction. However these studies were performed only for a single day with fixed workers' lifting load that had been determined in the planning phase. This approach is limited because simulation for specific days during the construction is performed with the previously estimated lifting loads and does not consider the dynamic construction performance changes during the finishing work time period. The project conditions including the top floor of the building and the lifting loads for each floor may change during construction.

Embedded Lift Information System (ELIS)

Encoder based position sensing

The encoder sensors are mainly used for layer recognition by checking the number of rotations of the rack gear. The method of checking the number of revolutions is appropriate for detecting the current position of the lift car. However, the direction of movement cannot be determined.

Therefore, another challenge in establishing a lift sensor system was to develop a method for determining the direction of travel. For the existing encoder, the lift is operated and the external gear that meshes with the rack gear is connected to the gear inside the encoder and one proximity sensor is installed so that the pulse value is measured while reading the groove of the internal gear in order to determine the stopping position of the lift.

The double sensor type encoder developed in this study can recognize the direction of the upward and downward movement of the lift, so that it can determine the direction of the movement after the lift stops at the target floor. Figure 3 shows a schematic of the double sensor type encoder and the graph showing the pulse value obtained by the encoder.

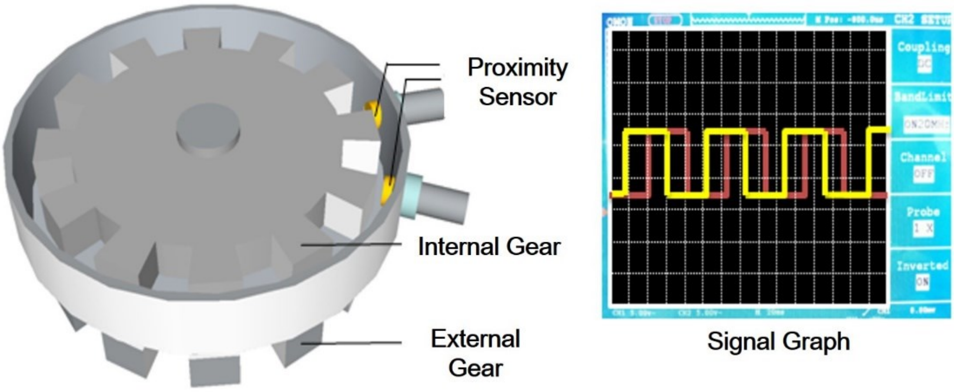


Figure 3: Encoder based position sensor(Shin, 2017)

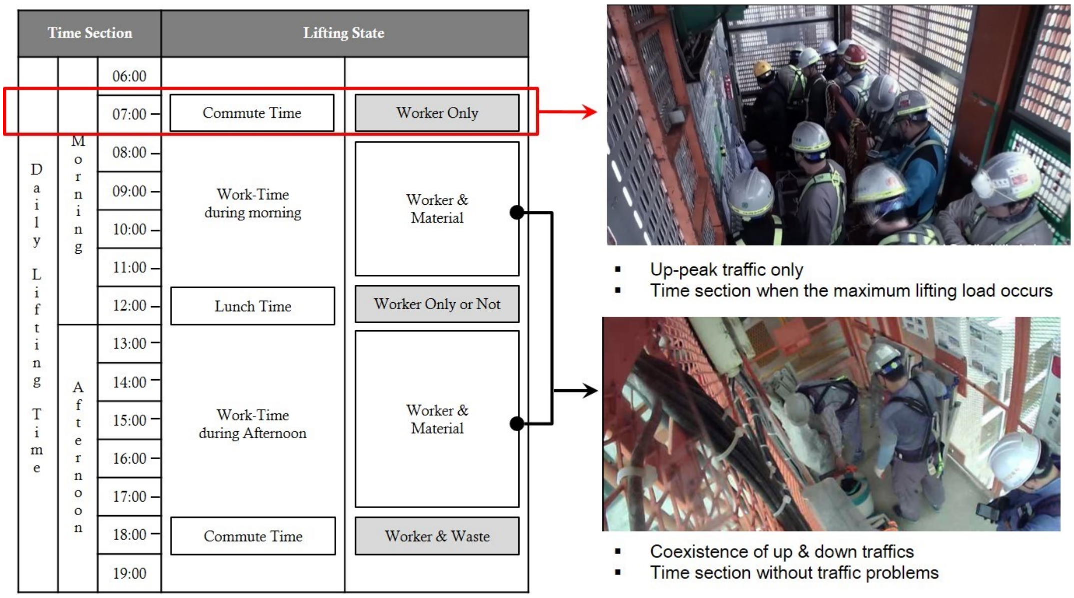
As shown in Figure 3, the double sensor type stop position sensing device obtains two pulse values using two proximity sensors. The operation status varies depending on the layer type of the two side signals. Therefore, the graph showing the pulse values also shows the intersection of the two curves, and the order of occurrence is known, so that the direction of the lift movement can be determined.

Camera based helmet sensing

Construction lifts vary in their characteristics during the construction period and during the daytime also. This study suggests a model to improve the efficiency of the lift operation stage based on the work load of morning commute time according to the progress of high-rise construction. The area of the morning commute time zone highlighted in Figure 4 is the time zone where up-peak traffic of worker load is concentrated among the site material and worker load. It is also the most traffic-intensive time of day.

In this research, a device to check the number of workers carried up by construction lift was developed to expand function of ELIS to vertical zoning analysis. Deep learning-based image detection technology has been chosen as an alternative to counting the number of workers in the lift cage by counting helmets worn by workers.

It is necessary to look at various image-detection and deep-learning technologies as open source considering the environment inside the construction lift-car, where frequent visibility redundancy occurs. Deep-learning based computer vision is the core technology to record object state changes inside the lift-car.



- Up-peak traffic only
- Time section when the maximum lifting load occurs

- Coexistence of up & down traffics
- Time section without traffic problems

Figure 4: Basis for target section of analysis

Considering the characteristics of the lift-car at which the internal conditions change from time to time, the accuracy of processing results, and the speed, we selected the YOLO(You Only Look Once) as the image detection technology. The image detection procedure using YOLO for our system is as follows.

(1) Generating image frame group sampling for analysis
(2) Runs a single convolutional network on the image
(3) Thresholds the resulting detections by the model's confidence
(4) Moves the frame group and repeats the processing analysis

Table 1: Example of object detection methods(Ko, 2018)

R-CNN	Testing time per image 50 seconds. The mean average precision (mAP) for each query is of 66% on VOC 2007 test-dev.
Fast R-CNN	It builds on previous work to efficiently classify object proposals using deep convolutional networks. Achieves near real-time rates using very deep networks, at 2s per image. Multi-scale design based on anchors, computed on a single-scale image.
Single Shot Detectors (SSDs)	The SSD approach is based on a feed-forward convolutional network that produces a fixed-size collection of bounding boxes and scores for the presence of object class instances in those boxes, followed by a non-maximum suppression step to produce the final detections.
You Only Look Once (YOLO)	It processes images in real-time at 45 frames per second. On a Pascal Titan X it processes images at 40-90 FPS.

Data processing for operation history

The existing predicted load and operation time of the lift have been made by scheduling with cooperative firms that deal with each of the materials. The expected average lifting frequency and timing of the combined materials per day are reflected on the plan for vertical operation zones. However, since it is not feasible to identify operation situations at every time of the process while the project is in progress, it is impossible to apply lift plans established in the planning stage and current situations at the same time.

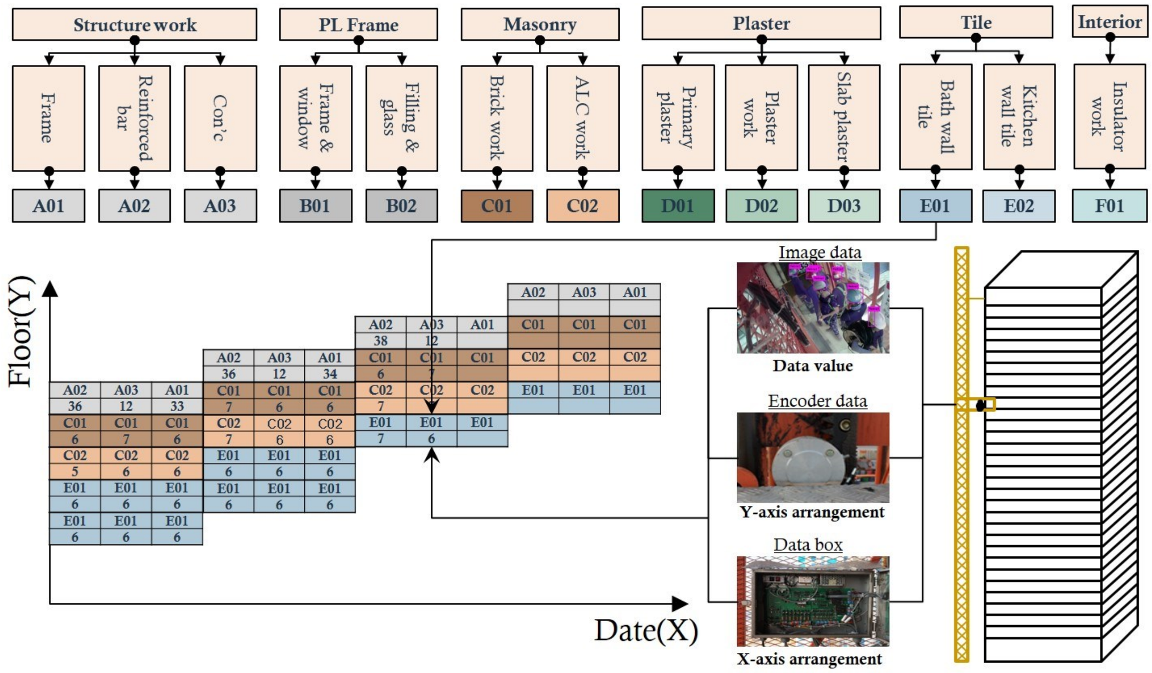


Figure 5: Data accumulation and work-activity based patterning

Therefore, this study shows the operation patterns of the lift in the current process of the project in a diagram shown in Figure 5. The data flow was systemized to make it convenient for a manager to analyze current situations. In addition, the vertical zoning simulation inputs were utilized.

The worker lifting load for each lifting event obtained from the camera image data is determined on the y-axis along the vertical position information written in the encoder data, and the y-axis position is determined along with the date information of the data storage & processing box. According to the work schedule of the building, it is possible to set the background of the floor work activity placement on each construction day, so that it is possible to quickly match the alighted workers to the activity code according to the encoder sensor and the data box record.

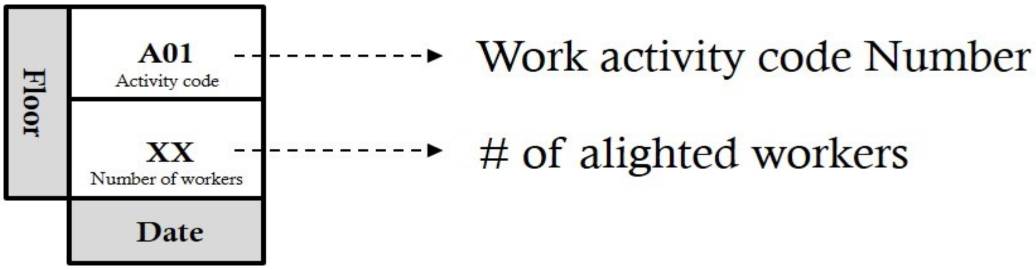


Figure 5: Data accumulation and work-activity based patterning(Shin, 2017)

According to the characteristics of the process of finishing work, where repetitive processes are vertically connected to coincide with work continuity, the operation history data module shown in Figure 3-13 can be used as an efficient tool for examining the current progress compared to the target process by adding objective data-based trend information from the manager on the monitoring of finishing work.

