Journal of Building Engineering 65 (2023) 105814

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

Construction inspection & monitoring with quadruped robots in future human-robot teaming: A preliminary study

Srijeet Halder [a], Kereshmeh Afsari [a,*], Erin Chiou [b], Rafael Patrick [c], Kaveh Akbari Hamed [d]

[a] Myers-Lawson School of Construction, Virginia Tech, Blacksburg, VA, USA
[b] Human Systems Engineering, Arizona State University, Mesa, AZ, USA
[c] Dept. of Industrial and Systems Engineering, Virginia Tech, Blacksburg, VA, USA
[d] Dept. of Mechanical Engineering, Virginia Tech, Blacksburg, VA, USA

ARTICLE INFO

Keywords:
Construction inspection
Construction automation
Quadruped robots
Construction monitoring
Human-technology partnership

ABSTRACT

Construction inspection and monitoring are key activities in construction projects. Automation of inspection tasks can address existing limitations and inefficiencies of the manual process to enable systematic and consistent construction inspection. However, there is a lack of an in-depth understanding of the process of construction inspection and monitoring and the tasks and sequences involved to provide the basis for task delegation in a human-technology partnership. The purpose of this research is to study the conventional process of inspection and monitoring of construction work currently implemented in construction projects and to develop an alternative process using a quadruped robot as an inspector assistant to overcome the limitations of the conventional process. This paper explores the use of quadruped robots for construction inspection and monitoring with an emphasis on a human-robot teaming approach. Technical development and testing of the robotic technology are not in the scope of this study. The results indicate how inspector assistant quadruped robots can enable a human-technology partnership in future construction inspection and monitoring tasks. The research was conducted through on-site experiments and observations of inspectors during construction inspection and monitoring followed by a semi-structured interview to develop a process map of the conventional construction inspection and monitoring process. The study also includes on-site robot training and experiments with the inspectors to develop an alternative process map to depict future construction inspection and monitoring work with the use of an inspector assistant quadruped robot. Both the conventional and alternative process maps were validated through interview surveys with industry experts against four criteria including, completeness, accuracy, generalizability, and comprehensibility. The findings suggest that the developed process maps reflect existing and future construction inspection and monitoring work.

1. Introduction

Inspection and monitoring in construction is a set of activities that are performed regularly to ensure the quality of construction work and to track the progress of the project according to the contract documents, standards, and regulations [1]. Inspection and

* Corresponding author.
E-mail addresses: srijeet@vt.edu (S. Halder), keresh@vt.edu (K. Afsari), erin.chiou@asu.edu (E. Chiou), rncp@vt.edu (R. Patrick), kavehakbarihamed@vt.edu (K.A. Hamed).

https://doi.org/10.1016/j.jobe.2022.105814
Received 23 August 2022; Received in revised form 17 December 2022; Accepted 30 December 2022
Available online 5 January 2023

monitoring activities play an important role in the construction process [2]. Construction projects are typically executed by a general or main contractor who in turn outsources different parts of the work to several subcontractors, such as electrical, painting, or drywall trade contractors [2]. Various subcontractors, as well as the general contractor (GC), work concurrently on the construction site. Due to their work being interdependent, they require regular coordination to maintain the expected rate of progress and project quality [2,3]. Prompt inspection of materials and installations can prevent costly repair and rework [4]. Proper inspections ensure that the owner gets the value and quality they are paying for in the construction project [4].

Although inspection and monitoring is an essential part of the construction management process [5], there is a lack of in-depth understanding of the tasks and sequences involved in this procedure. Currently, the construction inspection and monitoring process is a manual process and has led to inefficiencies that contributed to cost overruns in 66% of construction projects and schedule delays in 53% of the projects [6], affecting almost $1.4 trillion worth of structures being constructed each year in the United States [7]. The cost of rework due to construction deficiencies is estimated to be 6–12% of total construction costs [8]. Also, a significant portion of the inspection time (30–50%) is spent on visual data collection of the as-built status and on-site analysis [9]. Due to the lack of standardization and an intensely manual process of inspection, 77% of project review meeting time is spent on descriptive and explanatory tasks, while only 23% is spent on more important evaluative and predictive tasks [10]. It has also been reported that field inspections that are conducted by different inspectors lack consistency (Ciampa et al., 2019; [10]. The quality of inspection data is also determined by the inspector's experience and the methods used to collect measurements [11]. [5] identified several challenges with the conventional inspection process including (a) lack of specialized inspectors, (b) lack of proper documentation, (c) improper training, (d) lack of proper quality assurance procedures, (e) time-consuming activities, and (f) lack of technology adoption among inspectors. Construction progress monitoring which is a type of inspection during the construction process to allow timely interventions to prevent large deviations from the originally planned cost and schedule [10,12] is also challenged by the conventional manual process of inspection [11]. identified numerous challenges including non-systematic monitoring and reporting that results in a time lag between actual work execution and progress reporting, the inefficiency of the traditional progress reports in depicting complex relationships between various construction activities and entities, and the lack of shared standards for progress monitoring and reporting for timely corrective decision-making. It is important to conduct construction inspections at consistent time intervals to minimize the cost of failure and repair [5].

To address the limitations of the conventional inspection and monitoring process in construction, there is a growing interest in developing a systematic and organized way of performing inspections during construction [5]. Importantly, recent advances in technology including robotic technologies with agile locomotion as well as image processing, computer vision, and machine learning techniques have provided the potential to address current inefficiencies in the construction inspection and monitoring process. The authors have previously investigated the potential of a quadruped robot in automating the data collection stage in the construction inspection and monitoring process [13]; S [14]. Quadruped robots have a wider range of accessible terrains and are more versatile than wheeled robots [15], including better mobility, stability (S. [14], and flexibility due to having more Degrees of Freedom (DoF) per leg (Y [16]. Quadruped robots can traverse uneven terrains, move up and down stairs, and walk over small obstacles, making them more suitable for the construction environment (S [14]. Quadruped robots can assist humans on job sites in construction inspection and monitoring but they also require periodic human intervention on unstructured and dynamically changing construction sites [15].

However, past research has mainly focused on extending the technical capabilities of robots for performing inspection tasks. The integration of the technology with the overall process of monitoring has not been explored. There is a gap in understanding the required human-quadruped robot partnership in construction inspection and monitoring. Ineffective communication between humans and machines reduces the performance of the human-machine partnership [17]. Lack of integration of innovation with the existing processes and lack of acceptance by the target users cause undesirable outcomes of adopting new technology, such as a reduction in productivity [18]. Instead of the technical perspectives, this study explores the use of robotics from a managerial point of view. To understand how robotics can be integrated within the process of construction inspection and monitoring, it is important to first understand the process and identify the sequences and steps that are involved and that can be improved with the use of a quadruped robot as an inspector assistant. The goal of this research is to undertake an in-depth study of the process of construction inspection and monitoring process performed by the human inspector, and to identify opportunities for future efficiencies through human-technology partnership. Therefore, the research objectives are to (a) map the conventional process of construction inspection and monitoring and (b) identify human-quadruped robot teaming opportunities in future construction inspection and monitoring. This study used mixed methods including on-site observations of human inspectors to identify their inspection and monitoring processes followed by on-site interviews. The results of the on-site experiments were then verified through online surveys with industry experts.

This paper first provides a background review of the inspection and monitoring process in construction, the roles and responsibilities of human inspectors in this process, and the studies on robot-enabled construction inspection and monitoring. Section 3 explains the research methodology in detail. Research results are provided in Section 4, which comprise two identified process maps including the process of conventional inspection and monitoring in construction and the future construction inspection and monitoring with the proposed human-robot team. The validation method of the research results is also explained in Section 4. Further improvements to the developed process maps based on the validation are discussed in Section 5. Finally, Section 6 explains a summary of study contributions as well as recommendations for future research.

2. Background

2.1. Types of construction inspection and monitoring and stakeholders involved

Construction projects involve groups of companies and stakeholders working together during the project period with little or no long-term working relationships [9]. The success of the project depends on the coordinated functioning of project stakeholders together [2]. Inspections by project stakeholders or their representatives are performed routinely to check whether the work can be approved or needs modifications [2]. Inspectors performing the regular inspection of construction work face the challenge of deciding what to inspect at each stage and how to assess the quality of the construction work and products [8]. Also, real-time construction project control necessitates the availability of high-quality, up-to-date data of the construction status to detect and mitigate deviations and construction deficiencies in real-time [19]. Because several stakeholders are involved in the inspection and monitoring of construction work, some stakeholders or their representatives visit the site only periodically to inspect the construction status and ensure that the completed work is in accordance with standards, guidelines, and contract requirements. Manual inspection is time-consuming and increases project costs [11]. As a result, there is a considerable lack of up-to-date site information at the managerial levels which limits the ability of the managers to monitor the project and control project uncertainties [9]. While the average duration of construction activities is in days, the average frequency of inspection and monitoring reports is in months [9].

In fact, there are many types of inspections performed by various stakeholders during construction. Some of the important stakeholders commonly involved in the inspection and monitoring process and their work are briefly explained as follows:

Architect/Engineer (A/E) Inspections – The American Institute of Architects (AIA) General Conditions of the Contract for Construction (GCCC) [20] section 4.2.1 and 4.2.2 mandate that the architect must visit the construction site at appropriate intervals as an owner’s representative to be generally familiar with the progress and quality of the work completed. A “Memorandum of Understanding” between the owner and the contractor may also call for more frequent A/E inspections [108]. The A/E is responsible for protecting the owner from any defects, deviations, or shortcomings in the contractor's workmanship (Department of General Services, 2018) in the traditional design-bid-build project delivery method. The Architect is also responsible for issuing the Certificate of Substantial Completion once the project is “substantially complete” in the traditional design-bid-build project delivery method [20]. American Institute of Architects (AIA) defines Substantial Completion as “the stage in the progress of the Work where the Work or designated portion is sufficiently complete in accordance with the Contract Documents so that the Owner can occupy or utilize the Work for its intended use” [20,21]. The Architect performs the Substantial Completion Inspection before issuing the Certificate of Substantial Completion to the General Contractor [20].

- **Owner’s representative/CM’s inspections** - While the A/E representatives visit the site occasionally, the owner's project inspector, or the owner’s representative, inspects the site more frequently. Between visits, the A/E representative informs the project inspector of any particular checks or inspections that need to be performed (Department of General Services, 2018). The Project Inspector is the individual in charge of inspecting and overseeing the work daily. The Project Inspector may be a direct employee of the owner or maybe a Construction Manager (CM) hired by the owner as their representative. The CM or the owner’s representative is hired by the owner for better control of the scope of the work [22]. A complete inspection of the project site is one of the responsibilities of the CM to perform on behalf of the owner [23]. The owner’s representative also participates in reviewing the contractor’s payment application and measuring field quantities for payment purposes and coordinating other inspection activities [24].
- **General Contractor’s QA/QC team inspections -** The GC routinely monitors the construction project to ensure that the quality of workmanship is maintained and that the schedule is followed correctly. The inspection team of the GC may include the project manager, project engineer, or other team members, as well as consultants [25]. Depending on the size of the project, the GC may assign a specific inspector for each discipline of the project [25].
- **Building Regulation Authorities -** Aside from the A/E’s, owner’s, and GC’s inspections, the project is also inspected on occasion by building regulations authorities e.g. the Regional Office of the State Fire Marshal (Department of General Services, 2018). The State Fire Marshal Official (SFMO) inspects the projects several times throughout construction and conducts the Substantial Completion Inspection near the end. Additionally, a “Building Official” from the Division of Engineering & Buildings or similar authority is also present during interim inspections and the Substantial Completion Inspection near the end of the project (Department of General Services, 2018). The Building Official inspects the structure to ensure that it is code compliant.
- **Special inspections/third-party inspections -** Apart from regular inspection and monitoring by the owner, contractor, and A/E representatives, third-party inspectors are also contracted by the owner for special inspections (Department of General Services, 2018) or sometimes referred to as third-party inspections. Special inspection is defined by International Building Code (IBC) as the “inspection of construction requiring the expertise of an approved special inspector to ensure compliance with this code and the approved construction documents” [26]. Special inspections are performed for those building components that require special knowledge and attention [27]. The primary goal of special inspections is to ensure code compliance, which is critical for the integrity of structural elements [27]. Aside from the state-mandated special inspections, the facility's owner may also request additional special inspections (Department of General Services, 2018).

Apart from special inspections that check the construction work against the applicable building codes, the owner of the facility may also employ specialized agencies to perform inspections of various components of the building to ensure compliance of the work with project specifications e.g., mechanical inspection, coating inspector, electrical inspector, etc. [28].

2.2. Construction inspector roles and responsibilities

A construction inspector's responsibilities include periodically walking around the project site and visually inspecting the building [10]. The inspector also compares the work to a variety of contract documents, including drawings, project specifications, the schedule, and the Work Breakdown Structure (WBS) [29]. If an error or discrepancy is discovered in the construction work, the inspector must report it to the contractor/subcontractor (Department of General Services, 2018) for corrective actions.

The followings are some of the common inspection tasks performed by the project inspector (Department of General Services, 2018).

1. Inspect footing excavations and reinforcement material for concrete footings before placement of concrete.
2. Inspect foundation systems during phases of construction necessary to assure code compliance.
3. Inspect preparatory work before the placement of concrete.
4. Inspect structural members and fasteners before concealment.
5. Inspect electrical, mechanical, and plumbing materials, equipment, and systems before concealment. This also includes fire suppression sprinkler systems, clean agent systems, and fire detection and alarm systems.
6. Inspect energy conservation material before concealment.
7. Conduct final inspection.

According to the Bureau of Labor Statistics (2021), a construction and building inspector executes the following duties.

1. Review building plans and approve those that meet the requirements.
2. Monitor construction sites periodically to ensure overall compliance.
3. Use equipment and testing devices, such as moisture meters to check for plumbing leaks or flooding damage and electrical testers to ensure that electrical components are functional.
4. Inspect plumbing, electrical, and other systems to ensure that they meet the codes.
5. Use survey equipment to verify alignment, level, and elevation of structures and ensure building meets specifications.
6. Issue violation notices and stop-work orders if building is not compliant.
7. Keep daily logs, which may include digital images from inspections.
8. Document findings in writing.

The minimum educational qualification for a construction and building inspector in the U.S. is a high-school diploma, however, some employers may require a bachelor’s degree in engineering or architecture [28]. Many community colleges also offer a certificate or an associate’s degree in building inspection technology [28].