The target for image detection is a helmet, to count the number of workers on the construction lift and the number of workers aboard each floor. Because all person on the construction lift wear the safety helmet, the helmet-targeted counting is more effective than counting the shape of a person.

Optimal Vertical Zoning Analysis

Vertical construction lift zoning

In addition, as the number of high-rise buildings being constructed has increased, the daily amount of transported materials has also increased. In addition, most of the skyscrapers were built in the form of set-back type due to the issue of slenderness ratio. Therefore, the division and setup of lift operation zones has become an inevitable factor as shown in the domestic case in Figure 6.

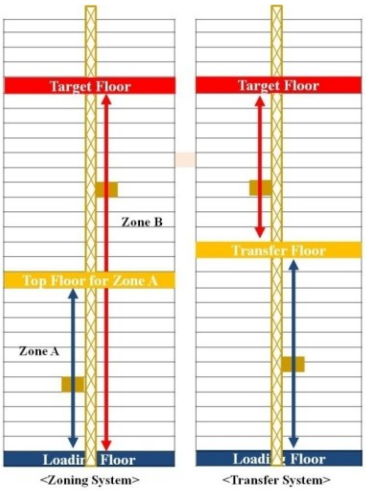


Figure 6: Type of vertical lift zoning(Shin 2017)

Meta-heuristic based search method

This research selected a method to collect data directly from the by sensor on the construction field in order to improve the limitation of existing heuristic based approach. And this adopted a meta-heuristic approach to solve the problem of having various variable of vertical lift zoning environment.

Tabu search is a meta-heuristic search method employing local search methods used for mathematical optimization. A local(or neighborhood) searches take potential solution to a problem and check its immediate neighbors in the hope of finding an improved solution. Local search methods frequently have a tendency to become stuck in local optimization. The implementation of tabu search uses memory structure that describe the visited solutions or user provided sets of rules(F. Glover, 1989). If a potential has been previously visited within a certain short-term period or if it has violated a rule, it is marked as 'tabu(forbidden)' so that the algorithm does not consider that possibility repeatedly.

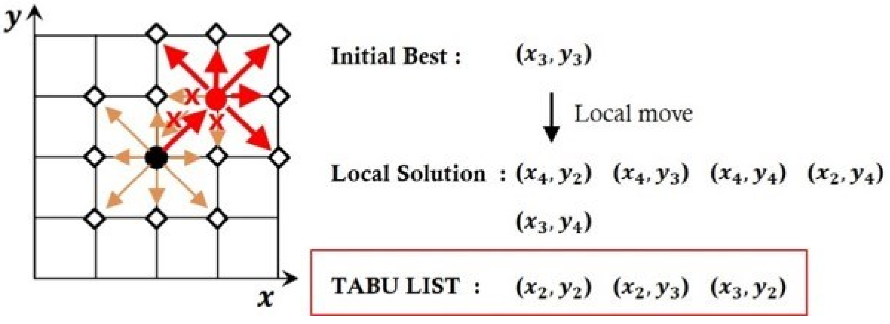


Figure 7: Type of vertical lift zoning

Case project based verification

Table 2: Lifting load on case building project

Floor	Height(m)	Number of workers	Construction progress
33F	167.6	6	
37F	184.0	8	
38F	188.2	24	
42F	206.9	16	
43F	211.3	16	
49F	233.5	9	
55F	255.7	12	
56F	259.4	24	
57F	263.1	4	
61F	277.9	59	
69F	307.5	74	
Over 80F	343.7	327	
Total		579	

Table 6-3 show the number of workers for each floor. As mentioned above, the number of workers heading to over 81th floor is assigned to the 80th floor on the simulation, since it is necessary to make the transfer from 80th floor.

The existing method without vertical lift zoning takes approximately 1 hour and 30 minutes to transport the entire workers at the commute peak-time. Not only the time to move the long travel distance but also the number of stopping point laying on the long vertical line is also a main factor in increasing the total cycle-time.

Table 3: Lifting load on case building project

Lift No.	Capacity(# of passengers)	Initial	Phase 6	Phase 16	Phase 28	Phase 38	Optimal
Lift 1	22	33-80F	38-80F	43-80F	55-80F	55-80F	55-80F
Lift 2	22	33-80F	33-80F	43-80F	55-80F	55-80F	55-80F
Lift 3	22	33-80F	33-80F	33-80F	45-80F	55-80F	55-80F
Lift 4	22	33-80F	33-80F	33-80F	33-80F	33-80F	33-69F
Lift 5	22	33-80F	33-80F	33-80F	33-80F	33-80F	33-69F
Lift 6	22	33-80F	33-80F	33-80F	33-80F	33-80F	33-80F

Lift 7	33	33-80F	33-80F	33-80F	33-80F	33-80F	33-80F
Lift 8	33	33-80F	33-80F	33-80F	33-80F	33-80F	33-80F
Total required cycle-time(sec)		5367.6	5352.8	5095.0	4559.1	4489.8	3306.2

The total cycle-time of the initial solution without vertical zoning is 5367.6 sec (1hour &30 min), and the total cycle-time of optimal solution is 3306.2 sec (55 min). Through the vertical zoning optimization search, the total cycle-time for entire lifting was reduced by 35 min.

Conclusion

As more high-rise buildings are being constructed in Korea, and the limits on the maximum floors lifted increases, the variables applied to the management of finishing work construction have become more complicated. Therefore, operation management of the lift is needed for the construction period following the implementation of the finishing work process, along with a decision-making procedure on the transport-circulation of finishing materials that are appropriate for flexibly adapting to the changing situations in the field.

Therefore, in this study, the operation history information was saved from the sensor attached to the lift through the development of Embedded Lift Information System (ELIS), which analyzes the operation pattern of the lift in the field. The expected operation for the following day was based on the lift operation patterns from a four-day cycle using the tact technique, and optimal vertical operation zones were established using a vertical zoning simulator.

In addition, the effect of the reduced standby time for users has been verified by development software simulation on the lift operation performance of an actual high-rise building project. The effectiveness of the suggested system was then reviewed. The result suggested that the system in this study is effective as it enables a reduced standby time for users in the scope of the same cases for request of a condition. Data as a basis in the suggested system were collected from sensors installed in the field for the purpose of comparison.

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Developing a roadmap for implementing on-site construction automation and robotics in Hong Kong

Wen Pan,
Technical University of Munich
(email: wen.pan@br2.ar.tum.de)
Rongbo Hu,
Technical University of Munich
(email: rongbo.hu@br2.ar.tum.de)
Thomas Linner,
Technical University of Munich
(email: Thomas.Linner@bri.arch.tu-muenchen.de)
Thomas Bock,
Technical University of Munich
(email: Thomas.Bock@bri.arch.tu-muenchen.de)

Abstract

For a long time, the conventional construction sector in Hong Kong has been perceived as old-fashioned and lagging behind compared to many other industrial sectors. Numerous challenges are facing the construction industry, such as diminishing productivity, unstable quality, increasing demand, as well as population aging and shortage in the local labor market. One possible solution is to identify and deploy the state-of-the-art technologies that could potentially be implemented in the Hong Kong construction industry. Many studies have been documented about the design and development of a specific construction robotic system. However, there is limited literature on how to investigate the implementation and integration of a range of proposed systems in a specific, local context, and to evaluate the process and impact from short-term, mid-term, and long-term perspectives. Based on the on-going consultancy project commissioned by the Construction Industry Council (CIC) in Hong Kong, this paper demonstrates the method adopted in proposing a systematic approach as well as the development of a comprehensive roadmap for implementing on-site construction automation and robotic technologies in the context of Hong Kong. In general, the proposed roadmap, which is structured based on the reviews of the current situation in Hong Kong's construction industry, will evaluate short-term and mid-term practical strategies and action plans. Furthermore, it will forecast a long-term perspective, aspirations, and potential business strategy. The activity of road-mapping is extended with the objective to mitigate existing risks and barriers, and to plan ahead. Eventually, it will serve as a guideline for the construction industry in Hong Kong and beyond to execute similar types of projects in the future.

Keywords: Consultancy, Construction automation and robotics, Hong Kong, on-site, roadmap

Introduction and background

Facing the challenges of an aging workforce, high demand of public housing, and stagnant productivity, the Hong Kong construction sector needs a more productive approach to deal with these issues. Recently, the manufacturing industry has successfully adopted automated production facilities and overall production efficiency has been boosted by utilizing industrial robots. In contrast, the degree of automation in the construction sector lags behind. The implementation of construction robotics and automation may hold the key to solve the aforementioned challenges. In light of this, the Construction Industry Council in Hong Kong (CIC) commissioned the Chair of Building Realization and Robotics (br^2) at Technical University of Munich (TUM) to develop feasible construction robotics and automation strategies that are tailor made for the housing development in Hong Kong. This paper aims to construct a comprehensive roadmap for implementing on-site construction automation and robotics in Hong Kong. The proposed roadmap is classified as a technology roadmap that is based on the on-going CIC project, focused on the Hong Kong Public Housing Construction (PHC) sector that demonstrates the research objectives, methods, holistic analysis action plans, project phases, and milestones that provide guidelines on how to execute the project in a short-, mid-, and long-term basis.

In general, the Hong Kong construction market is at its most active, yet stable, stage. It is expected that the ongoing and upcoming large-scale public infrastructure projects will help keep the number of construction projects in Hong Kong maintained at its current high-level. These key public projects cover the bridge, highway, commercial area development, and public housing, one of which is the long-term public housing supply plan for 480,000 units over the next 10 years (Census and Statistics Department, 2016). According to Frost & Sullivan, a global consultancy firm, the scale of the construction engineering market in Hong Kong is expected to reach 173.2 billion HK dollars in 2020. However, it cannot be ignored that some constraints and trends appear to influence future project implementation, in spite of a seemingly prosperous market (Financial Times, 2015). The predominant constraints facing the Hong Kong PHC sector include the aging workforce, skilled labor shortages, high construction costs, and increasing property prices. The government is attempting to explore the possibility of implementing construction automation and robotic strategies in the rather conservative construction industry. However, the construction project is completed and each has a set of unique requirements and goals that differ from one to another. This is due to the intricacy of the construction projects as well as various stakeholders who acquire a specific interest in the project. Hence, implementing robotic technology in an on-site construction environment is remarkably challenging. Consequently, to plan ahead and to have a systematic strategy in place will be extremely beneficial for the stakeholders.

Research objective and questions

The construction sector bears a cross-disciplinary characteristic whereby many stakeholders coexist and collaborate with each other. This trend will be intensified once automation and robotic technologies are introduced. The main objective of this paper is to review the works that have been completed in the first phase of the CIC project. On the other hand, the project roadmap demonstrates the work tasks that will be carried out in the follow-up projects. The proposed roadmap provides a detailed guideline that illustrates the methods that will be used in resolving technological, social, economic, and political factors. It can be used by the stakeholder while either preparing or conducting a similar project. It will become a useful tool which can capture and communicate the outputs from the strategic planning stage towards the final implementation stage (Holmes et al., 2004).

Many studies have been documented about the design and development of some specific construction robotic systems. However, there is limited literature on how to investigate the implementation and integration of a range of proposed systems in a specific local context, and to evaluate the process and impact from short-term, mid-term and long-term perspectives. In order to fulfil the research gap and to achieve the aforementioned objectives, the following research questions will be addressed:

- How to conduct the initial phase of such a project given that the industry and stakeholders are not familiar with the proposed technologies?
- How to identify key technology drivers and barriers in regards to the proposed technologies?
- What is the most suitable timeframe for implementing the proposed technologies?
- What are the main responsibilities of the stakeholders?
- How to deliver the proposed technologies from the conceptual stage to the dissemination stage and beyond?

Method

The roadmap was developed based on the data collected from Hong Kong PHC contractors, local authorities, consultants, architects, academics, and Non-Governmental Organizations (NGOs). The roadmap aims to give an introduction of the construction automation and robotic system, as well as to identify the technology drivers, facilitators, and responsibilities. The roadmap also provides detection of unforeseen barriers, feasible solutions, as well as recommendations for action plans. This section will provide an overview of relevant technology roadmap literature, state-of-the-art technologies, data collection methodology, requirement identification, system selection, and risk prediction.

Literature review

In general, technology roadmap is often presented as a creative analytical tool that predicts, analyzes, and visualizes the future development of products, technologies, markets, and services (Specht and Behrens, 2005). The literature review indicates that; in regards to the implementation of on-site construction automation and robotics, the topic of roadmapping is scarcely documented. However, the integrated method in technology roadmapping is widely available. For instance, the generic methods documented consist of the roadmap which is a visualization tool that can identify a process or an application (Bucher, 2005). On the other hand, some roadmaps are illustrated based on scenarios (Lizaso and Reger, 2001) and portfolios (Farrokhzad et al., 2005). A knowledge-based method proposed by Reger (2001) and the decision-making oriented roadmapping in decentralized control of the business operation proposed by Petrick and Provance, (2005) are considered to be highly valuable for the research. In addition, the most relevant to our research is the paper of Lischka and Gemunden, (2008). The authors applied a systematic approach that identified best practices in operative technology roadmap implementation. We have considered the methods analyzed by Lischka and Gemunden, (2008) and they will lay a good research groundwork for our studies.

The general purposes of technology roadmapping application can be summarized into eight types according to Kappel (2001), Phaal et al. (2004), and categorized by Golinska-Dawson et al. (2018).

Table 2: Roadmapping types (Source: Golinska-Dawson et al. 2018)

Type 1	Product planning
Type 2	Service/capability planning
Type 3	Strategic planning
Type4	Long-range planning

Type 5	Knowledge asset planning
Type 6	Program planning
Type 7	Process planning
Type 8	Integration planning

In this paper, due to the nature of the research topic, the proposed roadmap can be classified as a combination of all eight types (Table 1), yet mainly focuses on the following types: Type1; Product planning, where roadmaps are used to link planned technology and product development. Type 3; Strategic planning, where roadmaps are used to support the evaluation of different opportunities and threats. Type 5; Knowledge asset planning, where roadmap links the skills, technologies, and competencies required to meet future market demands. Type 8; Integration planning, where roadmap focuses on integration and evolution of technology and shows how different technologies can be combined to form new technology or systems (Golinska-Dawson et al., 2018).

In terms of technology development or innovation, one of the most influential concepts is to use the innovation S-Curve to determine technology performance in regards to time and effort (Figure 1). For example, the performance of a new emerging technology rises when more effort and time are spent on engineering activities. At the same time, the value of the performance decreases for the current technology. Furthermore, in regard to technology life cycle, there are four stages which include ferment, take-off, maturity, and discontinuity (Lischka, and Gemunden, 2008). Thus, the innovation S-Curve assists companies in deciding the right sequence of technologies, determining the level of maturity of the technologies, and most importantly, when to invest in the new technologies (Petrick and Echols, 2004).

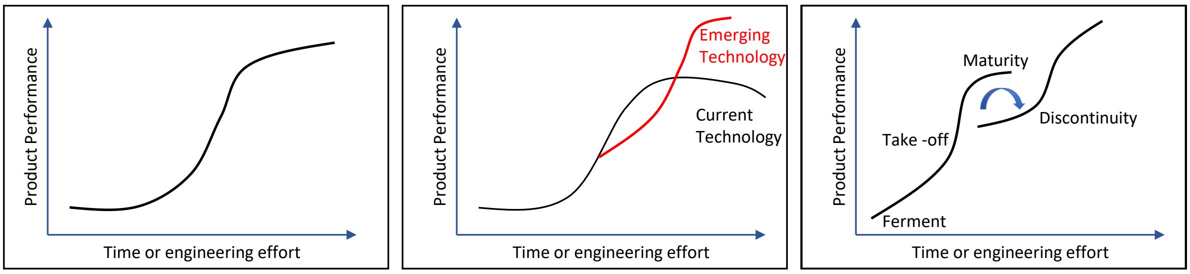

Figure 1: Innovation S-Curve

Table 2. Characteristics of layers of technology roadmap (based on Golinska-Dawson et al., 2018; Phaal and Muller, 2009; Phaal et al. 2005)

Layer	Sub-layer	The main obstacle	Qualifying question
L1: Market drivers	Market, Customers, Competition, Trends, Risk, Strategies	The fundamental Purpose	KNOW WHY?
L2: Product/ Process	Features, Functions, Services, processes, System Integration, Capabilities	The mechanism that achieves the purpose	KNOW WHAT?
L3: Technology/Resources	Technology, Competences, Knowledge, Infrastructure, business model, Research and Development (R&D), Collaboration, projects	Everything that is required to be developed	KNOW HOW?

The layers of the roadmap (Table 2) demonstrate some crucial topics that need to be analyzed in detail. The L1 is focused on market, customer relation, and social aspects of the roadmap. The L2 is concentrated on what type of functional requirements need to be developed that enables product or project success. The L3 defines what resources are required to achieve the predefined goals successfully (Phaal et al., 2005). In order to provide sufficient information that is required by those layers, a survey, site-visit, and co-creation workshop was organized. The outcomes of those activities will be described in a later section.

State-of-the-art technologies

Due to the research scope of the CIC project, only On-site Construction Robotics (OCR) will be discussed in this section. During the 1980's, the Japanese construction sector put huge investments into R&D for developing construction robots and automated construction sites. At the time, a shortage of skilled labor; a result of the aging society, had been a major concern in the Japanese construction industry (Kangari and Miyatake, 1997). Approximately 150 Single Task Robots (STR) were developed. Through research and development (R&D), prototyping, and on-site testing, the early pioneers have gained an understanding of the advantages and constraints of applied construction robotic systems over the years (Cousineau, 1998). The most influential OCRs that were developed for the similar market include the interior painting robot developed by French company, Les Companions (Les Companions, 2018), the ceiling drilling robot developed by Norwegian company, nlink (nlink, 2018), and the OutoBot for high-rise building external wall painting application developed by Singapore Nanyang Technological University (NTU, 2017). However, most of the systems are still under development and remain confidential. Therefore, limited information regarding the systems is available.

Data collection

The current CIC consultancy project has been divided into five phases. The first phase is initial research and pre-selection that aims to introduce construction automation and robotic technologies and to brainstorm feasible strategies for Hong Kong PHC. The second phase consists of on-line surveys and on-site visits, which identify stakeholder requirements and clarify the research direction. The third phase is co-creation workshops that identify priority areas and narrow down the research scopes. The fourth phase works on the concepts of development, detailing, and finalization of the selected system. The fifth phase includes a final demonstration of the system, construction of the demonstration mock-up, validation of the design, and planning for future work as well as recommendations for future development (Pan et al., 2018).

The third phase; co-creation workshops, is to be considered the most influential stage for this paper. The co-creation workshops were organized with the objective to gain practical feedback from the industry experts. The main objectives are, first, to evaluate market drivers, technical feasibility, and barriers to the implementation of the proposed technologies. Second, to identify product functions, working processes, and compatibility of the proposed technologies. Third, to identify functional and non-functional requirements, as well as to strategically map out plans and actions for the near feature. TUM and CIC have organized two Technical (T) Sessions and two Policy (P) Sessions. Over 40 participants joined the workshops who were from various disciplines including governmental representatives, property developers, contractors, architects, academics, consultants, and industry experts. The workshops evaluated how to implement appropriate technologies for the selected on-site tasks, in which socio-technical issues, work organization, safety concerns, financial implications, skill requirements, and regulation-related topics were discussed. In conjunction to this, the potential concerns and opportunities during the implementation of the proposed systems were examined. Subsequently, guidance and potential approaches were forthrightly discussed in terms of how to address economic, managerial, social, and political issues when introducing automation and robotics to the PHC sector. The outcomes from the workshops were presented to the CIC Committee on Productivity. The workshops were an important milestone of the consultancy project and the data was used to formulate the roadmap on adopting on-site construction technologies in Hong Kong (Pan et al., 2018).

The proposed technologies

Based on the output from the workshops, six high-priority areas were identified, which include Façade work and exterior work, Interior painting and plastering, Hoist and positioning, Automated formwork, and Automated on-site welding. In addition to this, three medium-priority areas were diagnosed: Mechanical and Electrical work (M&E), Inspection work, and On-site logistics. According to the investigation, the aforementioned on-site tasks need to be improved drastically to meet the current demands.

After several rounds of discussion amongst the stakeholders, the project team decided to use the façade and exterior work robot development as the lighthouse project. This was due to the following reasons 1) it addresses stakeholder requirements, 2) it provides a good background study that lays the foundation for future follow-up projects, 3) it is feasible to achieve both technologically and financially. The multifunctional façade and exterior finishing robot is designed as an extension of a suspended working platform system. The robot system consists of the main frame, interchangeable end effectors, servo motors that allow five degrees of freedom, sensors, and control systems. The main design goal is to achieve a fully or semi-automated façade processing robotic system that requires minimal human guidance, is multifunctional, and can operate in all weather conditions. The detailed design of the robot is completed, together with a 1:2 scale mock-up that was constructed, and is currently being featured at the Construction Innovation and Technology Application Centre (CITAC) Hong Kong since the 22nd of November, 2018.

Risk identification

During the research, potential risks were identified that will directly or indirectly affect the implementation of the proposed technologies. Subsequently, a SWOT analysis (Strengths, Weaknesses, Opportunities and Threats) was carried out (Figure 2). The result demonstrates that the strengths and opportunities are greater than the weaknesses and threats. Thus, the proposed strategy is viable for investors. This section will focus on describing the identified weaknesses and threats.

The weaknesses include:

- High R&D cost: The R&D expenditure for OCR is in the range of at least 2 million euro. This is a huge research investment for the investors.
- Long R&D duration: The minimum research period form conceptual development to on-site testing normally takes between 3-5 years. This is significantly longer than the other industry e.g. the Business-to-business (B2B), whose product's development cycle takes an average of 2.7 years (Griffin, 2002).
- Low market awareness: The construction industry is not familiar with the proposed technologies. The industry is reluctant to change, in terms of building methods and design.
- Lack of infrastructure: The existing construction industry is under-equipped for the proposed technologies. There is no infrastructure to support OCR implementation.
- Lack of skilled labor: The current labor force in the existing construction industry is neither capable nor qualified for handling OCR operation on-site.