2.3. Role of automation in construction inspection and monitoring

Automated inspection and monitoring attempt to alleviate some of the difficulties associated with manual inspection. Construction inspection and monitoring includes (a) data collection, (b) information retrieval, (c) progress estimation, and (d) visualization and one or more of these subprocesses can be systematized using various technologies [10]. Methods for automating inspection and monitoring sub-processes have been investigated in previous studies, for example.

- **Data Collection:** As-built data collection for inspection and monitoring is a labor-intensive and time-consuming task [10]. Collecting accurate information about the as-built conditions of the project is known as reality capture [30]. Data collection or reality capture can be automated through radio-frequency identification (RFID), laser scanning, or regular digital images and videos [10]. Ground and aerial robots can be used as data collection agents using cameras and LiDAR [13,31]; S [14]. Robots provide a safer and more efficient alternative to conducting building and infrastructure inspections [32–34]. They extend the reach of human inspectors to confined and risky spaces, such as bridge decks while isolating them from the associated health and safety risks [32,35,36]. More discussion on robotic inspection and monitoring in construction is provided in Section 2.4.
- **Information Retrieval:** Information retrieval in manual inspection occurs through the extraction of knowledge about the project from visual observations of the site [10]. Several automation techniques have been developed for automatically analyzing inspection data to extract meaningful information about the project [37–40]. Vision-based techniques, such as image processing and computer vision, can be used to identify construction defects or deficiencies, such as cracks, and/or missing components through visual analysis of the project site [39,41–44]. Image processing employs mathematical algorithms, whereas computer vision employs machine learning models to extract high-level information from images. Image processing techniques like photogrammetry can also be used to reconstruct the 3D structure of an object [45] and/or extract geometric information about an object from its photographic images [46,47]. Computer vision techniques like convolution neural network (CNN) provides powerful information extraction capabilities from images. However, computer vision models, especially deep-learning-based models like CNN, rely on large training datasets [48]. The accuracy of the computer vision models depends on the quality of the training data used [41].
- **Progress Estimation:** In previous studies, the progress estimation in construction progress monitoring was automated by comparing the information collected on-site, i.e., as-built status with the project's as-planned Building Information Model (BIM) [49–51]. The progress is estimated after registering/aligning the 3D reconstruction of the site with the as-planned BIM and by comparing the overlap of 3D points in the reconstructed structure and the as-planned 3D model [52]. Progress can also be estimated by comparing site scenes to the 3D model in the same location [53]. These methods, however, detect the presence or

absence of the components and they face difficulties in the progress monitoring of painting or tiling work due to a lack of texture in the end products of these tasks [10].

- **Visualization:** In addition to data collection and processing, effective visualization and reporting are also essential for construction inspection and monitoring [10]. Augmented Reality (AR) is a useful tool for visualizing on-site progress [54]. AR-based monitoring overlays the as-planned model on the project's real-life view to compare the as-built status with the as-planned 3D model in BIM. The augmented image can also be linked to the schedule so that schedule deviations can be compared [55]. The AR visualization can be real-time or it can be based on previously captured images [11,52]. Using AR with a model superimposed on previously captured images, the inspector can conduct a virtual walkthrough even remotely. The most difficult challenge with AR-based project status visualization for inspection is accurate model registration with reality [10]. Another way to visualize site information for inspection and monitoring is to display a 360° image of the site on a 2D floor plan [13] or inside a 3D BIM model (S [14].

The past research on automation technologies discussed above has demonstrated various ways to automate the construction inspection and monitoring subprocesses. These automation technologies can be used in future inspection process for partly or wholly automating the process. This research focuses on developing a process map to show how the conventional inspection process should be modified with these automation technologies in future. This research mainly focuses on the data collection and information retrieval parts of the construction inspection and monitoring process and studies the opportunities for an inspector assistant quadruped robot within this process.

2.4. Robotic inspection and monitoring in construction

Among the various inspection and monitoring subtasks, robots can play an important role in the data collection. Robots are automation tools that have been introduced in construction for various purposes, such as precast concrete production [56], painting (E. [57], cleaning [43], tiling [58], prefabricated building assembly [59], and demolition waste handling [60]. A robot is defined by International Organization for Standardization (ISO) as a "programmed actuated mechanism with a degree of autonomy to perform locomotion, manipulation, or positioning" [61]; p. 1). Robotics is the "science and practice of designing, manufacturing, and applying robots" [61]; p. 2). Various types of robots have been investigated for construction inspection and monitoring as well (K [62–67]. [65]. reviewed Unmanned Aerial Vehicles (UAVs), Unmanned Ground Vehicles (UGV), Unmanned Marine Vehicles (UMV), and wall-climbing robots for building and infrastructure inspection. UAVs, often known as drones, are employed to inspect bridges and building facades [68–71]. Wheeled robots have also been used in many studies for construction inspection and monitoring (K [62,72].

Specialized robots, such as the legged robot Alicia3 by Ref. [73] and the wall-climbing robot with suction mounts by Ref. [74] have also been designed for building construction and maintenance inspection [75]. also developed a chained robot to enter and inspect pipes and ducts that are not easily accessible to humans. Multi-robot collaboration has also been studied by Ref. [76] where a UAV and a ground robot collaborated to perform construction inspection tasks. Quadruped robots are another class of robots that can better navigate the cluttered environment of construction sites and can also climb stairs [15]; S [14]. Spot by Boston Dynamics is an example of a quadruped robot [14]. The authors in their previous work with Spot studied the potential of using the robot for progress monitoring by collecting 360° images [13,15]; S [14].

Construction inspection robots are often used as data collection agents for reality capture. Data is collected in the form of images or point cloud data using laser scanners by these robots and this method can relieve humans from the labor-intensive task of on-site data collection. Developing autonomous robot navigation has been the prime focus of research for many researchers [70,77–79]. Construction sites are unstructured and cluttered environments that change dynamically. To perform inspection tasks more efficiently, any autonomous robot must be able to navigate the construction site autonomously and dynamically adjust to site conditions (K [62]. An autonomous robot should be aware of its position relative to the space it is operating in, which is known as localization [80]. AprilTags fiducials were used for this purpose by Ref. [78]. For path planning and navigation, the Simultaneous Localization And Mapping (SLAM) technique has been used to create a 3D map of the environment while simultaneously navigating the robot in an unknown environment [81]. In robot navigation, the A* heuristic algorithm is used to calculate the shortest path between two points [72].

Many factors influence robotics adoption in construction, including the robotic technology itself as well as the organization and the environment in which it operates [56]. identified nine determinants for the adoption of robotics in a construction organization – a) relative advantage, b) compatibility, c) top management support, d) human resources, e) interconnectedness, f) firm size, g) market demand, h) market competitive pressure, and i) regulatory environment. Out of these determinants, relative advantage and compatibility are considered the technological determinants for the successful adoption of robotics in a construction organization. Top management support, human resources, interconnectedness, and firm size are considered organizational determinants. Market demand, market competitive pressure, and regulatory environment are considered environmental determinants for the successful adoption of robotics in a construction organization. Construction industry's difficulty in attracting digital talent is also one of the reasons behind low adoption of robotic technologies and other technologies [82].

2.5. Human-robot partnership

Although previous studies have investigated the technological aspects of using robotics for construction inspection, little work has been done regarding the use of human-robot teams in construction inspection. Previous research has designed and showcased robots as tools for humans that operate independently of humans [83]. But, because each construction project is complex and unique, not all problems can be standardized enough to be addressed by robots alone. To ensure the success of robotic construction monitoring, a human-robot teaming approach is required.

Human-robot teaming offers an increase in productivity and a decrease in the strain of repetitive and arduous physical tasks performed by humans [84]. Recent research has used the metaphor of human-robot "teaming" to investigate how to best integrate a system's human and technological components in light of increasing capabilities for autonomous systems [84]. Human-robot teams are a grouping of humans and robotic systems communicating, coordinating, and collaborating to perform a joint activity [83]. This teaming metaphor does not imply that technology (e.g., autonomous mobile robots) could or should try to function like human teammates; rather, it allows for the exploration of more collaborative relationships between humans and machines.

This research investigates existing processes in construction inspection and monitoring towards the identification of human-robot teaming opportunities. Understanding the interdependencies of each team member is essential for efficient team building, mission planning, and task delegation and for effectively accomplishing joint tasks in a human-robot team [83]. Researchers have identified that the trust of the human participants is a critical factor in successful human-machine team formation [85]. Therefore, the perceived reliability of a quadruped robot from the perspective of human inspectors is considered one of the key variables in this research.

2.6. Research gap

To summarize, construction inspection is a complex task. An inspector performs many different roles in the monitoring of the construction project. Various stakeholders are involved in the inspection process. Significant amount of time and cost is spent on inspection, which is a major limitation of the traditional inspection process [10]. Past research has explored automation and robotics for making the construction inspection task more efficient and effective (K [10,63]. However, past research has mainly focused on the technical aspects of using robots for the inspection and monitoring of construction. Little research has been performed on the managerial aspects of using robots for inspection and monitoring. As explained in the previous subsections, performing inspections in construction is a complex process. The human-robot partnership allows using human cognition and intellect to increase the automation capabilities of robots [84]. Effective interaction between robots and humans in human-robot partnerships has been considered a key bottleneck in utilizing robotic systems in the workplace [84]. Development and adoption of technology in the workplace require a detailed understanding of the existing processes [86]. In the context of construction inspection and monitoring, very limited research has been done to understand the process itself. Construction companies employ different methods from project to project for construction inspection and monitoring [29]. Therefore, this study aims to provide a fundamental understanding of construction inspection and monitoring as the main step toward automating this process in construction. This study also proposes an alternative process of inspection and monitoring using a robot assistant that can be adopted in future construction projects.

3. Research methodology

This research uses a mixed methodology to (a) demonstrate the conventional process of construction inspection and monitoring and (b) propose an approach to human-quadruped robot teaming in future construction inspection and monitoring. Two process maps were developed through a qualitative study of construction experts engaged in inspection and monitoring work through observations and interviews. The developed process maps were then validated through quantitative data analysis. The research was conducted in three phases. Phase one and phase two were performed on construction sites and included observations, semi-structured interviews, and robot experiments, while phase three included online and in-person interview surveys approved by the Virginia Tech Institutional Review Board (IRB #21–616). Fig. 1 shows the overview of the research methodology adopted in this research.

In phase 1 of the research, the study first conducted on-site observations of construction inspectors while they performed inspection and monitoring tasks on three construction sites. The inspectors were asked to perform their routine inspection tasks within a small section of the construction site. Inspectors were observed using the think-aloud approach. Think-aloud is a direct observation method where the research subjects are asked to verbalize their thoughts while performing a task [87]. The think-aloud method allows researchers to get a deeper understanding of human behavior and reasoning [87]. Each observation session lasted between 5 and 15 min and was video recorded. Semi-structured interviews were conducted with the inspectors immediately after the observation session. The interview survey was designed to provide a deeper understanding of the performed inspection tasks and to clarify any questions that arose during the observation session. Interview surveys were video recorded. The video recordings were then transcribed and analyzed after the on-site session was completed. The interview recordings were transcribed using the Transcribe feature of Microsoft Word Online. The sample size of the research participants was decided using the principle of saturation similar to Ref. [88]. Saturation is considered to occur when no new knowledge or opinion is added by recruiting additional study participants [88].

Phase 2 of the research was aimed at proposing a process for future construction inspection and monitoring with the use of an assistant quadruped robot. Phase 2 was conducted immediately following phase 1 on the construction site where the inspectors were trained to operate a quadruped robot (Spot by Boston Dynamics) on the job site using the robot's teleoperation with a remote control but within the inspector's line of sight. In this experiment, the base model of Spot was used running on firmware version 3.1. The attached payload included only a Ricoh Theta V 360° camera, which has a 4 k live-streaming resolution and weighed about 121 g [106]. The training involved first explaining the capabilities and features of the robot, its safety protocols (e.g., maintaining 6.5 feet distance from humans, avoiding glass objects, etc.), and then explaining the controls of the robot through its controller. After explaining the control and features of the robot, the inspector was given time to practice with the robot by walking it around and looking at the site through its cameras (Fig. 2). The training process took about 5–10 min.

After the training session, the inspectors were asked to perform a virtual inspection of the same area they inspected for phase 1 while they controlled the robot manually (via the robot controller) and guided it to the inspection area. They observed the inspection area using the live video from the 360° camera installed on top of the robot streamed on an iPad next to the inspector as shown in Fig.

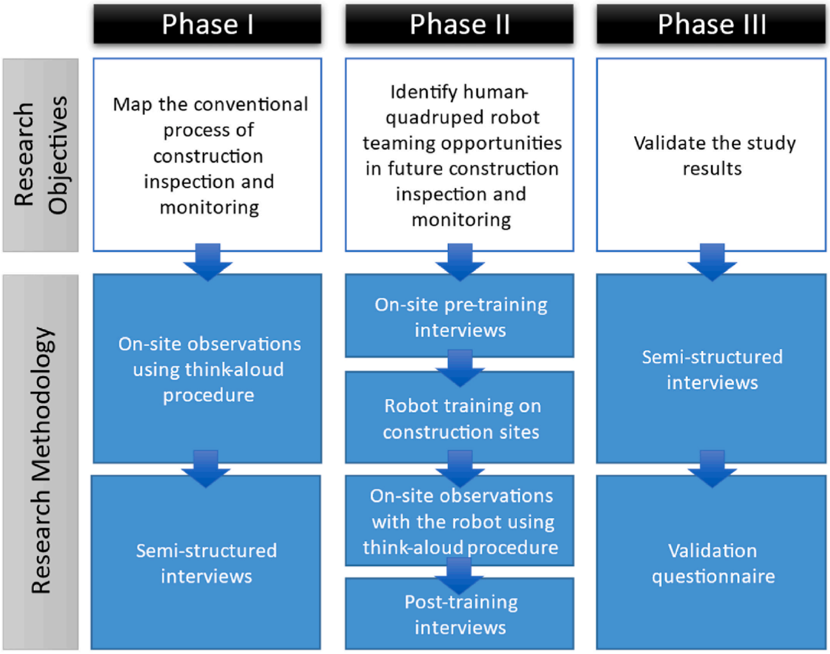

Fig. 1. Research methodology.