The threats include:

- Intellectual Property (IP) protection: Hong Kong has a very high standard of IP protection laws, whereas some project partners from Mainland China may not. Despite China’s efforts to improve and enforce IP rights, IP protection remains a major concern for businesses operating in Mainland China (Wang, 2004).
- Lack of finance: Construction automation and robotics is one of the most dynamic fields in construction engineering research. However, traditional sources of government private research funding for this field will likely remain insufficient due to unfamiliarity with the subject (Skibniewski, 1992).
- Policy: The existing housing policy and building regulations were drafted based on traditional construction methods, which will impose some constraints for construction automation and robotic transformation.
- Inadequate education and training: The mainstream academic research direction tends to emphasize market-driven theoretical teaching while is simultaneously lacking in interdisciplinary training. Consequently, limited cross-disciplinary knowledge transfer can be made in the field.

The aforementioned weaknesses and threats are thoroughly analyzed, and feasible solutions are developed in conjunction with the roadmap.

S	W	O	T
• Safety • Environmental • Quiet • Efficient • Quality assurance • High long-term return • Improve the image of the construction sector	• High R&D cost • Long R&D duration • Low market awareness • Lack of infrastructure • Lack of skilled labor	• Demographic change • Lack of labor • Increasing labor cost • Safety • Emerging markets • Large market potential	• IP protection • Lack of finance • Policy • Inadequate education and training

Figure 2: SWOT analysis

Development of the roadmap

The proposed project roadmap demonstrates the current CIC project that is almost complete, and the four follow-up projects (2A, 2B, 2C, 2D). The project roadmap describes the main phases, stages, and milestones that the follow-up projects need to go through in order to meet the future vision. The roadmap covers three time-spans (Initiation, Follow-up Development, Future Vision), and was divided into four milestones. At the time of this writing, the roadmap is only in its initial draft; the final roadmap will be drafted along with the key stakeholders, consortiums, and project partners (Figure 3).

The overall roadmap consists of four identified Milestones.

- Milestone 1 (Month 6): Completion of the design (2A).
- Milestone 2 (Month 12): Completion of the 1:1 mock-up, and tested under pilot projects (2A). Successful organization of the workshop (2D). Completion of the design (2B).

- Milestone 3 (Month 15): Completion of 2A, 2C project. Successful delivery of the proposed system to TRL 6-7 (2A).
- Milestone 4 (Month 21): Completion of 2B project.

Project 2A, further developing an advanced mechanized construction tool with robotic feature (the façade-processing robot): The objective of the 2A project is to finalize the proposed façade-processing robot based on the current development. The project team aims to bring the current design to Technology Readiness Level (TRL 7-8). A 1:1 scale functional demonstrator (mock-up) will be produced, ready for the on-site pilot project and testing. By the end of the 2A project, the proposed system will be fully functional, on-site tested and ready for market dissemination.

Project 2B, developing a fleet of construction robot mock-ups based on identified priority areas: The objective of the 2B project is to select appropriate systems that can be produced as scaled mock-ups with regards to the identified priority areas. The project team will conduct intellectual property related tasks, and initiate patent application.

Project 2C, training, standardization, and certification: In the 2C project, TUM will closely work together with CIC to develop the training and standardization program for operating and maintaining the robot system. Certification of operating and maintaining the robot system for the trained workers will be issued by CIC.

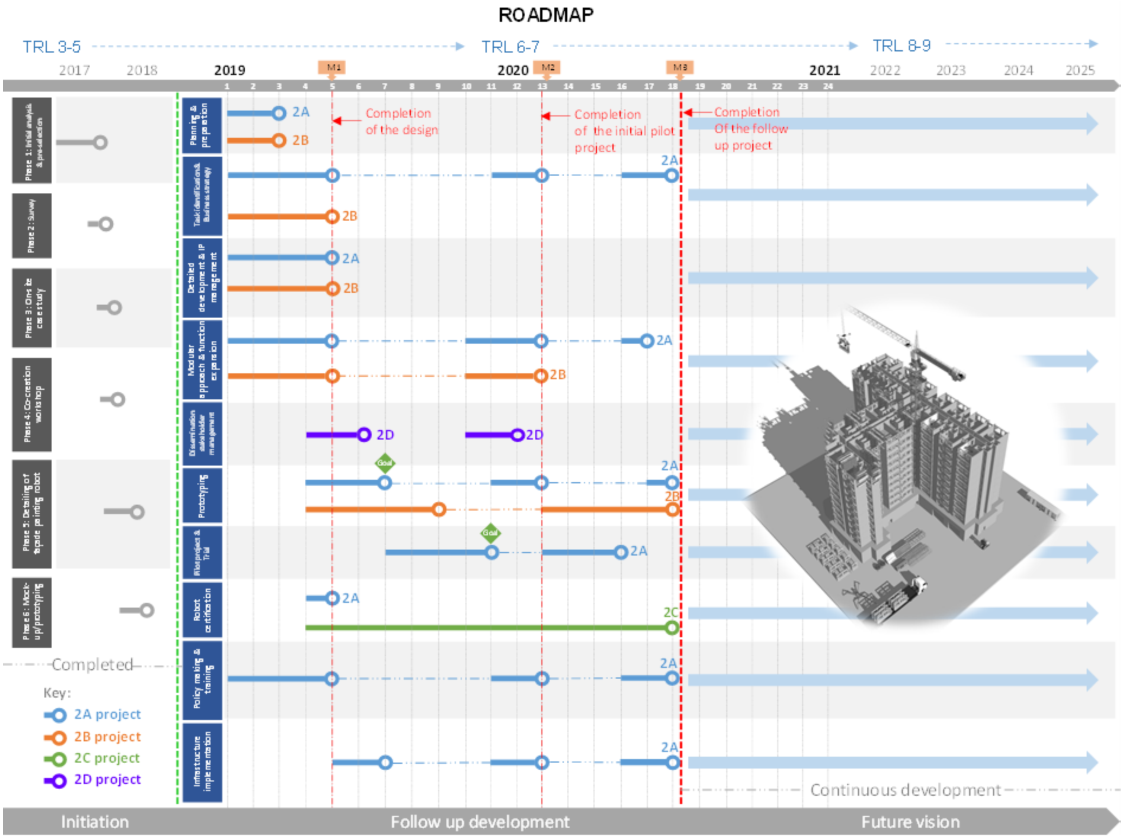

Figure 3: The proposed roadmap

Project 2D, dissemination stakeholder management: In the 2D project, TUM will work alongside with CIC in preparation of a two-day workshop. As proposed, the workshop consists of invited keynote speeches and roundtable discussions. The workshop focuses on the industry-driven research and technology transferring approach.

The objective of the future vision is to use the experience gained during the initiation and follow-up stages to build a case specific construction automation and robotic ecosystem that is tailor made for Hong Kong’s special characteristics in the next five to ten years.

Business strategy recommendations

Business strategies lead to design inputs and design requirements that need to be integrated into the robot design from the early conceptual stages onwards. In order to promote the technology of the facade robot system and its application, a synergy from all sides is necessary.

- The proposed robot system shall expand its volume of capability as long-term economic consideration
- Government must play a key role in providing incentive policies to initiate application
- CIC shall be an important general coordinator platform
- A novel form of service-oriented leasing center can be considered
- Cooperating with existing manufacturing fields will be a possible solution
- Accreditation scheme for construction robotics

Conclusions

This paper presented a systematic approach to develop a comprehensive roadmap for implementing on-site construction automation and robotic technologies in the context of the Hong Kong PHC sector. Through literature review, state-of-the-art technologies analysis, data collection, requirements generation, and risk prediction, a comprehensive technology roadmap for how to implement automation and robotics in Hong Kong PHC sector was developed. The proposed roadmap demonstrates the action plans, project phases, and milestones that provide guidelines on how to execute the project in various periods and under distinctive stakeholder requirements. However, there are also challenges imposed by the existing construction industry. The identified weaknesses and threats were evaluated and, through the development of the roadmap, feasible solutions were proposed to mitigate potential risks and barriers. The proposed roadmap provides a detailed guideline that illustrates the methods that will be used in resolving technological, social, economic, and political factors. It can be used by the stakeholders while either preparing, or while conducting a similar project.

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A non-intrusive method for measuring construction workers' muscle fatigue

Yantao Yu,
Department of Building and Real Estate, The Hong Kong Polytechnic University
(email: yt.yu@connect.polyu.hk)
Heng Li,
Department of Building and Real Estate, The Hong Kong Polytechnic University
(email: heng.li@polyu.edu.hk)
Arnold YL Wong,
Department of Rehabilitation Science, The Hong Kong Polytechnic University
(email: arnold.wong@polyu.edu.hk)

Abstract

The construction industry around the globe has unsatisfactory occupational health and safety records. One of the major reasons is attributed to high physical demands and hostile working environments. Construction work always requires workers to work for a long duration without sufficient breaks to recover from overexertion and to work under harsh climatic conditions and/or in confined workspaces. Such circumstances can increase the risk of physical fatigue. Traditionally, fatigue monitoring in the construction domain relies on self-reporting or subjective questionnaires. These methods require the manual collection of responses and are impractical for continuous fatigue monitoring. Some researchers have used on-body sensors for fatigue monitoring (such as heart rate monitors and surface electromyography (sEMG) sensors). Although these devices appear to be promising, they are intrusive, requiring sensors to be attached to the worker's body. Such on-body sensors are uncomfortable to wear and could easily cause irritation. Considering the limitations of these methodologies, the current research proposes a novel non-intrusive method to monitor the whole-body physical fatigue with computer vision for construction workers. A computer vision-based 3D motion capture algorithm was developed to model the motion of various body parts using an RGB camera. A fatigue assessment model was developed using the 3D model data from the developed motion capture algorithm and biomechanical analysis. The experiment showed that the proposed physical fatigue assessment method could provide joint-level physical fatigue assessments automatically. Then, a series of experiments demonstrated the potential of the method in assessing the physical fatigue level of different construction task conditions such as site layout and the work-rest schedules.

Keywords: Occupational health, biomechanics, deep learning, computer vision, physical fatigue

Introduction

Construction workers are prone to be fatigue due to the highly physical demanding tasks, confined workspace, and prolonged work durations without sufficient breaks (Fang *et al.*, 2015). High physical workload and the resulting fatigue status have resulted in negative effects on workers' health and efficiency. According to a survey in the US construction industry, 71% and 45% employers experiences productivity decreases and safety incidents resulting from fatigue (Cavazza and Serpe, 2009). Fatigue has been proved to be the main factors of occupational injuries and illness (U.S. Bureau of Labor Statistics, 2016), absence from work (Punnett *et al.*, 2004) and may even lead to deaths under harsh climate conditions (Ueno *et al.*, 2018). In addition, the shortage of manpower and aging of the labor force bring new challenges to construction industry. According to Autodesk, 70% of construction firms have difficulties in finding enough qualified construction workers in the US (Autodesk, 2017). In Hong Kong, there is a shortage of 5,000 to 10,000 construction workers (Koch *et al.*, 2015), and over 44% of the registered construction workers were aged over 50 (Y.K., Ng and Chan, 2015). The shortage and aging of workforces would increase the fatigue level of construction workers. Based on above evidences, fatigue prevention has been extremely important for improving construction workers' health and performance. Efficient fatigue assessment is the foundation of fatigue prevention (Entzel, Albers and Welch, 2007).

Fatigue represents tiredness and reduced functional capacity (Frone and Tidwell, 2015). "Tiredness" represents mental fatigue, i.e. the decrease of cognitive performance due to long periods of cognitive activity (Aryal, Ghahramani and Becerik-Gerber, 2017). "Reduced functional capacity" represents physical fatigue, also known as muscle fatigue, represents the inability of a muscle to main certain physical performance (Hagberg, 1981). This paper mainly focus on muscle fatigue, because (1) muscle fatigue could be quantified with physiological indicators or fatigue models; (2) muscle fatigue has clear relation with work conditions, such as construction size and external loads (González-Izal *et al.*, 2012; Ma *et al.*, 2015); (3) muscle fatigue has closed relations with work-related musculoskeletal disorders and injuries. This paper focuses on construction worker's muscle fatigue. In the rest of the paper, "fatigue" represents "muscle fatigue" if there is no specific indication.

Great efforts have been paid to assess construction worker's fatigue. Self-report collects construction workers' subjective feelings of fatigue through questionnaires, thus cannot provide objective and continuous data (Mitropoulos and Memarian, 2012; Zhang *et al.*, 2015). Other methods applied wearable sensors. Such sensors could measure physical fatigue accurately, but the sensors are uncomfortable to wear and may hinder normal construction activities (Hermens *et al.*, 2000). Recently, vision-based techniques have been applied to assess construction workers ergonomics based on posture data (Yan *et al.*, 2017). The problem is that muscle fatigue is related to not only postures, but also external loads, self-capacity and working procedures. Fatigue can also be evaluated in virtual environments through biomechanical analysis software (Seo, Lee and Seo, 2016). However, construction tasks are highly-non-routinized. It is difficult to simulate real construction tasks with regular working patterns.

In conclusion, the difficulties of muscle fatigue assessments for construction workers includes (1) collecting real-time data from construction sites in a non-invasive way and (2) assessing muscle fatigue in a comprehensive way. To solve the above problems, this paper aims to provide a novel approach for construction workers' muscle fatigue assessment. It is the first time that construction workers muscle fatigue could be automatically assessed based real construction data. Compared with previous methods, the proposed method is (1) non-invasive: the data is collected with cameras and insoles, which will not hinder normal construction workers; (2) objective: the results are based on objective data rather than workers' subjective feeling; (3) comprehensive: the method considers several fatigue causes, including poses, external loads, workers' self-capacity. Because of the advantages, the method could provide accurate fatigue assessment results and be suitable to construction site environments.

The rest of the paper is arranged as follows. In section 2, previous studies on fatigue assessments were reviewed to reveal the research gaps and select suitable data collection methods. The proposed method is explained in section 3 and validated through the experiments in section 4. Then the experimental results and limitations were discussed in section 5. Finally, a conclusion is given in section 6.

Previous fatigue assessment methods

As a main cause of safety accidents and low efficiency, fatigue has become a popular issue in various disciplines. In addition to construction management, other research fields, such as biomechanics and ergonomics, also interest in fatigue assessments. This section aims to find the research gaps through reviewing existing fatigue assessment methods.

Self-report is a traditional fatigue assessment method, which collects workers' subjective feeling about perceived fatigue levels through questionnaires. Borg RPE, for example, asks the workers to assess their fatigue level with a score from 6 to 20 (Borg, 1998). Self-report is easy to implement but the data is not objective. Besides, self-report can only provide the fatigue level after work, thus cannot provide the fatigue level during work status.

For accurate and continuous fatigue assessments, wearable sensors were applied to measure fatigue level. A widely-used muscle fatigue indicator is surface electromyographic (sEMG). sEMG is a non-invasive technique to measures the muscle electrical activity during muscle contraction and relaxation cycles (Alyea, 1966). The micro-electrical signals are captured with electrodes, then amplified, filtered and transferred to digital signals. When a muscle gets fatigue, the median frequency of the digital signal will decrease (Hermens *et al.*, 2000). sEMG has been widely used in biomechanical and medical science to detect muscle fatigue (González-Izal *et al.*, 2012). However, the method is not applicable on construction sites. The electrodes require direct touch with skins, which is not allowed on construction sites, and the accuracy will be affected if the worker sweats a lot. In addition, sEMG requires at least three electrodes to detect the fatigue of only one muscle, which limits the application in measuring construction workers' whole-body fatigue.

Simulation is another method to assess work fatigue. Simulation methods assess fatigue based on 3D (three-dimension) joint locations, ground reaction forces and biomechanical analysis. Since the musculoskeletal system of human body is extremely complex, simulation methods are usually realized though software tools such as 3DSSPP, OpenSim and AnyBody Modelling System (Delp *et al.*, 2007; *3D Static Strength Prediction Program*, 2018; *The AnyBody Modeling System*, 2018). Simulation methods have been applied in construction industry and other industries to assess worker's fatigue (Vignes, 2004; Seo *et al.*, 2015; Seo, Moon and Lee, 2015). However, most of the simulation methods are based on regular work-rest schedules. Construction procedures, on the contrary, are highly irregular. As a result, although simulation-based method could provide detailed and accurate fatigue assessment methods, its constraints on working patterns limits the application in construction industry.

In biomechanics, several muscle fatigue models have been built to predict muscle-level fatigue according to the fatigue development mechanism. For instance, a muscle fatigue level was propose based on Ca^{2+} cross-bridge mechanism, which focus on the muscle fatigue development process of quadriceps (Ding, Wexler and Binder-Macleod, 2000). Though the model can predict muscle fatigue correctly, it is not suitable for industrial application due to the high complexity (more than 20 variables just for quadriceps). Another muscle fatigue model was developed based on the muscle force-pH relations (Giat, Mizrahi and Levy, 1993). However, this model only predicts the maximum muscle force capacity, instead of analyzing the muscle force development during working. A new model was proposed to predict physical fatigue based on joint torques (Ma *et al.*, 2015). The model was first theoretically built based on the muscle motor fatigue development theory, then validated with a series of experiments (Ma *et al.*, 2015; Seth *et al.*, 2016).

In summary, simulation tools and fatigue models could provide accurate results on whole body level. The gap is motion data collection from construction workers. Recent progress in computer vision provides a possible solution to the data collection problem (Zhou *et al.*, 2017). By combining computer vision-based pose data collection, biomechanical analysis and fatigue model, this paper aims to provide an accurate and non-invasive fatigue assessment for construction workers.

Table 3: A summary of previous muscle fatigue assessment methods

Assessment method	*Accuracy*	*Body parts*	*Environment*	*Limitations*
Self-report	*Low*	*Whole body*	*Sites*	*Intermittent recording procedures*
sEMG Sensors	*High*	*Certain muscles*	*Lab*	*Uncomfortableness due to the electrodes*
Simulation methods	*High*	*Whole body*	*Lab*	*Regular working patterns*
Fatigue models	*High*	*Whole body*	-	-

Methodology

The research aims to develop a three-step fatigue evaluation method for construction workers. First 3D motion data was collected with computer vision automatically and non-invasively. Then given the exerted forced data and human body parameters, the muscle torques were calculated through biomechanical analysis. Finally, a muscle fatigue model was applied to assess the fatigue level.

3D pose estimation from 2D images

A computer vision method was used to estimate 3D pose data from 2D images, so that the workers' motion data could be collected non-intrusively (Zhou *et al.*, 2017). The method consists of two deep learning networks. The first network aims to identify the key joints (neck, shoulders, elbows, wrists, hips, knees and ankles) and estimate 2D locations of the joints. The basic structures of the network is stacked hourglass, which allows the network to capture both local information (joint recognition) and global information (human recognition) (Newell, Yang and Deng, 2016).

The second network aims to estimate the 3D joint locations according to the 2D joint locations and joint length constraints. The network is trained to infer the depths of the joints so that the differences between estimated bone length and the standard bone length could be minimized. The network was trained on Human 3.6M dataset, which includes the accurate 2D and 3D joint locations of 3.6 million frames from 11 actors during 15 daily activities (Ionescu *et al.*, 2014). However, as mentioned in the discussion session, peoples' daily motion may differ from construction workers' motion, which results in some failure cases of 3D pose estimation.

Muscle torque analysis based on biomechanics

Basic mechanics were applied to calculate the joint torques based on workers' 3D motion data. It is assumed that construction workers' self-weight, height and the external loads (the weight of the materials or tools hold by the worker) were known. The length, weight and center of mass of each body segmentation was estimated based on the worker's height and weight according to an anthropology database (Zheng, 2007). Considering the extreme complexity of the musculoskeletal system, the human body was simplified as a rigid lever system connected with hinges and tendons. Force balance equation and moment balance equation were applied here to calculate the joint and motion torques.

Muscle fatigue estimation based on muscle motor unit theory

A muscle fatigue/recovery model was applied to estimate the muscle fatigue level according the joint torques and joint load history (Ma *et al.*, 2010). The model is based on motor unit theory, which considers muscle fibers as the motor units to generate forces. There are three types of motor unites, two types of units generate large forces and lose capacity firstly, and then the third type of units could maintain smaller forces for a longer duration. During the recovery period, the first two types of motor units get capacity first, and then the third type gets recovered. Based on the above theory, the decease and recover of the muscle capacity should be first fast then slow. *Eq.*1 and *Eq.*2 depict the fatigue and recover process.

$$\varGamma_{cem}(t) = \varGamma_{cem}(t_0)\, exp(-\frac{k}{\varGamma_{max}}\int_{t_0}^{t}\varGamma(u)du) \qquad \textit{Eq.1}$$

$$\varGamma_{cem}(t) = \varGamma_{cem}(t_0) + (\varGamma_{max} - \varGamma_{cem}(t_0))(1 - e^{-Rt}) \qquad \textit{Eq.2}$$

$\varGamma_{max}$ is the maximum capacity of muscles, which is decided by age, gender and ethnicities (Shaunak *et al.*, 1987; Meldrum *et al.*, 2007). $\varGamma(u)$ represents the muscle forces at time u. $\varGamma_{cem}(t)$ is the muscle capacity at time *t*. The decrease of muscle capacity reflects fatigue. *k* and *R* represent fatigue coefficient and recover coefficient. Both are assumed to be 1.

Experiments and Results

This experiment aims to validate the accuracy of the fatigue assessment method by comparing the calculated fatigue level with the subject's sEMG signals.

Experiment design

Subjects: 3 health subjects, aged 20-30 years, was recruited to perform a simulated material handing task in a laboratory.

Equipment: The subjects were wearing a sEMG monitor system (BioRadioTM Great Lakes NeuroTechnologies, US) to retrieve the sEMG data for measuring muscle fatigue. The system includes 5 electrodes and 1 physiological signal processor/transmitter. The 5 electrodes were attached to the subject's right arm: two electrodes on biceps brachii, another two electrodes on brachialis, and the last electrode on the elbow. At the same time, an RGB camera captured the subject's postures during the task, as shown in Figure 1.

The simulated construction task: To ensure the accuracy of the heart rate monitor and the sEMG monitor, the experiment was conducted in a controlled laboratory environment (25℃). After putting on the sEMG sensors, the participants were required to do a simulated material handling task with both arms. The material is a heavy box (6 kg, 37 cm * 33 cm * 26 cm). The task includes 6 rounds. In each round, the subject was asked to (1) lift the box from a working platform (4 m * 3m * 1m); (2) walk around the platform holding the box with both elbows at a right angle; (3) repeat the above steps for three times and rest for 5 seconds to start another round.

Figure 2: The sEMG sensors and the simulated material handling task

Original data: The original data includes the demographic data of the three subjects (Table 2), sEMG data and video records data. The frequency of the sEMG signal is 1000 Hz. The frequency of the video data was 50fps. recorded every five seconds automatically by the heart rate monitor.