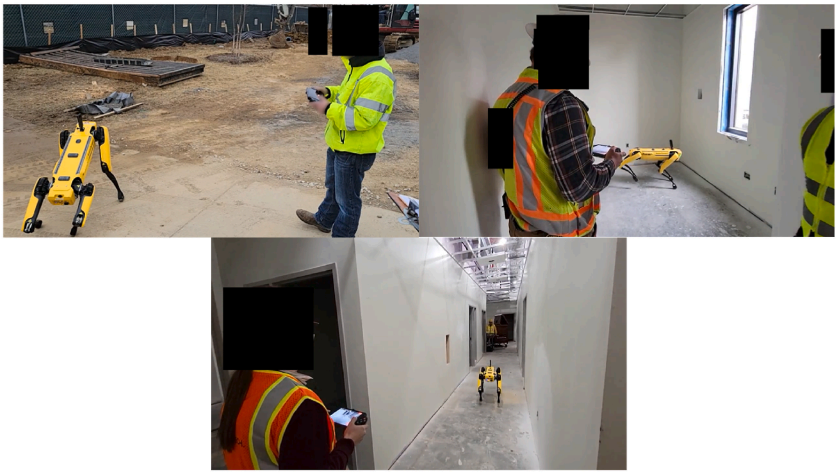

Fig. 2. Inspectors receiving on-site training on the use of the Spot robot.

3. The same think-aloud approach was used while the inspectors performed the virtual inspection using the robot. Each observation session in this phase lasted between 5 and 15 min and was video recorded. In phase 2, semi-structured interviews were conducted before and after the virtual inspection using the robot. Through the semi-structured interview, inspectors provided feedback on how a human-robot team can be formed and what tasks the robot can perform for them to facilitate inspection and monitoring.

After conducting the on-site sessions with the inspectors in phases 1 and 2, the study used Business Process Mapping and Notation (BPMN) to create two process maps based on the on-site study of the process of construction inspection and monitoring. These two process maps include: (a) a process map to demonstrate the conventional process of construction inspection and monitoring and, (b) a process map to capture potential future construction inspection and monitoring with the use of a quadruped robot assistant.

Phase 3 of the research was aimed at the verification of the research results from phases 1 and 2 and validation of the generalized process maps developed in phases 1 and 2. This phase was comprised of interview surveys with a larger and more diversified group of construction professionals involved in the inspection and monitoring process. In this phase, a new set of construction inspection and monitoring experts were recruited to participate in semi-structured interviews. The research participants were selected using snowball sampling starting from the professional network of the research team and then adding more participants through the introductions made by the research participants. The interviews were conducted both online and in person depending on the availability and preference of the participants. In this phase of the research, the study participants were first shown a short presentation of quadruped

Fig. 3. Site inspectors performing virtual inspection using a quadruped robot and ipad with video stream of the robot-mounted camera.

robot capabilities in construction inspection and monitoring based on the authors' previous research [13]; S [14,89]. The interview started with basic demographic questions about the participants. Then, two process maps were shown to the participants: (a) the conventional process map of construction inspection and monitoring (results from phase 1) and (b) the future process map of construction inspection and monitoring with an assistant quadruped robot (results from phase 2). The participants were given ample opportunity at each step to ask for clarification at multiple points. Once the participants confirmed their understanding of the process map, they were given a short questionnaire. The questionnaire comprised twelve questions of the five-point Likert scale type. The developed process maps were evaluated on four criteria – completeness, accuracy, generalizability, and comprehensibility. Each of these variables was measured through three questionnaire items as shown later in Table 2. Three out of twelve questions were reverse-scaled to ensure the attention of the participant while responding. After collecting a few responses, the internal reliability was tested through Cronbach's alpha. Cronbach's alpha value for each of the measured items after collecting the last data sample is shown in Table 2.

Finally, the evaluation criterion was set as a hypothesized mean of 3.0 or above for each measured variable through a one-sample non-parametric Wilcoxon Signed Rank test. The alpha value for the test was set at 0.05. Therefore, a p-value of less than 0.05 was required for the null hypothesis (mean $<$ 3.0) to be rejected and the alternative hypothesis (mean $\geq$ 3.0) to be true. The results of the hypothesis test are presented in the next section.

4. Results

Results from phase 1 address the first research objective, i.e., to demonstrate the conventional process of construction inspection and monitoring in a BPMN process map that indicates the conventional process of construction inspection and monitoring. Results from phase 2 address the second research objective, i.e., to propose an approach to human-quadruped robot teaming in future construction inspection and monitoring in a BPMN process map. Results from phase 3 validate the results from phase 1 and 2 of the research and identify improvements to the developed process maps.

4.1. Research participants

In phases 1 and 2, study subjects were recruited through convenience sampling from three different construction projects accessible to the research team. Project 1 was a commercial building including major renovation and new construction of a 102,000 square feet building. During the research sessions on site, the construction project was nearing its substantial completion. Project 2 was the construction of a new commercial building of 115,600 square feet. During the research sessions on-site, the steel framing was being built on the fourth level, with rough-ins, drywall, and painting work being performed on the lower levels. Project 3 was also a new commercial building of 100,000 square feet. During the research sessions on site, the project was still in the earthwork stage. All three projects are located in the southeast region with CM at-risk project delivery and have the same owner but represent two general contractors and three design (A/E) teams.

In phases 1 and 2, twelve inspectors were recruited between October 2021 and March 2022. The research participants were either general contractors, owners, or 3rd party inspectors representing four different companies. Fig. 4 (top-left) shows the distribution of the inspectors by their company type. The observed inspectors had a wide range of work experience from 1 year to 35 years. Fig. 4 (top-right) shows the demographics of the participants by their work experience. Fig. 4 (bottom) shows the gender demographics of the participants. Out of twelve inspectors observed, three (25%) were female. For comparison, women employees in the US construction sector were estimated to be 11% in the year 2021 [91]. Among construction and building inspectors, 10% are estimated to be women [92].

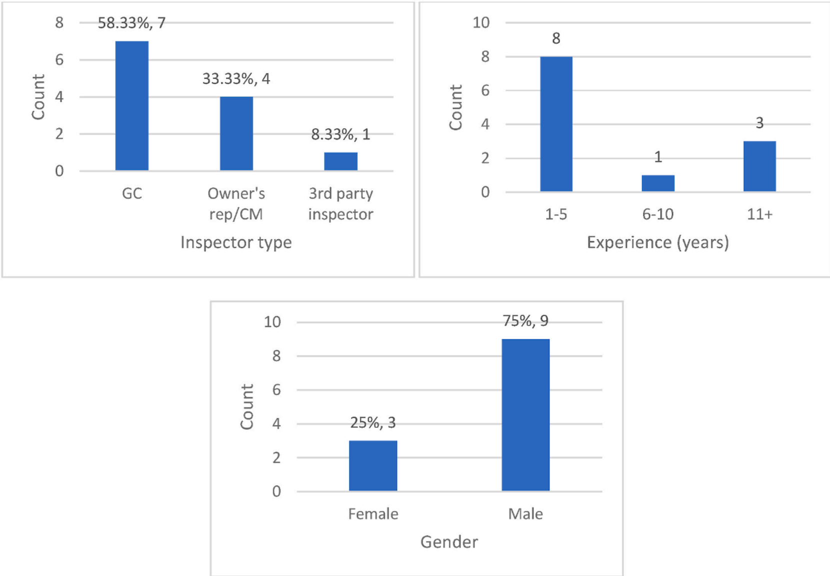

Fig. 4. Demographics of participants by company type (top-left), work experience (top-right), and gender (bottom).

In phase 3 of the study, a wider pool of construction inspection professionals was recruited to validate the two process maps. The demographics of the research participants for phase 3 are shown in Fig. 5. Twenty-five experts were interviewed in this phase. Out of those, four individuals participated already in phases 1 and 2 of the study. Other participants (twenty-one individuals) were new participants. Out of twenty-five research participants, four interviews were conducted in person, and the rest were conducted online. The interview procedure and content were the same for both in-person and online participants. The participants were from GC (44%), owner's rep/CM (32%), third-party consultants (20%), and building officials (4%) representing sixteen different companies. Three of the sixteen companies were represented in Phases 1 and 2 as well, while the rest thirteen companies were new in phase 3. Out of twenty-five, seven participants (28%) were female.

4.2. *Phase 1: conventional process of construction inspection and monitoring*

Fig. 6 shows the developed BPMN process map to demonstrate the conventional process of construction inspection and monitoring. The process is divided into three stages.

1. **Pre-inspection –** In this stage, the inspector refers to various project documents, such as drawings, BIM models, meeting notes, baseline and updated schedule, previous inspection notes or reports, etc., and prepares an inspection plan. Construction

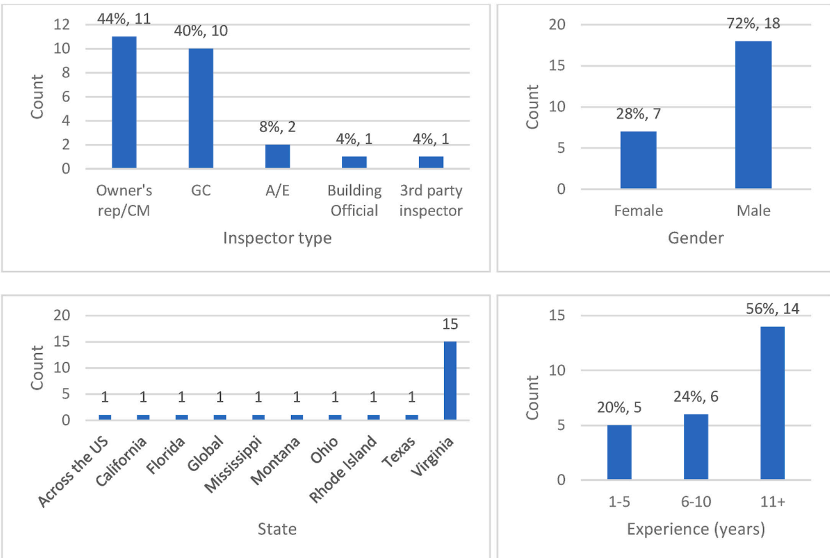

Fig. 5. Demographics of participants in phase 3 by company type (top-left), work experience (top-right), state (bottom-left) and gender (bottom-right).

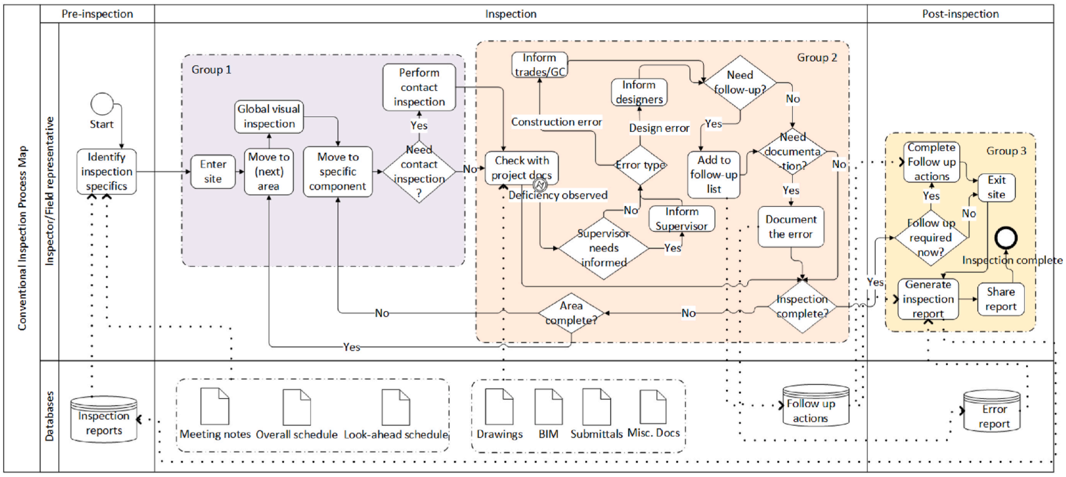

Fig. 6. The process map for conventional inspection and monitoring in construction.

inspection planning is a complex process owing to a large number of components, inspection goals, and available inspection methods [8]. Based on the planned and current state of the project, the inspector identifies the inspection specifics and decides the inspection goals and the right inspection method to meet the inspection objective. Inspection goals are discrete units of information collected by the inspector to assess the property or behavior of a building element [8]. Construction specifications play an important role in deciding the inspection specifics by specifying the level of accuracy and tolerances required for the construction work, which ultimately decides the required accuracy of measurements for inspection [93].

2. **Inspection –** The inspector performs a walkthrough of the construction site, observing the construction status, focusing on the specific components identified already in the inspection specifics, taking notes, and capturing images of the as-built status wherever required, identifying any construction deficiencies, and identifying follow-up items. They may or may not interact with their supervisor and/or project stakeholders on-site when needed.
3. **Post-inspection –** In this stage, the inspector follows up on any items identified during the inspection and completes their on-site inspection. Then, the observations from the on-site inspection are used to prepare the inspection report which could be in the official template of the company, or within an information management system used by the project team, or Portable Document Format (PDF) files and emails.

In the process of construction inspection and monitoring, the tasks in the "inspection" and "post-inspection" stages (as shown in Fig. 6) are grouped into the following three groups.

4.2.1. Group 1 – inspection initialization and data collection

The *Inspection* stage starts with the inspector entering the construction site and entering a target area as shown in Fig. 7. The target area can be a room, a hallway, or any small section of the facility under construction. After entering a target area, the inspector performs a global visual inspection of the space. The objective of this task is to observe and capture a general sense of the construction work completed or underway in the target area. After the global visual inspection, the inspector locates and focuses on specific com-

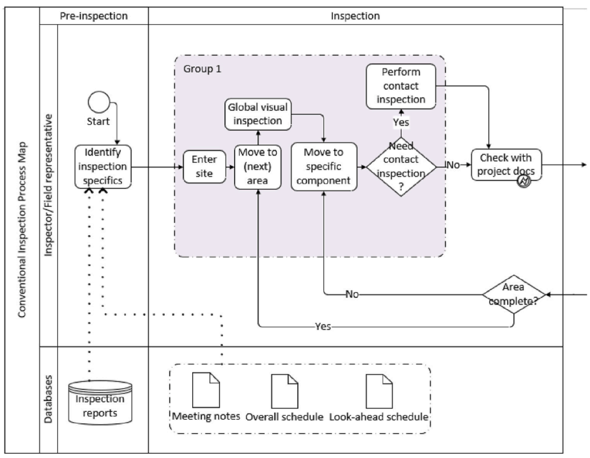

Fig. 7. Group 1 tasks.

ponents to inspect based on the identified "inspection specifics" in the pre-inspection stage (Fig. 6). Once the inspector locates a specific component, the inspector then often checks the construction documents (e.g., drawings) and compares the as-built work with the as-planned documents.