Table 2: The demographic parameters of the experiment subjects

Subject	*Height[m]*	*Weight [kg]*	*Age*	*Gender*
#1	*1.78*	*69.3*	*30*	*Male*
#2	*1.70*	*61*	*24*	*Male*
#3	*1.69*	*51*	*30*	*Male*

Experiment results

The videos data and the demographic data were used to calculate the joint fatigue index. The calculated fatigue index data contains the index of 8 key joints every 5 seconds. The median frequency of the sEMG signals were also calculated every 5 seconds with MATLAB Toolbox. After that, both the calculated fatigue data and the heart rate data were standardized by setting the initial value as 100. Figure 2-4 shows the experiment results. The upper figure depicts the current muscle capacity curve based on the proposed methodology; the lower one depicts the median frequency of sEMG. The shaded area represents work status, while the rest of the area represents rest status. It could be found that under work status, the estimated current muscle capacity decreases, and the median frequency of the sEMG signal was low, which means the muscles were getting fatigue. Under rest status, the estimated current capacity increased, and the median frequency of the sEMG signal was high, which means the muscles were getting recovered. The synchronization between the current muscle capacity and the sEMG median frequency demonstrates that the proposed methodology could reflect muscle fatigue.

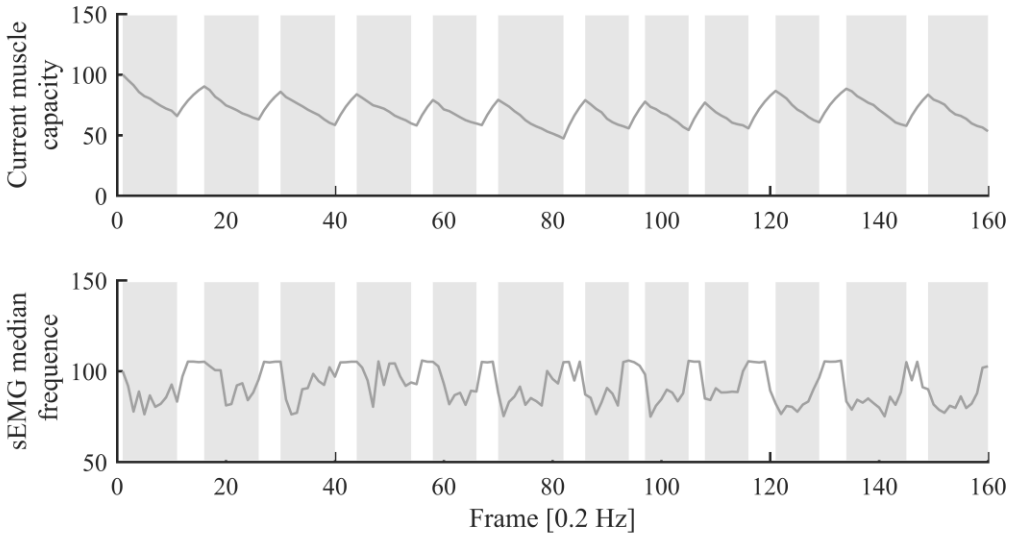

Figure 2: The current muscle capacity and the sEMG median frequency of subject No.1

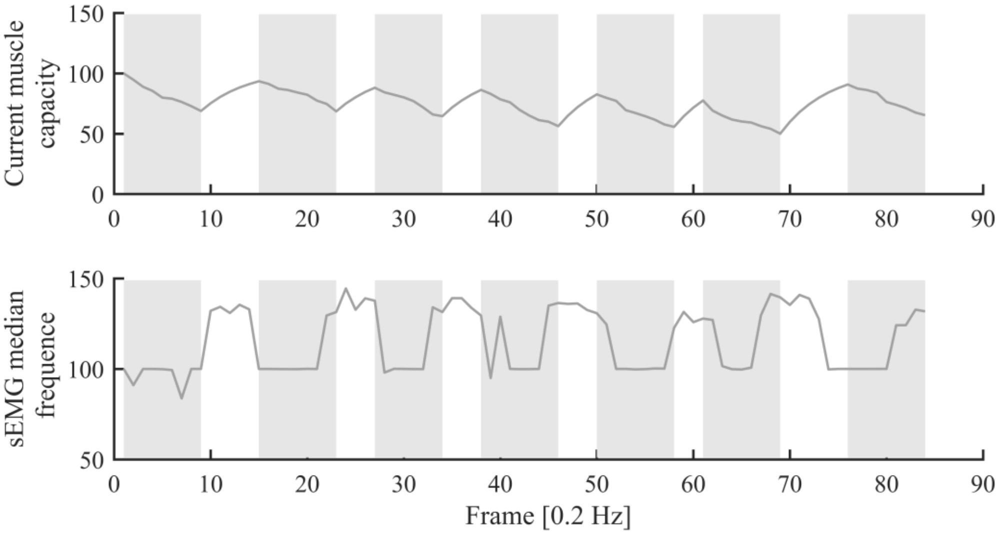

Figure 3: The current muscle capacity and the sEMG median frequency of subject No.2

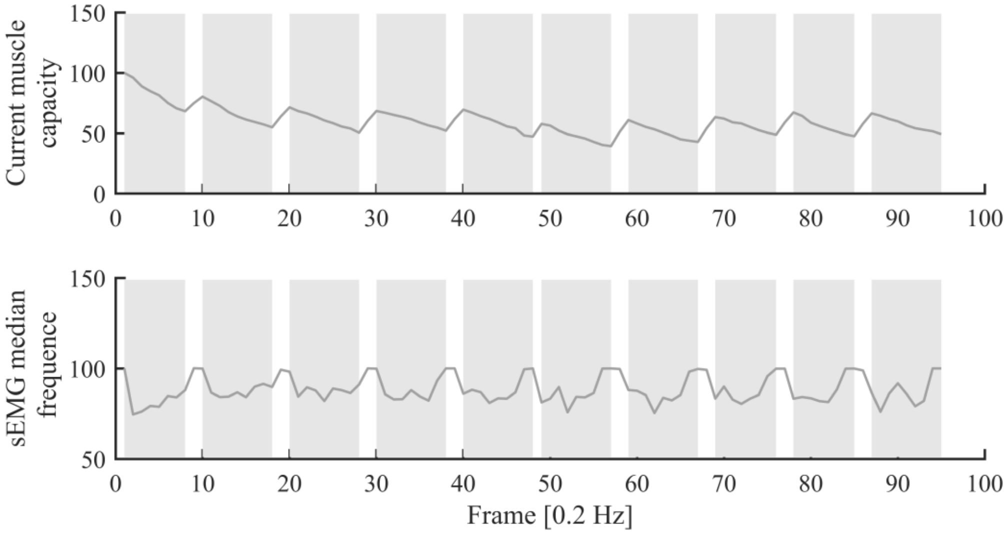

Figure 4: The current muscle capacity and the sEMG median frequency of subject No.3

Discussion

An automatic and non-invasive muscle-fatigue assessment method for construction workers was proposed in this paper. An experiment was conducted to demonstrate the feasibility and accuracy of the methodology. The results showed that the proposed method could provide continuous muscle fatigue assessment from the view of muscle capacity. The comparison between the calculated muscle capacity and the sEMG median frequency shows that the proposed method could reflect the muscle fatigue. Compared with the previous methods, the proposed method could collect workers motion data non-invasively and provide muscle fatigue assessment based on the motion data, instead of using uncomfortable wearable sensors. The non-invasive data collection and the objective make it possible to apply muscle fatigue assessment for construction workers on real construction sites. If applied on construction sites, the method could provide continuous fatigue assessment for each worker based on video frames and the workers anthropology parameters. In addition, the fatigue assessment result could serve as the foundation for data-based site managements, such as designing work platform and scheduling work-rest schedules for a more safe and healthy construction working environment.

The proposed method, however, has the following limitations. First, the method assumed that the workers' motions were slow and steady, so the acceleration was not taken into consideration, which may result in the underestimation of construction workers. The reason is that the vision-based 3D pose estimation method is not accurate enough to support the estimation of velocity and acceleration based on the trajectories of 3D joint poses. Secondly, the experiment only validated two muscles (biceps brachii and brachialis) during material handling. Real construction motions usually involve more complex and larger number of muscles, which increases the complexity of biomechanical analysis.

Based on above limitations, future studies should focus on the dynamic analysis of human body and detailed muscle biomechanical analysis. The dynamical analysis of human body requires extremely high accurate motion data analysis methods. It is very difficult for computer vision-based motion capture algorithms to satisfy such high accuracy. As a result, comfortable and economic sensors would be a possible solution for construction workers motion data analysis. For detailed muscle biomechanical analysis, the combination of human body simulation tools (such as OpenSim) (Delp *et al.*, 2007) and accurate 3D pose data would be a possible solution.

Conclusion

A non-invasive and automatic muscle fatigue assessment method for construction workers was proposed in this paper. In data collection period, the method utilizes the state-of-art computer vision algorithms to collect 3D motion data non-invasively and continuously. In fatigue analysis period, the method combines biomechanics and muscle fatigue models to provide objective fatigue assessment results. An experiment demonstrated the feasibility of the proposed methodology. The methodology makes it possible to assess construction workers muscle fatigue based on objective, big and real data, rather than subjective, small and simulated data. This would benefit the health of construction workers through improve site layouts or work-rest schedules. However, there still exist some gap between the current research and real on-site applications, including more accurate motion data collection methods and detailed muscle-level biomechanical analysis. Comfortable wearable sensors and biomechanical simulation tools would be helpful to solve the above limitations.

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System boundaries of implementing construction robots for buildings

Mi Pan,
The University of Hong Kong
(email: panmi@connect.hku.hk)
Wei Pan,
The University of Hong Kong
(email: wpan@hku.hk)

Abstract

Robotics has been raised for years as radical innovation to reform and renovate the building and construction industry, yet the uptake has been low. A key reason is that the dynamic, unique, human interacted site environment presents grave challenges for robot manipulation for construction works. To underpin the development of construction robots as complicated systems, it is essential to clearly define their system boundaries and explicitly examine their interdependency. This knowledge however is missing in previous literature. This paper develops a new theoretical model of system boundaries to examine the implementation of construction robots for buildings in a systematic manner. The system boundaries are identified in three dimensions (human, building, societal) including the autonomic, technical, building lifecycle, task, environment, stakeholder, and institutional boundaries. These boundaries define the contexts in which construction robots are developed and implemented, laying the analytical lens for understanding the technology complexity and variability, and providing pathways for technology transfer from other sectors. The developed model is then elucidated using four case studies. The results reveal the complexity of and interaction between the boundaries that restrict or facilitate the implementation of construction robots. The paper offers a ground-breaking new direction for research into construction robots for buildings.

Keywords: robotics, construction, system boundaries, building

Introduction

Robotics has been raised for years as radical innovation to reform and renovate the building and construction industry. A series of specific robotic systems have been developed, intergrading intelligent functions like sensibility, motion control, and navigation, to assist in conducting the dangerous, monotonous or unreasonable building construction jobs, such as robotic excavators, bricklaying robots, and external finishing robots (Bock, 2015). Many robotic technologies emerged outside the industry can also be applied to construction, such as robotic drones, welding robots, exoskeletons, and forklift robots (Pan et al., 2018b). However, the real-world adoption of many construction robots has been low (Saidi et al., 2016). A construction robot is a complex system consists of numerous components and interacts with diverse physical and non-physical environments. Its development and implementation lie in the fundamental understanding of the complex systems interfaces and contexts. The dynamic, cluttered, complicated, human-robot interacted site environment presents grave challenges for robot manipulation for construction works (Saidi et al., 2016). The project complexity and uniqueness, combined with industry fragmentation, limit the interoperability and knowledge sharing of construction robots (Mahbub, 2008). There is still a lack of comprehensive systematic studies to address these complexities on the construction robots, the implementation issues, guidance for implementation, and routes of technology transfer cannot be accurately identified and developed.