Certain components may require physical contact during the inspection. Examples of contact-based inspections include checking the electrical connections and opening access panels to inspect pipes and conduits. Fig. 8 shows inspectors performing contact-based inspection tasks. In Fig. 8 (left), the inspector checked the electrical panels with his hands to ensure that the cables are not loose or disconnected. In Fig. 8 (right), the inspector opened a small plumbing access panel with a key to inspect the mixing valves. The mixing valves mix the hot water with cold water before it flows to the sink. During the inspection, the inspector ensured that the valves are properly connected.

4.2.2. Group 2 – deficiency detection and resolution

Group 2 tasks (Fig. 9) involve verifying the work and sometimes informing relevant project stakeholders of any construction deficiencies observed. Through visual and other sensory observations (e.g., touching in contact-based inspection) of the building component and verifying the as-built status with as-planned construction documents, the inspector sometimes detects a deficiency in the construction work. Deficiency here refers to any work that does not meet all the requirements of the construction contract, design documents, guidelines, building codes, etc.

Once a deficiency is detected, the tasks that follow depend on the type of component, type of error, and the severity of the deficiency. For example, identifying a safety issue (e.g., an improperly guarded leading edge as shown in Fig. 10) may require immediate action and interactions with the responsible parties (e.g., trades), whereas a typical construction defect, such as a damaged non-structural component as shown in Fig. 11, might not need immediate action and can be addressed through the normal cycle of inspection reporting. Depending on the extent and type of the identified deficiency, the inspector may or may not need to notify their supervisor while they are on-site either for information or further consultation.

If the deficiency is a construction error, the inspector informs the trade contractors or the General Contractor (GC). What party the inspector is representing influences whom the information is directed to. For example, the owner's representative might inform the

Fig. 8. Examples of contact-based inspection. Left: the inspector checks the electrical wires for proper connection. Right: the inspector checks the connection of valves through a plumbing access panel.

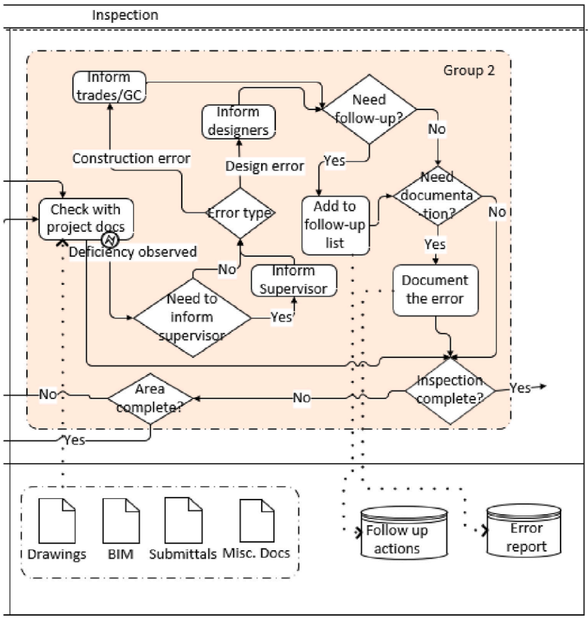

Fig. 9. Group 2 tasks.

Fig. 10. An improperly guarded leading edge causing a potential safety hazard.

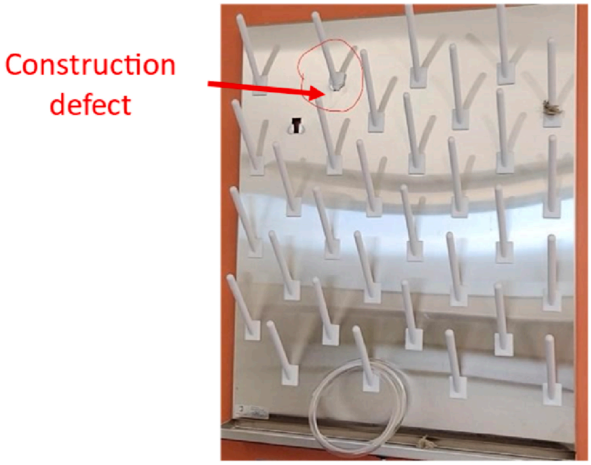

Fig. 11. Damaged plastic hooks as an example of a deficiency observed during a regular inspection.

GC but the GC's engineer would inform the foreman of the responsible trade directly. The information-sharing might occur through on-site interactions, phone calls, or emails. If the issue is a design error, the inspector (e.g., the owner's representative or the GC's engineer) informs the designers through a phone call or an email or they might issue an RFI for clarification or remediation. If the deficiency cannot be resolved immediately, the inspector might need to follow up on the same day or at a later date. The inspector maintains a list of items to follow up on. The inspector decides whether the deficiency needs follow-up and adds it to a follow-up list accordingly.

After follow-up, the inspector's next decision point is whether or not to document the identified deficiency. As observed in this research, the inspector might not document certain deficiencies, such as minor damages during construction unless not rectified after repeated intimation. However, most major deficienciesdeficiencies are documented by the inspector through the use of any documentation system used by the company (e.g., taking pictures, collecting point cloud data, using collaboration tools like BlueBeam, etc.). After information-sharing and documentation of the identified deficiencies, the inspector moves to the next component in the target area. When all needed components in the target area have been inspected, the inspector goes on to the next area, and this process loop continues until the inspection of all areas inside the facility under construction is finished, and thus the inspection stage is complete. After the inspector has completed all of the inspection goals, the process advances to the post-inspection stage, where the tasks in Group 3 are undertaken.

4.2.3. Group 3 – inspection finalization

The next group of tasks is to finalize the inspection and disseminate information as shown in Fig. 12. After the on-site walkthrough and inspection are completed as per the inspection specifics identified in the pre-inspection stage, if any follow-up items are remaining from the inspection stage the inspector follows up with the responsible parties (e.g., GC or trades) before leaving the site. For example, the GC's inspector might have noticed a segment of a wall in a room that had not received an appropriate amount of paint coats and warned the painters working nearby before proceeding with the inspection walk. After the completion of the inspection, the inspector may return to the room to check on the painting activity to confirm that the needed work has been completed. After completing the follow-up, the inspector exits the site. Finally, the inspector compiles their on-site inspection documentation (e.g., images, notes, etc.) prepared during the inspection along with the subjective observations from the site into an inspection report (or progress report, daily report, etc.). The inspection report is saved in the project database (through a documentation platform like Procore or SharePoint, or simply through shared files and emails), where it is referred to later by responsible project stakeholders, as well as the

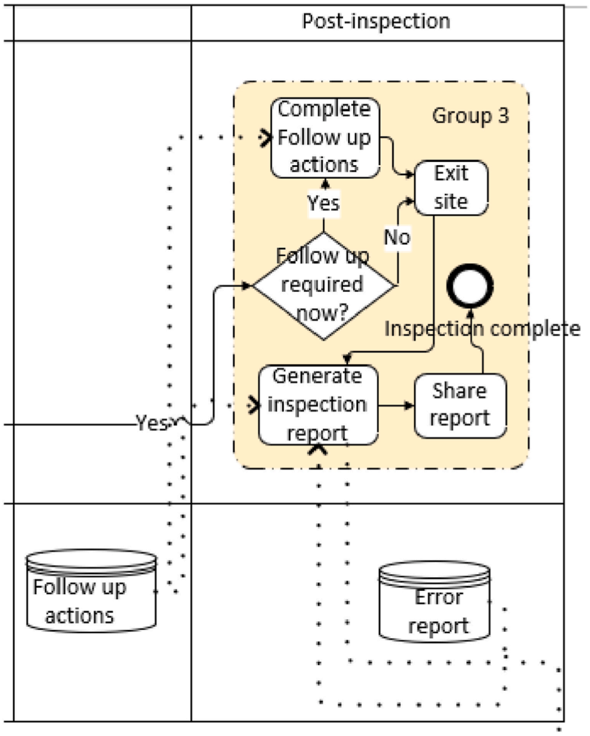

Fig. 12. Group 3 tasks.

inspector for future inspections and follow-ups. The content of the inspection reports is also important for any possible insurance or liability claims or conflict resolution later in the project.

4.3. Phase 2: future construction inspection and monitoring through human-robot teaming

As explained in Section 3, phase 2 involved providing the inspectors brief training on using the Spot robot and asking them to perform a virtual inspection with the robot. The inspectors were also interviewed before and after the training and virtual inspection. The inspectors were asked during the interview about their expectations from the robot and how the robot can help them in their job. The results of the interviews are coded and presented in Table 1. Although similar expectations were identified from the interviews before and after the inspectors worked with the robot, before working with the robot, 'take pictures' and 'take measurements' were the top two mentioned work expected by the inspectors from the robot whereas after working with the robot 'remote inspection' and 'take pictures' were the most common expectations. The data in Table 1 is sorted by the frequency of mentions for each of the expectations by the inspectors.

Based on the on-site observations and semi-structured interviews in phase 2, a process map was developed to propose a new paradigm for human-robot partnership in construction inspection and monitoring. Fig. 13 shows the alternative process map developed in this study. The proposed process is demonstrating how future inspection work can be conducted with the help of an inspector robot assistant. The purpose of the proposed process is not to eliminate the human from construction inspection and monitoring but to develop a human-robot partnership that allows the human inspector to focus on more high-level inspection and monitoring tasks that require human intelligence and allocate repetitive time-consuming site walkthroughs that require walking around the job site regularly for reality capture to the quadruped robot. The main robot task that can assist the human inspector with construction inspection and monitoring is to perform the first round of visual inspection to detect and highlight construction deficiencies for the human inspector to focus on. The quadruped robot can provide the reality capture during its site walkthroughs and if the robot is capable of performing a visual inspection to pass the construction components that meet the inspection specifications (i.e., building components with no deficiency) to a certain degree, then the human inspector can allocate more time on the construction components and items that need more attention e.g. areas that are of concern or components with any deficiency. The study assumes that the robot has an intelligently engineered system capable of visual inspection and deficiency detection. As discussed in Sections 2.3 and 2.4, previous research has used vision-based techniques for construction inspection such as photogrammetry and computer vision to take measurements, identify installed components, characterize human behavior, and detect construction defects [37,40,51,94]. This study focuses on the managerial and procedural aspects of robotic inspection and monitoring in construction and not on the technical aspects.

The proposed inspection process with quadruped robot assistant (Fig. 13) is explained below.

- **Pre-inspection -** the process starts in the pre-inspection stage similar to the conventional process when the human inspector identifies the inspection specifics for the current inspection and monitoring round. This involves referring to the project

Table 1
Expectations of construction inspection experts from the robot in performing inspection and monitoring tasks.

Before the robot experiment			After the robot experiment		
Expectation	**Description**	**#**	**Expectation**	**Description**	**#**
Take pictures	Robot can be used as a tool to autonomously take pictures.	8	Remote inspection	Robot may allow the inspector to remotely inspect the site and collect data if the inspector cannot travel to the site.	7
Take measurements	Robot can take measurements and check dimensions.	3	Take pictures	Robot can be used as a tool to autonomously take pictures.	6
Remote inspection	Robot may allow the inspector to remotely inspect the site and collect data if the inspector cannot travel to the site.	3	Quality control	Robot may detect construction defects or test material or color of installed components.	2
Progress update	Robot may identify the components installed and update progress/schedule.	2	Progress update	Robot may identify the components installed and update progress/schedule.	2
Follow-up previous errors	Robot may autonomously check the status of previously identified errors.	2	Follow-up previous errors	Robot may autonomously check the status of previously identified errors.	1
Weather monitoring	Robot may perform weather monitoring.	1	Take measurements	Robot can take measurements and check dimensions.	1
Safety monitoring	Robot may monitor activities and human behavior to identify any unsafe behavior.	1	Night vision	Robot may need lights or night vision to perform inspection during night.	1
Quality control	Robot may detect construction defects or test material or color of installed components.	1			
Steady navigation	Robot may have steady navigation and provide steady visuals of the site.	1			
Check for housekeeping	Robot may monitor the site for clutter and identify need for housekeeping.	1			

Table 2
Internal reliability test of the questionnaire.

Metric	Question	α	
Completeness	Above process map shows all the activities of the given process	0.50	Overall questionnaire reliability α = 0.84
	There are other activities for the given process that are not shown in the above process map (reverse scaled)		
	All the activities in the given process are reflected in the process map		
Accuracy	The process map accurately describes the given process	0.70	
	The name of the activities accurately describes the corresponding activity		
	The activities in the process map are relevant to the given process		
Generalizability	The process map can be generalized to a wide range of situations	0.44	
	The process map shows the process in only a limited type of situations (reverse scaled)		
	The variation in the process from day-to-day or project-to-project is captured in the process map		
Comprehensibility	It was easy for me to understand the process from the process map	0.72	
	The names of the activities, events, or decisions in the process map were confusing (reverse scaled)		
	The connections between the activities are easy to follow		
Reliability	I am confident that the robotic process map can be implemented in real construction projects	0.81	
	I am confident in the ability of robots to perform the tasks depicted in the process map		
	I can rely on the information provided by robots		

As discussed in the Research Methodology section, the sample size was decided using the principle of saturation [90], i.e., data collection was stopped when the additional data points did not change the mean of the measured variables significantly. As can be seen from Fig. 14, after collecting twenty data points, the mean of the five measured variables had stabilized, i.e., did not move significantly with additional data points. Data collection was stopped after collecting twenty-five data points, since saturation had been achieved and adding more data would not affect the mean of the variables significantly.

documents including schedules, drawings, any meeting notes, etc. to determine what construction work has been completed or is underway. Then the human inspector can plan the inspection specifics (i.e., the robot's mission) as well as inspection criteria (that can include the tolerance level of inspection) and upload them to the robot's interface. The tolerances allowed in the construction work, such as in terms of verticality, linearity, and dimensions are governed by the construction specifications [93].

- **Data collection –** After the human inspector specifies the inspection specifics and criteria, a mission is generated for the robot for its site walkthrough and data collection. The quadruped robot can utilize the BIM model to find an optimum path through the target locations where inspection should be performed (S [14]. Then the robot can walk through the mission path to reach the first inspection area (e.g., room or hallway). If the robot encounters an obstacle that prevents the robot from reaching the area, the robot will need to stop and mark that area as inaccessible thus adding the inspection area and its construction components to the *Inspector Actions* list. This list contains the items that require human attention and will be reported to the human inspector

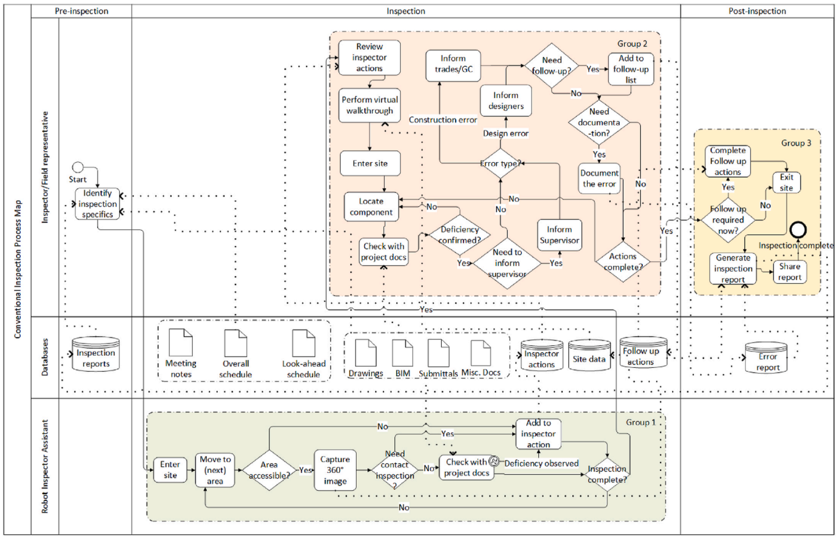

Fig. 13. Alternative process map for construction inspection and monitoring with an inspector assistant robot.

once the on-site walkthrough and inspection by the assistant robot are completed. The area accessibility is a critical success factor for the quadruped robot assistant [15].

If the area is accessible, the robot enters the area and performs reality capture in the form of a 360° image. A 360° (or spherical) image provides a realistic and detailed view of the site [95]. Spherical imaging also eliminates the need for multiple images captured within the same area. The reality capture is then added to the *Site data* database which can be later reviewed by the human inspector for an overall virtual inspection before entering the construction site. At this point, the robot will need to determine whether any building components in the area require contact-based inspection. As explained in Section 4.2.1, some elements need a contact-based inspection, such as electrical wires, water faucets, etc. Those components will need to be tagged in the robot's report to be addressed by the human inspector.

- **Information retrieval** – The robot will process the reality capture data using computer vision techniques, such as convolutional neural network (CNN) to detect the as-built construction components and compare them with the as-planned documents (e.g., BIM) similar to the methodologies proposed by Refs. [96,97]. Natural Language Processing (NLP) will be used to analyze codes and contract documents for compliance checking [98]. Low confidence in matching between the as-built information and as-planned information below a preset level will trigger the robot to flag the corresponding components as deficient. The robot will highlight the areas of concern on the site images collected by it for review by the human inspector and further actions.
- **Visualization** – Finally, once the whole project site is inspected by the quadruped robot, the human inspector will be notified. The human inspector can access the site data captured and generated by the assistant robot. The site data can include annotated visual data with labels on the components that have been inspected by the assistant robot and the preliminary results from visual processing as to whether the system has detected any deficiencies or not). Using the site data, the human inspector can then perform a virtual walkthrough of the construction site and can review the action items tagged by the robot assistant system including any areas or components that were not inspected by the robot or the components that are tagged as deficient. With this site data in hand, the human inspector can then perform an informed and focused visit to the job site. For this, the inspector can directly locate the components that need closer attention. During this focused inspection, the inspector can use their expertise and check the component against project documents to decide whether a deficiency exists or not and decide on the actions to follow (similar to the conventional process of construction inspection and monitoring). If the deficiency does not exist, the inspector can move forward to the next action item. If not, then the error resolution process follows similar to the conventional process of construction inspection and monitoring.

4.4. Phase 3: validation of the developed process maps

The process maps developed in phases 1 and 2 of the study were validated through semi-structured interviews with twenty-five construction professionals involved in the inspection and monitoring of construction projects. The interview questionnaire measured the validity of the developed BPMN process maps for the conventional and future process of construction inspection and monitoring in four metrics, i.e., completeness, accuracy, generalizability, and comprehensibility. For the alternative process map for robotic inspection, another factor was added, i.e., reliability of the data collected by robot from the inspector's point-of-value. Each metric had three questions to ensure the internal reliability of the scale used. The internal reliability was measured through Cronbach's alpha test with the data for both the process maps combined. The results of the Cronbach's alpha test are shown in Table 2 [99]. recommended an alpha value of 0.70–0.95. Although, the value of Cronbach's alpha was found to be greater or equal to 0.70 for the Accuracy, Comprehensibility, and Reliability factors, the alpha was found to be low for Completeness and Generalizability. However, it should be noted that Cronbach's alpha only measures internal reliability, i.e., how well the items for the single factor correlates with each other. Tavakol and Dennick noted that the Cronbach's alpha can be low for many reasons, such as less number of test items for one factor, poor inter-relatedness between items, or heterogenous constructs, i.e., the items measuring more than one factor. Additionally, the overall reliability of the questionnaire, i.e., Cronbach's alpha for all the questionnaire items combined together was found to be 0.84, which shows good overall internal reliability of the questionnaire. Hence, the results were accepted for evaluation of the process maps.

A power analysis was also performed to ascertain the suitability of the sample size. The power of a statistical test measures the probability of rejecting a null hypothesis when it is indeed false [100]. The power depends on the standard deviation of the sample. The power of the tests for each of the variables are shown in Table 3. The powers were calculated with the sample size of 25 and the effect size, i.e., the difference in mean to detect of 0.5.

4.4.1. Validation of phase 1 results

The distribution of responses on each of the metrics is shown in Fig. 15. The significance of the results was tested through the Wilcoxon Signed Rank test for ordinal data using the JMP statistical package. The mean value of each of the parameters was hypothesized to be greater than 3.0. A p-value less than 0.05 shows the probability that the distribution is higher than 3.0 by chance is less than 5%. The mean value for each of the parameters is presented in Table 4 along with the p-value associated with the mean being greater than 3.0.

As can be seen from Table 4, the mean values of the four parameters, namely, completeness, accuracy, generalizability, and comprehensibility are more than 3.0. For the scale used in the questionnaire, a value above 3.0 shows agreement with the questionnaire item, and the Wilcoxon Signed Rank test shows that the mean is significantly higher than 3.0 ($p < 0.05$).

Table 3
Power analysis results for the measured variables.

Variable	Standard deviation of the sample	Power
Completeness	0.64	98.41%
Accuracy	0.41	99.99%
Generalizability	0.54	99.78%
Comprehensibility	0.45	99.99%
Reliability	0.64	98.41%

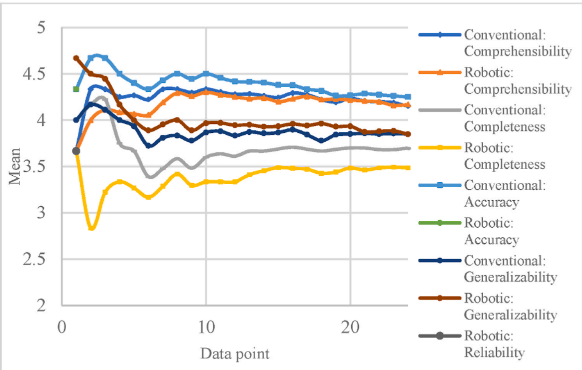

Fig. 14. Variation of the measured variables with additional data points.

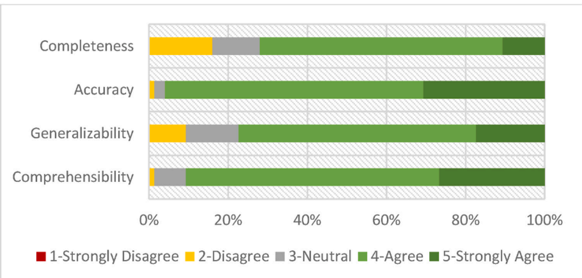

Fig. 15. Distribution of responses for validation of conventional inspection process map.

Table 4
Results of the validation of the conventional inspection process map.

Parameter	Mean (μ)	Std. dev.	p-value (μ > 3.0)
Completeness	3.67	0.65	< 0.0001
Accuracy	4.25	0.43	< 0.0001
Generalizability	3.84	0.55	< 0.0001
Comprehensibility	4.14	0.48	< 0.0001

During the validation phase (phase 3), the experts provided feedback on how the process map could be improved. The suggestions and feedback from the experts were transcribed and coded. After analyzing the transcripts, seventeen different improvements were identified for the conventional process map. These improvement changes are tabulated in Table 5.

4.4.2. Validation of phase 2 results

Similar to the validation of the conventional inspection process map (phase 1 results validation), the proposed process map for future construction inspection and monitoring with human-robot teaming was also validated within the same semi-structured interview surveys. In the questionnaire for the validation of phase 2 results, an additional variable was added which is the perceived reliability of the assistant robot in the context of performing the proposed inspection tasks. The results of the phase 2 validation are shown in Fig. 16 and Table 6.

Similar to the conventional process map, feedback from the interview participants was sought to improve the proposed process map for future construction inspection and monitoring with human-robot teaming. The suggestions and feedback were transcribed and coded. Nine different improvement changes were identified from the interview analysis, which is presented in Table 7.

5. Discussion

Based on the feedback from experts in phase 3, the two process maps were updated. The updated process map for the conventional process of construction inspection and monitoring is shown in Fig. 17. The following changes were made to the conventional process map in response to the suggestions received from the experts presented in Table 5.

1. The inspector may go to an area and take pictures even before they detect any deficiency. For this, a decision point and a task were added after *Global Visual Inspection* in *Group 1* for reality capture which may be a 2D image, a 360° image, or a laser scan. The output of the *Reality Capture* task is added to the *Site data* database which is also used for preparing the inspection report in the *Post-inspection* stage.
2. The inspector may revise the inspection specifics/goals if new work is observed during the inspection. Therefore, a new task "*Revise inspection specifics*" is added in *Group 1*.
3. The contract is an important document that is referred to during the inspection and monitoring. Therefore, *Contract* has been added as a document that is referred to in the *Check with project docs* task.
4. During the *Pre-inspection* stage, in addition to meeting notes and schedules, the inspector may also refer to the drawings, BIM, submittals, and contract to familiarize themselves with the work to be inspected. Therefore, those documents are associated with the *Identify inspection specifics* task in addition to the *Check with project docs* task.
5. Once a deficiency is observed, the inspector may choose to inform the responsible party, such as the GC or the trade either from the site or from the office after finishing the inspection. Therefore, a decision point *Inform responsible party now* has been added in *Group 2.* If the inspector chooses to inform the responsible party from the site based on the urgency of the deficiency, the inspector first decides the error type as the error/deficiency can be a construction error or can be a design error. Based on the error type, the inspector identifies the responsible party who can be the trade, GC, or designer. For certain types of inspectors, such as building officials, the GC may be the single point of contact. Therefore, from those inspectors' point of view, the responsible party may remain the same for all error types. For them, the *Identify responsible party* will be a zero-duration task.
6. A new decision point and a task have been added in *Group 3* for informing responsible parties of any deficiencies after finishing the inspection.
7. Documenting the identified deficiency is not optional and all deficiencies should be documented. Therefore, the decision point *Need documentation* in the original conventional process map has been removed.

Similarly, the robotic inspection process map proposed in this study was improved based on the feedback received from the experts. Fig. 18 shows the improved robotic inspection map. Following changes were made in response to the suggestions received from the expert and presented in Table 7.

1. After the inspector has identified the inspection goals in the *Identify inspection specifics* task, an intermediate task *Prepare robot mission* is added to upload the inspection goals to the robot's system interface.
2. As pointed out by some experts, not all types of errors might be detected through 360° images. Therefore, the robot may need to perform multi-modal inspection through the use of laser scanning or other reality capture tools. The choice of inspection mode will be decided from the inputs received from the robot including the target components, inspection criteria (dimensions, presence, color, texture, etc.), and tolerance. The task of collecting relevant data for inspection by the robot has been renamed to *Reality capture* to cover all data collection techniques.

Table 5
Improvements suggested by the experts in the conventional process map.