Robots for construction applications are multi-faced and multi-interpreted (Saidi et al., 2016). The traditional technological studies successfully investigated specific construction robots and examined their interactions with the external environment. However, they failed to thoroughly explain the interaction patterns of different robots and elicit the transferrable lessons to guide the research and practice. To invigorate the uptake of construction robots in the complicated environment, it is essential to clearly define and explicitly examine their system boundaries, and thereby guiding the real-world implementation and promoting the sharing and collaboration.

This paper develops a new theoretical model of system boundaries to examine the implementation of construction robots for buildings in a systematic manner. The system boundaries are identified in three dimensions to conceptually illustrate how construction robots are demarcated from other systems, and then verified using four selected case robots. The developed model lays the analytical lens for understanding the technology complexity and variability, thus offering the attempt to capture the essence of effective robot implementation, extract transferrable lessons, facilitate cross-industry technology transfer, and provide a prospective direction for future research into construction robots for buildings.

Literature Review

Relevant terms and definitions of construction robots for buildings

There is still a lack of consensus about a clear definition of a construction robot (Mahbub, 2008). Different scholars have proposed a diversity of definitions in terms of “construction automation”, “construction robotics” or “construction robot”. Skibniewski (1992) defined construction robotics as advanced construction equipment with the capability related to teleoperation, acquisition and analysis of sensory data, numerically controlled, or autonomous tasks. According to Mahbub (2008), construction automation and robotics is the use of self-control mechanical and electronic machinery with intelligent control mechanisms to conduct construction tasks and operations automatically. Saidi et al. (2016) termed construction robotics as “an advanced form of mechanization (automation) in which an endeavor is made to automate some industrially important operation and thereby reduce the cost of this operation by either removing a human operator from the control loop, or enhance operational efficiency through machine control systems". The terms often overlap in use, covering systems from mechanical machinery manipulated by a human, to semi-automated or automated devices with remote control, to autonomous robots with more sensible and intelligent characteristics. These robots, with certain degrees of freedom, are primarily developed to perform construction tasks which normally ascribed to humans.

Despite the definition, the development and applications are also manifold, ranging from upgraded construction equipment with robotic features (e.g. robotic excavators, robotic cranes), derived robots from other industries (e.g. welding robots, robotic drones), to construction specific robots (e.g. facade installation robots, integrated robotized construction sites) (Bock, 2015). Therefore, how robots could be implemented for assisting construction tasks for buildings is various, dynamic and changing. Many studies have devoted to solving technological challenging problems in fields like kinematics, dynamics, design, actuation, sensing, motion planning and control (Bock and Linner, 2016). However, there is still a lack of comprehensive exploration of construction robots and the external systems. To invigorate the development and implementation of construction robots for buildings, it is critical to thoroughly define and understand the boundaries from the environment.

Systems thinking and system boundaries

Systems thinking is widely applied to address the challenging complexity of modern construction (Pan et al., 2018a). A "system" is defined as a construct or collection of different components or elements that together produce results which are unobtainable by the elements alone (NASA, 2007). It is an entity that interacts with other systems, including software, hardware, humans, and the physical world, formulating the environment of the given system (Avizienis et al., 2004). The system boundary is defined as the common frontier between the system and its external environment (Avizienis et al., 2004), and also could be denoted as a set of valuables that demarcate the system from other systems (Luhmann, 2006). Although system boundary models have been proposed and applied differently, the literature exhibits the usefulness of system boundary demarcation in understanding the system complexities. For example, Distelberg and Blow (2011) focused on the strength variations of the boundary around the family system to conceptualize the family involvement complexity. Pan (2014) proposed a theoretical model of eight system boundaries of zero carbon buildings to help elaborate its concept and guide future research. Specifying system boundaries is also critical in life cycle assessment studies for analyzing systemic problems in the assessment (Merrild et al., 2008; Pan et al., 2018a). Therefore, this paper examines and develops a conceptual model of system boundaries of construction robots to facilitate understanding and real-world implementation.

A Conceptual Model of System Boundaries of Construction Robots for Buildings

The system boundaries of construction robots for buildings are defined systemically to examine the implementation. Drawing on the examination of the external environment of robot implementation, boundaries are identified in three dimensions which demarcate the robot system from the human system, the building system, and the broader societal system. The human system dimension defines the boundaries of construction robots with human environment. Goodrich and Schultz (2008) define the seven roles of human and robot during interaction: supervisor, operator, mechanic, peer, bystander, mentor and information consumer, echoing the complexity of boundaries between robots and humans that should be systematically defined and examined. The building system dimension defines the boundaries of construction robots with buildings as the operating environment. Many construction robots are fundamentally categorized to mobile robots that moving from one location to another during its operation. Key to mobile robotics is the navigation system and the environment maps. However, the uncertain and changing sites creates enormous difficulties to develop an accurate map for robot navigation, which should be fully understood to harness robots for construction applications. The societal system dimension defines the boundaries of construction robots with the external socio-technical environment, which could explain the underlying societal mechanisms of the development and real-world implementation of construction robots.

Fehler! Verweisquelle konnte nicht gefunden werden. illustrates the developed conceptual model of system boundaries of construction robots for buildings, elaborated in three dimensions including seven boundaries as autonomic, shared interaction, time-space, building lifecycle, task, environment, and institutional. These boundaries are dynamic and interactive, and described separately in the following sub-sections.

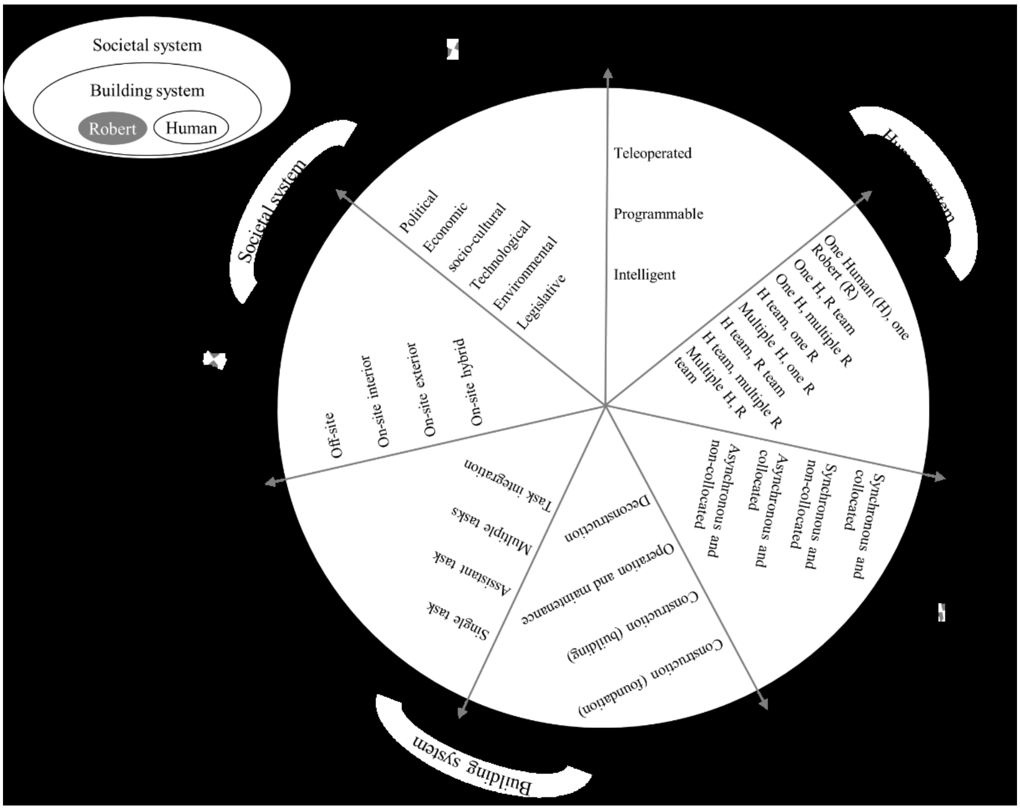

Figure 3: System Boundaries of Implementing Construction Robots for Buildings

Autonomic boundary

The autonomic boundary defines the level of autonomy which distinguishes robots by the control mechanism. The autonomy level is a complex property in the human-robot interaction context, which could be defined by the amount of intervention from humans (Goodrich and Schultz, 2008). As for construction robots, there are three general classes based on the autonomy level, as teleoperated, programmable, and intelligent (Saidi et al., 2016). Teleoperated robots are controlled purely by human operators, with the lowest autonomy level. Programmable robots perform tasks with pre-programmed instructions or teaching by the human operator. Intelligent robots have a high level of autonomy, which could control itself to achieve goals either in a semi- or fully autonomous mode, with little or without human intervention.

Shared interaction boundary

The shared interaction boundary refers to how the robot interacts with humans and other robots that as the human-robot system in conducting the task. This paper adopts the eight possible combinations of humans and robots proposed by Yanco and Drury (2004) to define the shared interaction boundary, as illustrated in Figure 4. Humans could interact independently, or as a team, with robots, and vice versa. Construction as a dynamically changing environment, the shared interaction mode could transfer during the different stages of robot operation, resulting in difficulties for robot coordinate and control. If considering the bystanders in the labor-intensive construction sites, the case of multiple humans could easily occur. Therefore, the shared interaction analysis limited to humans that offer commands or control to the robots, whilst the safety assurance of other human workers during robot operation is a crucial and common consideration for all kinds of applications.

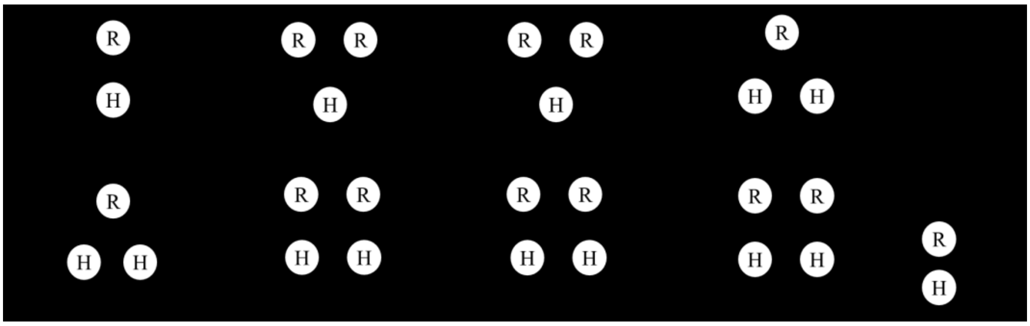

Figure 4: Possible combinations of humans and robots (adapted from Yanco and Drury, 2004)

Time-space boundary

The time-space boundary defines whether or not humans and robots work at the same time (synchronous or asynchronous) and space (collocated or non-collocated). Ellis et al. (1991) proposed this time-space concept in computer-supported cooperative work for identifying time and space of using computing systems, which was extended by Yanco and Drury (2004) into human-robot interaction studies. Therefore, time-space is classified as synchronous and collocated (e.g., exoskeletons that jointly work together with humans), synchronous and non-collocated (e.g., remote-controlled demolition robots that are teleoperated by humans), asynchronous and collocated (e.g., interior wall painting robots that are supervised by humans), and asynchronous and non-collocated (e.g., automated facade cleaning robots that operate autonomously after setting up by humans).

Building lifecycle boundary

The building lifecycle boundary refers to the lifecycle stage of the building project that the construction robot is implemented, mainly considered as construction, operation and maintenance, and demolition stages (Pan et al., 2018b). Construction stage could be further classified as foundation and building. Lifecycle stages could impinge on the implementation contexts of construction robots, such as operating time requirements, environmental conditions, and stakeholder groups, which are firmly related to the technology feasibility and preference.

5.1 Task boundary

The task boundary denotes the attributes of the tasks conducted by the robots. Typically, construction robots could be applied to execute specific construction tasks individually or networked in an integrated way, classified as single task construction robots and automated/robotic on-site factories (Bock, 2015). Apart from facilitating specific construction tasks (e.g., concreting, plastering, and painting), there are also robots supporting construction workers for general assistance, like exoskeletons for power augmentation, logistics assistant robots for carrying tools and materials while following around construction workers. Furthermore, the capability of robots to conduct multiple tasks is considered to cater for the need of increasing flexibility and multi-functionality. Therefore, the task boundary is delineated as single task, assistant task, multiple tasks, and tasks integration, as outlined in Figure 5.

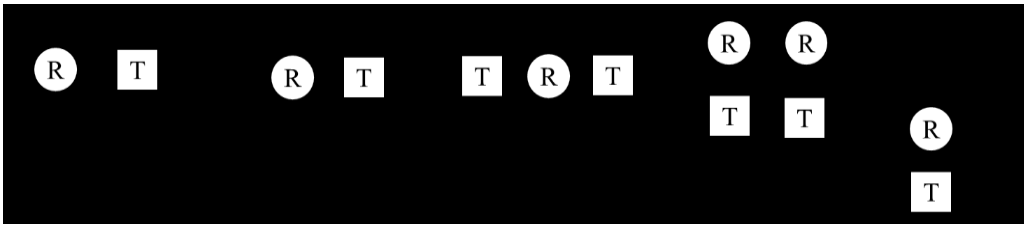

Figure 5: Possible attributes of tasks conducted by construction robots

Environment boundary

The environment boundary defines the physical working environment of the construction robot. Construction robots for buildings could be applied on-site or off-site, distinguished by whether at a construction site or at an off-site or near-site factory. On-site applications could be further classified by whether interior or exterior to the building. Accordingly, the environment could be off-site, on-site interior, on-site exterior, and on-site hybrid (both interior and exterior). A supplemental consideration of on-site environment boundary is the density features regarding height (low-rise, medium-rise, high-rise) and urban density (low-dense, medium-dense, high-dense) of the building (Pan, 2014), and could be elaborated to applicable cases in the more delicate analysis. Compare with manufacturing counterparts, where industrial robots with firmly fixed bases that flourish in the controlled environment, construction is generally characterized by the unstructured, congested, perpetually changing environment, creating difficulties for robots to operate in (Saidi et al., 2016). Therefore, the environment boundary analysis reifies how different robots are designed and implemented in different environmental conditions.

Institutional boundary

The institutional boundary refers to the institutional context within which construction robots are developed and implemented. Pan (2014) suggested the use of PESTEL (political, economic, socio-cultural, technological, environmental and legislative) framework for analyzing institutional contexts, which are applied in this study. The considerations from PESTEL aspects of construction robots have been investigated in previous studies (Mahbub 2008; Pan et al., 2018b), which could help to identify and analyze the broader socio-technical aspects involved in and influence the implementation of construction robots.

Case Studies

The developed model of system boundaries defines the contexts in which construction robots are developed and implemented, laying the analytical lens for understanding the technology complexity and variability. These boundaries are verified using four cases, painting robot PictoBot for interior finishing (Asadi et al., 2018), robotic exoskeleton EksoVest for power augmentation (Ekso Bionics, 2018), facade cleaning robot SIRIUSc for high-rise buildings (Elkmann et al., 2005) and Brokk demolition robots (Brokk, 2018), as in **Fehler! Verweisquelle konnte nicht gefunden werden.** and Figure 6.

The cases were selected using the purposive sampling (Tongco, 2007) to demonstrate both cutting-edge and terminated technologies, and elucidate both the similarities and diversities of boundaries for comparison and cross-technology learning. PictoBot is still under development, whereas research and development of SIRIUSc have been terminated, both are initiated by the research institute. EksoVest and Brokk are commercialized products and developed by the industry.

The cases verify the conceptual model of system boundaries could characterize the complexity and variety of implementation features of construction robots and provide the framework to derive similarity and diversity patterns of different construction robots for buildings to elicit transferrable lessons. All boundaries are interactive and the results elucidated how the complexity of boundaries restricts or facilitates the implementation of construction robots. Key findings from the case comparison are summarised as follows.

- For boundaries related to the human system, similarity and diversity are observed. Four cases have differing autonomic and time-space features, but all can operate with the shared interaction of "one human, one robot", which is then deemed as the basic shared interaction mode. For other shared interaction, PictoBot could have one human supervising several robots as a team to execute the painting tasks; SIRIUSc requires the human team for setting up rooftop gantry and cantilever before the root can be started, visualized, monitored and stopped by a human operator; several Brokk robots could work together and be teleoperated by a human team. The cases reveal that human system is vital for the construction robot, where a higher level of autonomy may not result in wider robot implementation. It is therefore of great importance to formulate a harmonized interaction between robots and humans for successful implementation.
- For boundaries related to the building system, environment and task boundaries unveil some interesting findings. In terms of the environment, two commercialized case robots, EksoVest and Brokk, work more flexible and adaptable as on-site hybrid, while the other two have the more regulated working environment, either internal or external. This discloses that flexibility of robots to the environment might facilitate the adoption and commercialization of construction robots and should be prioritized in robot design. Additionally, task boundary divulges that robots for assistance or for multiple tasks might have greater implementation potential than single task ones, possibly explained by that the former two have more application scenarios to increase the economic justification.
- For boundaries related to the societal system, the implementation of robots is related to multi-faced intuitional aspects. The cases reveal the importance of government support and research funding in the development of robots, as well as collaborations between academic institutes and the industry. The analysis also indicates that the implementation of construction robots could yield fruitful environmental and social benefits, while economic gains, except improved productivity, are uncertain. The unsatisfied economic benefits lower the attractiveness of implementing SIRIUSc and terminate its development, which is an overwhelming barrier to the full utilization of construction robots.

Table 4: Four Construction Robots Cases for System Boundaries Verification

External Systems	Boundary	Case robots (status)			
		PictoBot (under development)	EksoVest (commercialized)	SIRIUSc (terminated)	Brokk (commercialized)

Human system	Autonomic	Intelligent	Intelligent	Programmable	Teleoperated
	Shared interaction	One human, one robot/One human, robot team	One human, one robot	One human, one robot/Human team, one robot	One human, one robot/Human team, multiple robots
	Time-space	Asynchronous and collocated	Synchronous and collocated	Asynchronous and non-collocated	Synchronous and non-collocated
Building system	Building lifecycle	Construction (building)	Construction (building), applicable to the entire lifecycle	Operation and maintenance	Demolition
	Task	Single task	Assistant task	Single task	Multiple task
	Environment	On-site interior	On-site hybrid	On-site external	On-site hybrid
Societal system	Institutional	Funded/supported by the government; untapped market; improve productivity, worker health and safety; reduce emissions of harmful volatile organic compounds; affect painter employment.	Originated from a university laboratory; 6000 USD per set; improve productivity, worker health and safety; open up job opportunities.	Prototyped by a national research institute; economically unjustified; environmentally friendly; improved worker safety.	For sale or rent; cheaper and more efficient than cutting & coring; mature market; improve worker safety; minimize vibration, reduce dust/toxic fume pollution and noise pollution.

a) PictoBot (image: Asadi et al., 2018)
b) EksoVest (image: courtesy of Ekso Bionics)
c) SIRIUSc (image: Elkmann et al., 2005)
d) Brokk (image: courtesy of Brokk)

Figure 6: Figures of four case robots

Discussion

Robotics is an emerging concept in the construction industry, albeit many technologies have been developed for years (Saidi et al., 2016). The developed model of system boundaries contributes an innovative approach to examining the implementation of construction robots in a systemic manner.

The case studies demonstrate that system boundaries can conceptually illustrate how robots are demarcated from other systems in the implementation and provide significant implications for future research and practices. The boundaries to human system highlight that construction robots are not almighty and cannot eliminate human workers, necessitating future studies on physical, ethical, legal and social issues in human-robot collaboration. The boundaries to building system decipher the practical constraints from the diversity and complexity of working environment to the construction robots. The observations in the case studies uncover the complexity and diversity of robots to humans and building. More efforts should be made on the interaction, coordination and integration of construction robots to on-site humans and the building system. Interoperability is still an unsolved technical problem for construction robotics (Saidi et al., 2016). Advances of the Internet of Things and Artificial intelligence may provide better solutions. The boundaries to societal system help to structurally identify the socio-technical challenges and consequences in the development and implementation of construction robots. The case studies reveal that government funding support for prototype deployment and industry participation for real-world trails are crucial to speed up the implementation and commercialization of construction robots.

The developed model lays the analytical lens for understanding the technology complexity and variability of construction robots. The main contributions of this paper lie in the following three areas.

- First, the system boundaries conceptualize construction robots from the complicated interactions between robots and other systems, contributing to the better understanding of the real-world implementation of construction robots. Construction robotics is still an under developed discipline. These boundaries could support the in-depth characterization and systems understanding of construction robots for buildings, capture the essence of robot implementation, identify new research needs and directions, and contribute to the enrichment of the construction robotics discipline.
- Second, the boundaries offer a systematic framework for characterizing different robots through cross-comparison for knowledge sharing and technology transfer from other disciplines. On the one hand, design features and implementation experiences can be extracted from successful robot cases to elicit transferrable lessons for others under similar circumstances. On the other hand, construction professionals are generally lacking robotic knowledge while robotics specialists are unclear about construction practices. Such unfamiliarity could lead to impediments to cross-industry collaboration and slow progress of construction robotics. Therefore, system boundaries will help to facilitate technology transfer and advancement.
- Third, the similarity and diversity patterns of robot implementation derived through comparative analysis could offer important implications for policy and managerial strategy formulation. The feasibility and applicability of different construction robots may be affected by different socio-technical contexts. The derived patterns distinguish possible technological developments, alternatives, challenges and socio-technical consequences, and contribute to policy formulation for technology funding and implementation, as well as the development of management and investment strategies.

Conclusions

This paper has developed a new theoretical model of system boundaries to examine the implementation of construction robots for buildings in a systematic manner. The system boundaries are identified in three dimensions which demarcate the robot system from the human system, the building system and the broader societal system, including the autonomic, shared interaction, time-space, building lifecycle, task, environment, and institutional boundaries. These boundaries define the contexts in which construction robots are implemented, laying the analytical lens for understanding the technology complexity and variability, and providing pathways for technology transfer from other sectors. The developed model was verified using four case studies. The results elucidated the diversity and interaction of boundaries and how the complexity of boundaries restricts or facilitates the implementation of construction robots, and offer important implications for both future research and practice.

The developed model of system boundaries contributes to the in-depth characterization and systems understanding of construction robots for buildings. By offering a systematic framework for cross-comparison of different robots, the boundaries could help to derive similarity and diversity patterns of robot implementation for knowledge sharing and technology transfer, and provide important implications for policy and strategy formulation. The paper offers a ground-breaking new direction for research into construction robots for buildings. Future research could examine the system boundaries with more cases to extract patterns of good design and practice and develop technical solutions for commonly observed issues, which will support the effective implementation of construction robots.

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