Suggested Change	Description	Example Quote
Revise inspection specifics on-the-go	The inspector may add or remove items from the inspection specifics while performing the inspection based on the site observations.	"I have a pretty good idea what I am going to look at, but it may change when I get here."
Include contract	The inspector, in addition to BIM and drawings, also refers to contract specifications for checking the components.	"Under the project documents … often specifications trump drawings in terms of hierarchy. So I would absolutely have listed specifications …" "… keep misc. documents in there, but you might wanna add like contract documents …"
Refer all docs in pre-inspection	The inspector reviews almost all the project-related documents during the pre-inspection stage as well as during inspection.	"I will have smoother inspection by reviewing the BIM, drawings, submittals, etc. in pre-inspection stage as well."
Informing trade/GC/ designer after exit site	Sometimes, the inspector may defer informing the responsible party until the end of the inspection round.	"The identification of who is responsible doesn't happen until the reporting process when you look into who you need to coordinate with" "You can have an option that it (informing trades/designers) can go in group 2 or in group 3"
Informing through supervisor	Sometimes, the inspector may only need to inform their supervisor, who in turn will identify the responsible party and pass the information.	"… we are design-build firm. So I manage both the engineering and the construction ….in those style projects under that contract type, the only difference would be … you would just consolidate the designer, trade, GC portion of it 'cause … they always come to me because I'm the one who then formally ask the designer and or formally ask our Superintendent …"
Multi-modal inspection	The inspector may need to take measurements or perform testing in addition to visual inspection.	"Most of the time visual inspection also has follow-up with some kind of testing."
Root cause analysis	The inspector may also need to identify the root cause of the deficiency.	"Something that typically exists in large projects is make sure we not just identify the items but also track them back afterwards."
Refer to building codes as well	The inspector refers to building codes more than BIM or drawings.	"We rely on building codes"
Prioritizing errors	The inspector may prioritize resolution of one deficiency over another.	"Typically, there is a mechanism to prioritize punch list items accordingly."
Pre-inspection as a sub-process	The identification of inspection specifics is an involved step and may be represented as a sub-process instead of a task.	"That pre-inspection box that says identify inspection specifics is a huge box. It is a very huge task for a human to review …..to ensure that the inspection is performed exactly how it should be performed. Without that knowledge and experience, someone may see identifying inspection specifics as a very minor step …..but it is huge and it defines the success of the inspection."
Parallelization of informing GC and supervisor	Informing trade/GC and informing supervisor may happen in any order.	"It [order of informing GC and supervisor] can go either way"
Informing designer through GC	The inspector, especially a building official, may inform only the GC even if it's a design error.	"We do not choose whether to send it to designer or GC. We send everything to GC. We don't decide whether it's construction error or design error, we just say it's a non-compliance."
Predicting future deficiency	The inspector may also identify and inform others about something which is not a deficiency at the time of inspection but may create one in the future.	"Sometimes we are not checking something against project doc. Sometimes we are predicting problem along the way."
Different process map for safety inspection	For safety inspection, the process may differ from other types of inspection.	"safety inspections can get a little tricky because sometimes you need like an immediate reaction before you can even do any documentation."
Documenting global inspection	Inspectors also document (take pictures) even if there is no deficiency, for future review.	"I often go in and just snap a whole bunch of pictures in the room, and then I would go take specific pictures if there was a deficiency"
100% documentation	All deficiencies must be documented.	"When we talk about document the error….in terms of full transparency and integrity of the system ….'No' should not be an option."
Skipping global inspection for a pre-known deficiency	Sometimes the inspector may directly go to a specific component because a previous inspection report or a team member has informed about a deficiency previously identified.	"Sometimes you're going through the space and you're looking for deficiencies, but sometimes you're going out specifically to look at something that somebody else has already pointed ….it's (inspection report) sometimes that skips you straight to move to specific component …"

3. While the human inspector is performing the virtual walkthrough, other deficiencies that were missed by the robot may be found. As a result, if the human inspector detects new deficiencies during the virtual walkthrough, the inspector will update the action items and add new items to be inspected during the physical walkthrough.
4. In contrast to the preceding point, the inspector may confirm or reject deficiencies detected by the robot assistant through the virtual walkthrough. On some occasions, this may remove the need for a physical walkthrough. As a result, a decision point in Group 2 has been added to determine whether a physical walkthrough is necessary.
5. The other *Group 2* and *Group 3* tasks have been updated according to the revisions made in the conventional process map.

As discussed in Section 2.4, the adoption of robotics depends on various technological and organizational factors. In fact, it has been argued that technology is not the primary determining factor that hinders the successful adoption of technology, rather it is the organizational and procedural difficulties [101]. Compatibility with the existing process is one of the key determinants of the success-

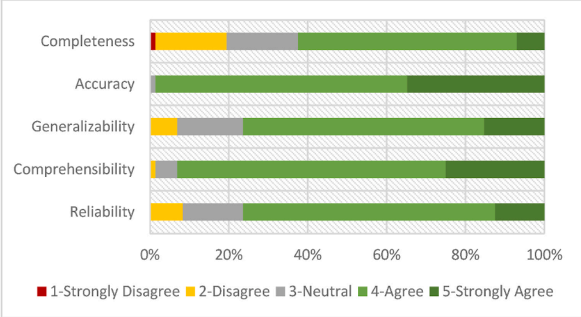

Fig. 16. Distribution of responses for validation of conventional inspection process map.

Table 6
Validation results for proposed robotic inspection process map.

Parameter	Mean (μ)	Std. dev.	p-value (μ > 3.0)
Completeness	3.49	0.63	0.0005
Accuracy	4.33	0.41	< 0.0001
Generalizability	3.85	0.55	< 0.0001
Comprehensibility	4.17	0.43	< 0.0001
Reliability	3.81	0.66	< 0.0001

Table 7
Improvements suggested by the experts in the robotic process map.

Suggested Change	Description	Example Quote
Continual learning	Robots should learn from the human inspector, so that human involvement may be reduced over time.	"When you do like if the human interface says that the deficiency was not an actual deficiency can that get reported back to the robot somehow and so in the future they're not reporting that same non-deficiency."
Prep work	A task should be added for mission planning and preparation of the robot.	"There is a little prep work goes before you send the robot to the site."
Physical manipulation	The robot may put physical markers on the structure for assisting the human inspector.	"Sometimes people still need physical things to reference. I think if you could add it. If the robot could, you know, spray paint might not be the best idea. But you know, just put a flag there or. In some way, flag it in the physical world. That would be super helpful."
Multi-modal inspection	Other sensors can be added to the robot	"360° [image] is not the only sensor, you can have multiple sensors. You can [have] from [laser] scanning to other sensors which reflects safety and material strengths and some other things." "If you talk about the federal projects, they talk like a 1/16 inch tolerance, 1/8th inch tolerance ….. When you talk about the 360° photographs, most of the times, they don't work for those kinds of tolerances. So you need to select what kind of hardware you wanna put on a robot like Lidars ……You need to select the options, the process, based on the specs."
Mission re-attempt	If an area is inaccessible or if the robot is out of power, the robot may suspend the mission and re-attempt later.	"Humans may wait for other human to finish their work. Robot may need to wait or decide it cannot go right now, so it should come back later." "Does the robot know when to stop because its battery life is like 80% done. He needs to go back to its space."
Optional human visit	A physical visit by a human may not always be required.	"What if the inspector performs a virtual walkthrough and sees that it is all okay. Then may not need to go to the site. The person may identify the deficiency from the photograph."
Off hours inspection	Since people working at the site may obscure the details for the robot, sending the robot during off-hours may be better.	"I think for a small to medium size project where not too many crazy things or 1000 subs working on top of each other and I think this is a perfect flow chart but I think it gets a little more tricky when you have more trades involved and limited area … and especially trying to get a 360 image."
Code review	Building codes should be added to check as-built status against.	"But you're never gonna get rid of that code review that jurisdictional reviewer."
BIM as 4D BIM	A 4D BIM might be required for the robot to navigate and inspect the project.	"It's not just we have BIM model, we need the 4D BIM model which reflects the current state of the environment."

ful adoption of robotics [56]. Therefore, the alternative process of construction inspection and monitoring developed in this study is grounded in the existing process being applied in the industry. The human-human interaction goes beyond just communicating project issues to project partners and also plays an important role in trust building [102]. Multiple human-human interactions were identified in the existing construction inspection and monitoring process, e.g., the interactions between the inspector and their supervisor in group 2 tasks in Fig. 17. Therefore, the proposed robotic process (Fig. 18) retains the identified human-human interactions, and utilizes the robot as a data collection and primary filtering tool. The robot's main duty in the new process is to reduce the number of

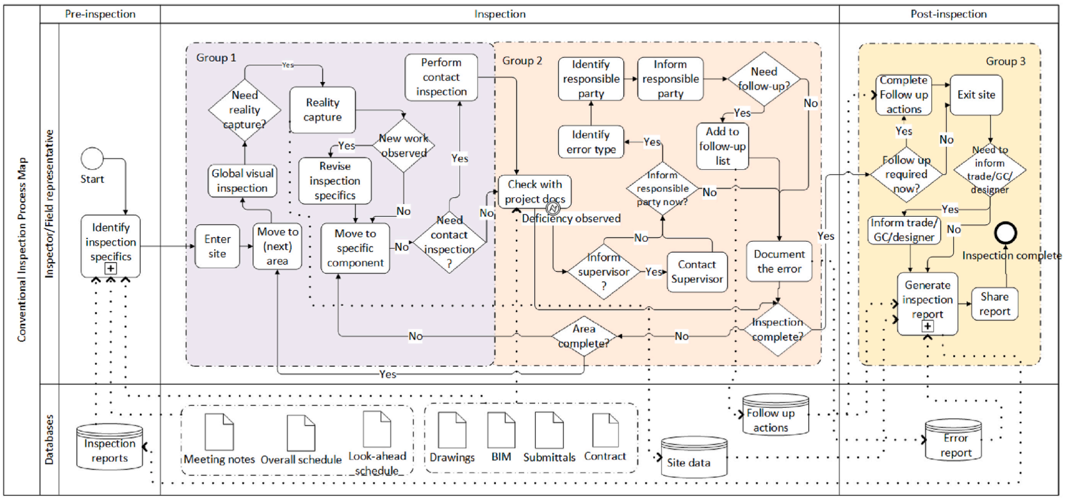

Fig. 17. Finalized process map for conventional inspection and monitroing process in construction.

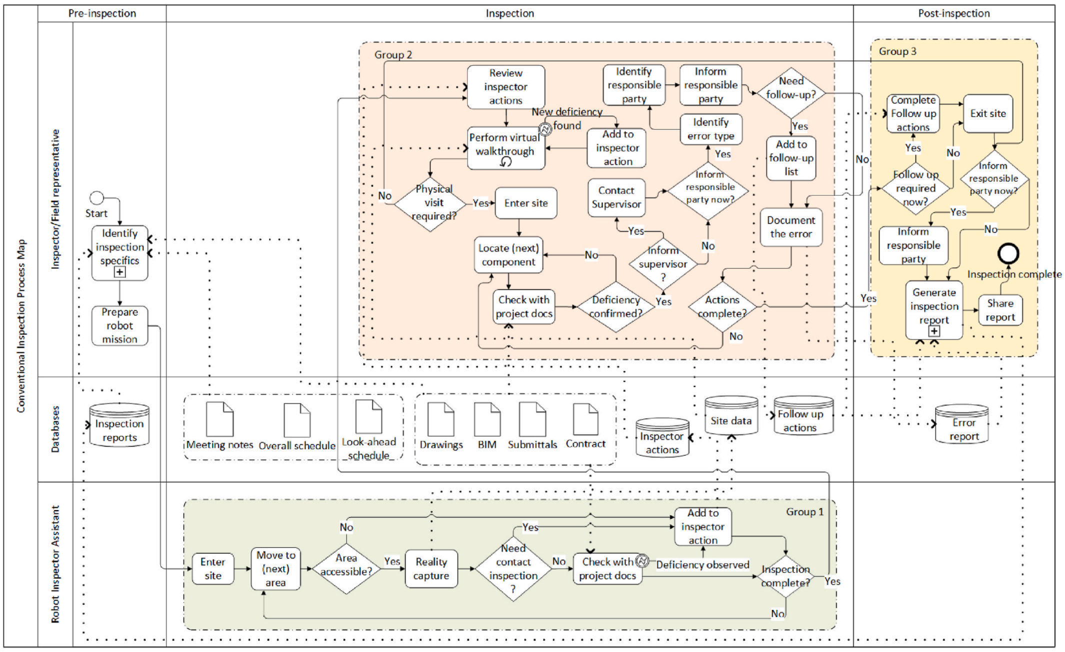

Fig. 18. Finalized process map for construction inspection and monitoring with an inspector assistant robot.

repetitive and mundane tasks an inspector performs. The robot also gathers and delivers prior information to the human inspector, ensuring that the human inspector arrives at the site fully informed on the work completed to date.

6. Conclusion

Construction inspection and monitoring is a critical component of effective construction management. Many project stakeholders (e.g., owner's representatives, designers, engineers, general contractor's field engineers, etc.) inspect and monitor the project during the construction phase. However, conventional inspection has several limitations, including lack of specialized inspectors, lack of suitable documentation methods, and being time-consuming, unsystematic, and subjective. By studying the conventional inspection and monitoring process in construction, this study proposed an alternative approach to performing construction inspection and monitoring through human-robot teaming with an assistant quadruped robot. A generalized process map for the inspection and monitoring process in construction was first developed by conducting on-site observations of twelve construction experts executing inspection and monitoring work. An alternative process map for construction inspection and monitoring with a quadruped robot was developed after interviewing the same experts, training them to operate the robot on-site, and further observations of them repeating the inspection tasks but this time with the quadruped robot. Both process maps were validated through interviews with twenty-five construction professionals who also engage in construction inspection and monitoring. On the four evaluation criteria, namely, completeness, accuracy, generalizability, and comprehensibility, all of which were scored using a five-point Likert scale (5 being strongly agree and 1 being strongly disagree), the construction inspection professionals rated 3.67, 4.25, 3.84, and 4.14 respectively for the conventional process map. The same experts rated 3.49, 4.33, 3.85, and 4.17 on the same four evaluation criteria for the alternative process map for robotic inspection. This shows that (a) the conventional process map reflects the existing process of inspection and monitoring followed on construction sites and (b) the proposed alternative process map within human-robot teaming can be implemented for future inspection and monitoring in construction. On the reliability scale that measures how much construction experts can rely on a quadruped robot to assist them with inspection and monitoring work, the construction experts assigned a rating of 3.81 (5 being the most reliable). This shows that the experts can rely on the robot if adopted in the future for construction inspection and monitoring.

The findings of this study provide a fundamental understanding of the conventional process of construction inspection and monitoring by identifying the sequence of tasks within the process. The proposed process map also depicts the future construction inspection and monitoring process with the use of human-quadruped robot teaming. Additionally, the contribution of this study to the state of practice includes the identification of a systematic construction inspection and monitoring process to inform construction companies and project participants for project management and decision-making.

The study's limitation is that it focuses on construction inspection and monitoring in the commercial construction sector, thus the process of inspection and monitoring in the residential and heavy civil construction sectors would need to be investigated further. Another limitation is that during phase 1 of the study, inspection experts from the owner, general contractor, and third-party inspectors were observed. A/E inspection was not observed for preparing the conventional process map although research participants from A/E teams were included in the validation interviews. This study took place in the United States, and the research participants for both onsite observations and online interviews were from projects in the United States. Future research may use the methodology of this study in other countries or regions to confirm parallels and variations in the inspection and monitoring processes. Future research can also conduct simulation studies of the developed process maps in this paper to quantify time and resource savings in the proposed process compared to the conventional process to evaluate the potential of adopting inspector assistant robots in construction inspection and monitoring. During this research, many insights were generated through the interactions with construction inspection experts. Some of the insights were related to robot application scenarios that are out of the scope of this work. For example, some scenarios in which quadruped robots may also assist in construction projects are updating schedule, security surveillance, and housekeeping. Future research can adopt a similar methodology as in this study to develop alternative processes for these application scenarios. In this research, the process of construction inspection and monitoring was investigated from a managerial standpoint by defining the tasks and sequences involved. The socio-technical and socioeconomic implications of the application of an inspector assistant quadruped robot on construction sites will be investigated in a future study. In this research, a one-to-one human-robot partnership was considered, i.e., one inspector and one inspector assistant robot. With future development in the field of social robotics and human-robot interaction, more complex human-robot partnerships may emerge, such as one-to-many, many-to-one, and many-to-many [103,104].

With the introduction of human-robot teams, new competencies and skillsets will be required in the future workplace. With the advancements in Industry 4.0 technologies which includes robotics, education 4.0 should also evolve simultaneously [105]. Future research should identify the required competencies that need to be developed and integrated into construction education to train future construction professionals [107].

Author statement

Srijeet Halder: Writing - Original Draft, Writing - Review & Editing, Methodology, Investigation, Validation, Formal analysis, Visualization, Project administration. **Kereshmeh Afsari:** Writing - Review & Editing, Conceptualization, Methodology, Investigation, Supervision, Funding acquisition, Project administration. **Erin Chiou:** Writing - Review & Editing, Resources. **Rafael Patrick:** Investigation, Resources, Supervision, Funding acquisition, Writing - Review & Editing. **Kaveh Akbari Hamed:** Conceptualization, Supervision, Funding acquisition, Writing - Review & Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

This material is based upon the work supported by the National Science Foundation (NSF) Future of Work at the Human-Technology Frontier Big Idea under Grant No. 2128948. The authors would also like to thank Mr. Paul Ely and Mr. John Thompson for their valuable support and help throughout the research.

References

[1] C.-W. Feng, C.-W. Chen, Using BIM and MR to improve the process of job site construction and inspection, WIT Trans. Built Environ. 192 (2019) 21–32.
[2] S.F. Ochoa, G. Bravo, J.A. Pino, J. Rodríguez-Covili, Coordinating loosely-coupled work in construction inspection activities, Group Decis. Negot. 20 (2011) 39–56.
[3] H. White, R. Marasini, Management of interface between main contractor and subcontractors for successful project outcomes, J. Eng. Proj. Prod. Manag. 4 (2014) 36–50.
[4] W.D. Mahoney, Construction Inspection Manual, eighth ed., Craftsman Book Company, 2008.
[5] B. Rouhanizadeh, S. Kermanshachi, Challenges and strategies incorporated with transportation construction inspection, in: Construction Research Congress 2020, 2020, pp. 446–454, https://doi.org/10.1061/9780784482889.047.
[6] K. Han, J. Degol, M. Golparvar-Fard, Geometry-and appearance-based reasoning of construction progress monitoring, J. Construct. Eng. Manag. 144 (2018) 4017110.
[7] Ken Simonson, Construction Data [WWW Document]. Associated General Contractors of America. URL. https://www.agc.org/learn/construction-data, 2022, 7.14.22.
[8] C. Gordon, B. Akinci, J.H. GarrettJr, Formalism for construction inspection planning: requirements and process concept, J. Comput. Civ. Eng. 21 (2007) 29–38 https://doi.org/10.1061/(ASCE)0887-3801, 2007)21:1(29.
[9] R. Navon, R. Sacks, Assessing research issues in automated project performance control (APPC), Autom. ConStruct. 16 (2007) 474–484, https://doi.org/10.1016/J.AUTCON.2006.08.001.
[10] M. Kopsida, I. Brilakis, P. Vela, A review of automated construction progress and inspection methods, in: Proceedings of the 32nd CIB W78 Conference on Construction IT, 2015, pp. 421–431.
[11] M. Golparvar-Fard, F. Peña-Mora, S. Savarese, Monitoring of construction performance using daily progress photograph logs and 4D as-planned models, Proc. 2009 ASCE Int. Workshop on Comput. Civ. Eng. 346 (2009) 53–63, https://doi.org/10.1061/41052(346)6.
[12] R. Samsami, A. Mukherjee, M. Asce, C.N. Brooks, Application of unmanned aerial system (UAS) in highway construction progress monitoring automation, in: Presented at the Construction Research Congress 2022, American Society of Civil Engineers, Arlington, Virginia, 2022, pp. 698–707, https://doi.org/10.1061/9780784483961.073.
[13] K. Afsari, S. Halder, M. Ensafi, S. DeVito, J. Serdakowski, Fundamentals and prospects of four-legged robot application in construction progress monitoring, in: ASC International Proceedings of the Annual Conference, 2021, pp. 271–278.
[14] S. Halder, K. Afsari, J. Serdakowski, S. DeVito, A methodology for BIM-enabled automated reality capture in construction inspection with quadruped robots, in: Proceedings of the International Symposium on Automation and Robotics in Construction, 2021, pp. 17–24.
[15] K. Afsari, S. Halder, R. King, W. Thabet, J. Serdakowski, S. Devito, Mahnaz Ensafi, J. Lopez, Identification of indicators for effectiveness evaluation of four-legged robots in automated construction progress monitoring, in: Construction Research Congress, American Society of Civil Engineers, Arlington, 2022, pp. 610–620, https://doi.org/10.1061/9780784483961.064.
[16] Y. Li, B. Li, J. Ruan, X. Rong, Research of mammal bionic quadruped robots: a review, in: 2011 IEEE 5th International Conference on Robotics, Automation and Mechatronics (RAM), IEEE 5th International Conference on Robotics, Automation and Mechatronics (RAM), 2011, pp. 166–171 https://doi.org/10.1109/RAMECH.2011.6070476, Presented at the 2011.
[17] C.-F. Fan, C.-C. Chan, H.-Y. Yu, S. Yih, A simulation platform for human-machine interaction safety analysis of cyber-physical systems, Int. J. Ind. Ergon. 68 (2018) 89–100, https://doi.org/10.1016/j.ergon.2018.06.008.
[18] E.S. Park, M.S. Park, Factors of the technology acceptance model for construction IT, Appl. Sci. 10 (2020), https://doi.org/10.3390/app10228299.
[19] R. Navon, Y. Shpatnitsky, Field experiments in automated monitoring of road construction, J. Construct. Eng. Manag. 131 (2005) 487–493 https://doi.org/10.1061/(ASCE)0733-9364, 2005)131:4(487.
[20] American Institute of Architects, A201- 2017 General Conditions of the Contract for Construction, 2017 [WWW Document]. URL. https://www.aiacontracts.org/contract-documents/25131-general-conditions-of-the-contract-for-construction. 8.10.22.
[21] J.B. Atkins, G.A. Simpson, Substan. Compl. Where Art Thou? (2006) [WWW Document]. AIA best practices. URL http://info.aia.org/aiarchitect/thisweek06/0127/0127bp_risk.htm (accessed 7.16.22).
[22] The Construction Management Association of America, An Owner's Guide to Construction and Program Management - Enabling Project Success under Any Delivery Method, 2011.
[23] H. Nassereddine, T. Endres, A. Hanna, Assessment of the role of owner's representative on construction performance: an owner's perspective, in: S.M. Ahmed, P. Hampton, S. Azhar, A. D.Saul (Eds.), Collaboration and Integration in Construction, Engineering, Management and Technology, Springer International Publishing, Cham, 2021, pp. 471–476.
[24] Y. Li, S. Al-Haddad, T.R. Taylor, P.M. Goodrum, R.E. Sturgill, Impact of utilizing construction engineering and inspection consultants on highway construction project cost and schedule performance, Transport. Res. Rec. 2673 (2019) 716–725.
[25] LetsBuild, Construction Site Inspection: Why It's Important to Your Construction Project and Business, LetsBuild, 2019 URL. https://www.letsbuild.com/blog/construction-site-inspection-why-its-important-to-your-construction-project-and-business. 7.21.22.
[26] International Code Council, International Building Code, 2021.
[27] International Code Council, 2018 International Building Code Illustrated Handbook, McGraw-Hill Education, 2018.
[28] Bureau of Labor Statistics, U.S.D. of L, Construction and Building Inspectors, 2021 [WWW Document]. Occupational Outlook Handbook. URL. https://www.bls.gov/ooh/construction-and-extraction/construction-and-building-inspectors.htm. 10.18.21.
[29] M. Golparvar-Fard, Feniosky Peña-Mora, C.A. Arboleda, S. Lee, Visualization of construction progress monitoring with 4D simulation model overlaid on time-lapsed photographs, J. Comput. Civ. Eng. 23 (2009) 391–404, https://doi.org/10.1061/ASCE0887-3801200923:6391.
[30] A. Almukhtar, Z.O. Saeed, H. Abanda, J.H. Tah, Reality capture of buildings using 3D laser scanners, Civ. Eng. 2 (2021) 214–235.
[31] I. Amir, G.-F. Mani, B. Timothy, E.-R. Khaled, Model-Driven visual data capture on construction sites: method and metrics of success, Comput. Civ. Eng. 2017, Proc. (2021), https://doi.org/10.1061/9780784480847.014.
[32] F. Khan, A. Ellenberg, M. Mazzotti, A. Kontsos, F. Moon, A. Pradhan, I. Bartoli, Investigation on Bridge Assessment Using Unmanned Aerial Systems 404–413, 2015, https://doi.org/10.1061/9780784479117.035.
[33] Y. Tan, S. Li, H. Liu, P. Chen, Z. Zhou, Automatic inspection data collection of building surface based on BIM and UAV, Autom. ConStruct. 131 (2021), https://doi.org/10.1016/j.autcon.2021.103881.
[34] M. Torok Matthew & Golparvar-Fard Mani, B. Kochersberger Kevin, Image-based automated 3D crack detection for post-disaster building assessment, J. Comput. Civ. Eng. 28 (2014) A4014004, https://doi.org/10.1061/(ASCE)CP.1943-5487.0000334.
[35] A. Bulgakov, D. Sayfeddine, Air conditioning ducts inspection and cleaning using telerobotics, Procedia Eng. 164 (2016) 121–126.
[36] Y. Wang, J. Su, Automated defect and contaminant inspection of HVAC duct, Autom. ConStruct. 41 (2014) 15–24.
[37] H. Hamledari, B. McCabe, S. Davari, Automated computer vision-based detection of components of under-construction indoor partitions, Autom. ConStruct. 74 (2017) 78–94, https://doi.org/10.1016/j.autcon.2016.11.009.
[38] Y. Li, X. Li, H. Wang, S. Wang, S. Gu, H. Zhang, Exposed aggregate detection of stilling basin slabs using attention U-net network, KSCE J. Civ. Eng. 24 (2020) 1740–1749, https://doi.org/10.1007/s12205-020-1431-1.
[39] H. Munawar, F. Ullah, A. Heravi, M. Thaheem, A. Maqsoom, Inspecting buildings using drones and computer vision: a machine learning approach to detect cracks and damages, DRONES 6 (2022), https://doi.org/10.3390/drones6010005.
[40] J. Seo, S. Han, S. Lee, H. Kim, Computer vision techniques for construction safety and health monitoring, Adv. Eng. Inf. 29 (2015) 239–251.
[41] K. Chen, G. Reichard, X. Xu, A. Akanmu, Automated crack segmentation in close-range building facade inspection images using deep learning techniques, J. Build. Eng. 43 (2021), https://doi.org/10.1016/j.jobe.2021.102913.
[42] S. Choi, E. Kim, in: J.J. Park, H. Jong, H.-C. Chao, H. Arabnia, N.Y. Yen (Eds.), Image Acquisition System for Construction Inspection Based on Small

Unmanned Aerial Vehicle BT - Advanced Multimedia and Ubiquitous Engineering, Springer Berlin Heidelberg, Berlin, Heidelberg, 2015, pp. 273–280.

[43] M. Kouzehgar, Y. Krishnasamy Tamilselvam, M. Vega Heredia, M. Rajesh Elara, Self-reconfigurable façade-cleaning robot equipped with deep-learning-based crack detection based on convolutional neural networks, Autom. ConStruct. 108 (2019) 102959, https://doi.org/10.1016/j.autcon.2019.102959.

[44] R.-J. Yan, E. Kayacan, I.-M. Chen, L. Tiong, J. Wu, QuicaBot: Quality Inspection and Assessment Robot, IEEE Transactions on Automation Science and Engineering, 2018, https://doi.org/10.1109/tase.2018.2829927.

[45] H. Omar, L. Mahdjoubi, G. Kheder, Towards an automated photogrammetry-based approach for monitoring and controlling construction site activities, Comput. Ind. 98 (2018) 172–182, https://doi.org/10.1016/J.COMPIND.2018.03.012.

[46] S. El-Omari, O. Moselhi, Integrating 3D laser scanning and photogrammetry for progress measurement of construction work, Autom. ConStruct. 18 (2008) 1–9, https://doi.org/10.1016/j.autcon.2008.05.006.

[47] E. Kwak, I. Detchev, A. Habib, Mamdouh El-Badry, M. Asce, C. Hughes, Precise photogrammetric reconstruction using model-based image fitting for 3D beam deformation monitoring, J. Survey Eng. 139 (2013) 143–155, https://doi.org/10.1061/(ASCE)SU.1943-5428.0000105.

[48] F. Kucuksubasi, A.G. Sorguc, Transfer learning-based crack detection by autonomous UAVs, in: J. Teizer (Ed.), Proceedings of the 35th International Symposium on Automation and Robotics in Construction (ISARC). International Association for Automation and Robotics in Construction (IAARC), Taipei, Taiwan, 2018, pp. 593–600, https://doi.org/10.22260/ISARC2018/0081.

[49] R. Abbas, F.A. Westling, C. Skinner, M. Hanus-Smith, A. Harris, N. Kirchner, BuiltView: integrating LiDAR and BIM for real-time quality control of construction projects, in: Presented at the Proceedings of the 37th International Symposium on Automation and Robotics in Construction, ISARC 2020: from Demonstration to Practical Use - to New Stage of Construction Robot, 2020, pp. 233–239.

[50] M. Golparvar Fard, F. Peña Mora, S. Silvio, D4AR-A 4-dimensional augmented reality model for automating construction progress monitoring data collection, processing and communication, J. Inf. Technol. Construct. 14 (2009) 129–153.

[51] O.S. Kwon, C.S. Park, C.R. Lim, A defect management system for reinforced concrete work utilizing BIM, image-matching and augmented reality, Autom. ConStruct. 46 (2014) 74–81, https://doi.org/10.1016/J.AUTCON.2014.05.005.

[52] M. Golparvar-Fard, F. Peña-Mora, S. Savarese, Automated progress monitoring using unordered daily construction photographs and IFC-based building information models, J. Comput. Civ. Eng. 29 (2015) 4014025, https://doi.org/10.1061/(ASCE)CP.1943-5487.0000205.

[53] H. Hamledari, S. Davari, E.R. Azar, B. McCabe, F. Flager, M. Fischer, UAV-enabled Site-to-BIM automation: aerial robotic- and computer vision-based development of As-Built/As-Is BIMs and quality control, in: Construction Research Congress 2018: Construction Information Technology - Selected Papers from the Construction Research Congress 2018, American Society of Civil Engineers (ASCE), 2018, pp. 336–346, https://doi.org/10.1061/9780784481264.033.

[54] M. Kopsida, I. Brilakis, Markerless BIM registration for mobile augmented reality based inspection, in: Proceedings of the International Conference on Smart Infrastructure and Construction, Osaka, 2016, pp. 1631–1636.

[55] S. Lee, F. Peña-Mora, Visualization of construction progress monitoring, in: Joint International Conference on Computing and Decision Making in Civil and Building Engineering, 2006, pp. 2527–2533.

[56] Mi Pan, Wei Pan, Determinants of adoption of robotics in precast concrete production for buildings, J. Manag. Eng. 35 (2019) 05019007, https://doi.org/10.1061/(ASCE)ME.1943-5479.0000706.

[57] E. Asadi, B. Li, I.-M. Chen, Pictobot: a cooperative painting robot for interior finishing of industrial developments, IEEE Robot. Autom. Mag. 25 (2018) 82–94.

[58] D. Apostolopoulos, H. Schempf, J. West, Mobile robot for automatic installation of floor tiles, in: Proceedings of IEEE International Conference on Robotics and Automation, 1996, pp. 3652–3657.

[59] M. Gharbia, A. Chang-Richards, Y. Lu, R.Y. Zhong, H. Li, Robotic technologies for on-site building construction: a systematic review, J. Build. Eng. (2020) 101584, https://doi.org/10.1016/j.jobe.2020.101584.

[60] Z. Wang, H. Li, X. Yang, Vision-based robotic system for on-site construction and demolition waste sorting and recycling, J. Build. Eng. 32 (2020) 101769, https://doi.org/10.1016/j.jobe.2020.101769.

[61] ISO, ISO 8373:2021 - Robotics -- Vocabulary, 2021.

[62] K. Asadi, H. Ramshankar, H. Pullagurla, A. Bhandare, S. Shanbhag, P. Mehta, S. Kundu, K. Han, E. Lobaton, T. Wu, Vision-based integrated mobile robotic system for real-time applications in construction, Autom. ConStruct. 96 (2018) 470–482.

[63] K. Asadi, H. Ramshankar, H. Pullagurla, A. Bhandare, S. Shanbhag, P. Mehta, S. Kundu, K. Han, E. Lobaton, T. Wu, Building an integrated mobile robotic system for real-time applications in construction, in: J. Teizer (Ed.), Proceedings of the 35th International Symposium on Automation and Robotics in Construction (ISARC). International Association for Automation and Robotics in Construction (IAARC), Taipei, Taiwan, 2018, pp. 453–461, https://doi.org/10.22260/ISARC2018/0063.

[64] A. Ibrahim, D. Roberts, M. Golparvar-Fard, T. Bretl, An interactive model-driven path planning and data capture system for camera-equipped aerial robots on construction sites, in: ASCE International Workshop on Computing in Civil Engineering 2017, American Society of Civil Engineers (ASCE), Seattle, 2017, pp. 117–124, https://doi.org/10.1061/9780784480847.015.

[65] D. Lattanzi, G. Miller, Review of robotic infrastructure inspection systems, J. Infrastruct. Syst. 23 (2017) 1–16, https://doi.org/10.1061/(ASCE)IS.1943-555X.0000353.

[66] D. Lattanzi, G.R. Miller, 3D scene reconstruction for robotic bridge inspection, J. Infrastruct. Syst. 21 (2015) 4014041, https://doi.org/10.1061/(ASCE)IS.1943-555X.0000229.

[67] B. Mantha, C. Menassa, V. Kamat, Multi-robot task allocation and route planning for indoor building environment applications, in: Construction Research Congress 2018, American Society of Civil Engineers (ASCE), New Orleans, 2018, pp. 137–146, https://doi.org/10.1061/9780784481264.014.

[68] M. Gheisari, A. Rashidi, B. Esmaeili, Using unmanned aerial systems for automated fall hazard monitoring, Construct. Res. Congr. (2018) 62–72 https://doi.org/10.1061/9780784481288.007, 2018.

[69] T. Patel, V. Suthar, N. Bhatt, in: K.K. Pathak, J.M.S.J. Bandara, R. Agrawal (Eds.), Application of Remotely Piloted Unmanned Aerial Vehicle in Construction Management BT - Recent Trends in Civil Engineering, Springer Singapore, Singapore, 2021, pp. 319–329.

[70] S. Phillips, S. Narasimhan, Automating data collection for robotic bridge inspections, J. Bridge Eng. 24 (2019) 04019075, https://doi.org/10.1061/(asce)be.1943-5592.0001442.

[71] T. Rakha, A. Gorodetsky, Review of Unmanned Aerial System (UAS) applications in the built environment: towards automated building inspection procedures using drones, Autom. ConStruct. 93 (2018) 252–264, https://doi.org/10.1016/j.autcon.2018.05.002.

[72] A. Ibrahim, A. Sabet, M. Golparvar-Fard, BIM-driven mission planning and navigation for automatic indoor construction progress detection using robotic ground platform, Proc. 2019 Eur. Conf. Comput. Construct. 1 (2019) 182–189, https://doi.org/10.35490/ec3.2019.195.

[73] D. Longo, G. Muscato, The Alicia3 climbing robot, IEEE Robot. Autom. Mag. 13 (2006) 42–50, https://doi.org/10.1109/MRA.2006.1598052.

[74] J.-U. Shin, D. Kim, S. Jung, H. Myung, Dynamics Analysis and Controller Design of a Quadrotor-Based Wall-climbing Robot for Structural Health Monitoring, Structural Health Monitoring, 2015 2015.

[75] A. Brunete, M. Hernando, J.E. Torres, E. Gambao, Heterogeneous multi-configurable chained microrobot for the exploration of small cavities, Autom. ConStruct. 21 (2012) 184–198, https://doi.org/10.1016/j.autcon.2011.06.003.

[76] K. Asadi, A. Kalkunte Suresh, A. Ender, S. Gotad, S. Maniyar, S. Anand, M. Noghabaei, K. Han, E. Lobaton, T. Wu, An integrated UGV-UAV system for construction site data collection, Autom. ConStruct. 112 (2020) 103068.

[77] K. Asadi, P. Chen, K. Han, T. Wu, E. Lobaton, Real-time scene segmentation using a light deep neural network architecture for autonomous robot navigation on construction sites, in: Computing in Civil Engineering 2019: Data, Sensing, and Analytics, American Society of Civil Engineers Reston, VA, 2019, pp. 320–327.

[78] B.R. Mantha, B. de Soto, Designing a reliable fiducial marker network for autonomous indoor robot navigation, in: Proceedings of the 36th International Symposium on Automation and Robotics in Construction (ISARC), 2019, pp. 21–24.

[79] A.K. Raja, Z. Pang, High accuracy indoor localization for robot-based fine-grain inspection of smart buildings, in: 2016 IEEE International Conference on Industrial Technology (ICIT), 2016, pp. 2010–2015, https://doi.org/10.1109/ICIT.2016.7475076.

[80] H. Myung, J. Jung, H. Jeon, Robotic SHM and model-based positioning system for monitoring and construction automation, Adv. Struct. Eng. 15 (2012)

943–954.
[81] P. Kim, J. Chen, J. Kim, Y.K. Cho, SLAM-driven intelligent autonomous mobile robot navigation for construction applications, in: I.F.C. Smith, B. Domer (Eds.), Advanced Computing Strategies for Engineering, Springer International Publishing, Cham, 2018, pp. 254–269.
[82] X. Ma, C. Mao, G. Liu, Can robots replace human beings? —assessment on the developmental potential of construction robot, J. Build. Eng. 56 (2022) 104727, https://doi.org/10.1016/j.jobe.2022.104727.
[83] L. Mingyue Ma, T. Fong, M.J. Micire, Y.K. Kim, K. Feigh, Human-robot teaming: concepts and components for design, in: Field and Service Robotics, Springer, 2018, pp. 649–663.
[84] M.C. Gombolay, C. Huang, J. Shah, Coordination of human-robot teaming with human task preferences, in: 2015 AAAI Fall Symposium Series, 2015.
[85] K. Stowers, L.L. Brady, C. MacLellan, R. Wohleber, E. Salas, Improving teamwork competencies in human-machine teams: perspectives from team science, Front. Psychol. 12 (2021).
[86] G. Button, W. Sharrock, Studies of work and the workplace in HCI: concepts and techniques, Synthesis Lectures on Human-Centered Informatics 2 (2009) 1–96, https://doi.org/10.2200/S00177ED1V01Y200903HCI003.
[87] Z.A. Nasruddin, A. Markom, M. Abdul Aziz, Evaluating construction defect mobile app using think aloud, in: International Conference on User Science and Engineering, Springer, 2018, pp. 3–11.
[88] H. Zhang, S. Chi, J. Yang, M. Nepal, S. Moon, Development of a safety inspection framework on construction sites using mobile computing, J. Manag. Eng. 33 (2017) 4016048.
[89] S. Halder, K. Afsari, Real-time construction inspection in an immersive environment with an inspector assistant robot, in: T. Leathem, W. Collins, A. Perrenoud (Eds.), ASC2022. 58th Annual Associated Schools of Construction International Conference, EasyChair, Atlanta, 2022, pp. 389–397, https://doi.org/10.29007/CK81.
[90] R.F. Fellows, A.M.M. Liu, Research Methods for Construction, John Wiley \& Sons, 2015.
[91] Statista Research Department, U.S. construction employees by gender 2002-2021 [WWW Document]. Statista. URL. https://www.statista.com/statistics/434758/employment-within-us-construction-by-gender/, 2022, 8.7.22.
[92] National Taskforce on Tradeswomen's Issues, Numbers Matter: Clarifying the Data on Women Working in Construction, Institute for Women's Policy Research, 2022 URL. https://iwpr.org/iwpr-publications/briefing-paper/numbers-matter-clarifying-the-data-on-women-working-in-construction/. 8.8.22.
[93] F. Boukamp, B. Akinci, Automated processing of construction specifications to support inspection and quality control, Autom. ConStruct. 17 (2007) 90–106, https://doi.org/10.1016/j.autcon.2007.03.002.
[94] G. Caroti, A. Piemonte, I.M.-E. Zaragoza, G. Brambilla, Indoor photogrammetry using UAVs with protective structures: issues and precision tests, Int. Arch. Photogram. Rem. Sens. Spatial Inf. Sci. 42 (2018).
[95] R.E. Pereira, M. Gheisari, 360-Degree panoramas as a reality capturing technique in construction domain: applications and limitations, in: 55th ASC Annual International Conference Proceedings, 2019.
[96] S.A. Prieto, N. Giakoumidis, B. García de Soto, AutoCIS: an Automated Construction Inspection System for Quality Inspection of Buildings, 2021, https://doi.org/10.22260/ISARC2021/0090.
[97] E.B. Anil, P. Tang, B. Akinci, D. Huber, Deviation analysis method for the assessment of the quality of the as-is Building Information Models generated from point cloud data, Autom. ConStruct. 35 (2013) 507–516, https://doi.org/10.1016/j.autcon.2013.06.003.
[98] J. Zhang, N.M. El-Gohary, Semantic NLP-based information extraction from construction regulatory documents for automated compliance checking, J. Comput. Civ. Eng. 30 (2016) 04015014.
[99] M. Tavakol, R. Dennick, Making sense of Cronbach's alpha, Int. J. Med. Educ. 2 (2011) 53–55, https://doi.org/10.5116/ijme.4dfb.8dfd.
[100] R. Verma, J.C. Goodale, Statistical power in operations management research, J. Oper. Manag. 13 (1995) 139–152, https://doi.org/10.1016/0272-6963(95)00020-S.
[101] Mi Pan, Wei Pan, Stakeholder perceptions of the future application of construction robots for buildings in a dialectical system framework, J. Manag. Eng. 36 (2020) 04020080, https://doi.org/10.1061/(ASCE)ME.1943-5479.0000846.
[102] S. Strahorn, G. Brewer, T. Gajendran, The influence of trust on project management practice within the construction industry, Construct. econ. build. 17 (2017) 1–19.
[103] F. Correia, S. Petisca, P. Alves-Oliveira, T. Ribeiro, F.S. Melo, A. Paiva, I Choose... YOU!" Membership preferences in human–robot teams, Aut. Robots 43 (2019) 359–373, https://doi.org/10.1007/s10514-018-9767-9.
[104] H. Zhang, S. Chi, J. Yang, M. Nepal, S. Moon, Development of a safety inspection framework on construction sites using mobile computing, J. Manag. Eng. 33 (2017) 4016048.
[105] A. Richert, M. Shehadeh, L. Plumanns, K. Groß, K. Schuster, S. Jeschke, Educating engineers for industry 4.0: virtual worlds and human-robot-teams: empirical studies towards a new educational age, in: 2016 IEEE Global Engineering Education Conference (EDUCON), Ieee, 2016, pp. 142–149.
[106] Ricoh Company Ltd, RICOH THETA V [WWW Document]. URL. https://theta360.com/en/about/theta/v.html, 2017, 6.6.22.
[107] Srijeet Halder, K. Afsari, J. Serdakowski, S. DeVito, R. King, Accuracy estimation for autonomous navigation of a quadruped robot in construction progress monitoring, in: 2021 ASCE International Conference on Computing in Civil Engineering, 2021.
[108] Department of General Services, Commonwealth of Virginia Construction and Professional Services Manual, Bureau of Capital Outlay Management, 2018.