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SENSING TECHNOLOGIES IN CONSTRUCTION ENGINEERING EDUCATION: INDUSTRY EXPERIENCES AND EXPECTATIONS

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Omobolanle Ogunseiju, Ph.D.
Georgia Institute of Technology, Georgia, United States
omobolanle@gatech.edu

Nihar Gonsalves, Ph.D. Candidate
Virginia Polytechnic Institute and State University, Virginia, United States
gonsnihar@vt.edu

Abiola Akanmu, Ph.D.
Virginia Polytechnic Institute and State University, Virginia, United States
abiola@vt.edu

Diana Bairaktarova, Ph.D.
Virginia Polytechnic Institute and State University, Virginia, United States
dibairak@vt.edu

Philip Agee, Ph.D.
Virginia Polytechnic Institute and State University, Virginia, United States
pragee@vt.edu

Kereshmeh Asfari, Ph.D.
Virginia Polytechnic Institute and State University, Virginia, United States
Keresh@vt.edu

SUMMARY: *As the construction industry continues to advance technologically, the adoption of sensing technologies is gradually gaining momentum. Sensing technologies (such as radio frequency identification systems, laser scanners, cameras, and global position systems) play a significant role in reducing costs, improving project productivity, and enhancing workers' health and safety. This has prompted the need for a workforce with the required skills and knowledge for deploying sensing technologies in the industry. Since construction-related education is aimed at preparing students for the future of the industry, it is important to investigate the industry's expectations for equipping the future workforce with the required skills. This study adopts a mixed-method research approach. Data are collected from surveys, case studies, and a focus group discussion with industry practitioners. The data elucidate participants' perceptions, attitudes, and beliefs regarding: the skills required, and level of knowledge transfer required to advance sensing technologies on construction projects, and the value and anticipated demand for these skills. The findings also revealed the extent to which sensing technologies are deployed in the industry and the benefits driving the adoption of these technologies. The results reveal a high rate of adoption of sensing technologies amongst industry practitioners and inform construction applications and skills to be taught in construction engineering education. This study contributes to the existing scarce literature on the knowledge and skill demands of the industry to implement sensing technologies. The findings provide critical feedback for expanding the construction education curriculum to meet up the industry's demand and adequately prepare the future workforce.*

KEYWORDS: *Knowledge, Skills, Sensing technologies, Future workforce, Industry demands*

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1 INTRODUCTION

Effective monitoring of construction projects enhances situational awareness of project stakeholders. This improves their ability to make decisions that could reduce some of the long-standing risks to project performance (Chan 2017, Guo, Li et al. 2019). Sensing technologies (e.g., radio frequency identification systems, laser scanners, cameras, and global position systems) play a significant role in improving the visibility of construction worksites and workers. Many studies have demonstrated the potential of sensing technologies in providing access to critical information for improving project productivity (Grau, Caldas et al. 2009), safety (Cheng and Teizer 2013), and the health of workers (Choi, Hwang et al. 2017). This evidence and their resulting cost-saving implications have triggered the construction industry to begin investing in sensing technologies. For example, construction companies such as Skanska and Balfour Beatty, known for early technology adoption, are currently deploying laser scanners and Radio-Frequency Identification (RFID) for tracking the progress of construction work. Miller (2008) reported cost savings of a million dollars from utilizing RFID for tracking precast concrete seats on a stadium construction project. Industry reports such as the Forum (2016) have predicted that the increasing rate of adoption of sensing technologies could result in significant annual global cost savings of 13 to 21 percent in the design and construction phases and 10 to 17 percent in the operations and maintenance phase of a project lifecycle.

The diffusion of sensing technologies into the construction industry is transforming construction work and resulting in new project delivery methods (Pariafsai and Behzadan 2021). New ways of thinking are emerging as a new generation of graduating students from construction-related disciplines join the workforce (García de Soto, Agustí-Juan et al. 2019, Calvetti, Mêda et al. 2020). One way of sustaining the industry's momentum of adoption of sensing technologies is by equipping the future workforce with the knowledge and skills to implement the technologies. This is significant as a number of contracting firms have identified that one of the biggest impediments to the successful embrace of technologies in the construction industry, a sector that is traditionally known to be slow in the uptake of new technologies (Mitropoulos and Tatum 2000, Takim, Harris et al. 2013), has been the workforce's unfamiliarity with technologies and their capabilities (Whyte and Hartmann 2017, Moon, Becerik-Gerber et al. 2019). While some construction-related programs have started incorporating sensing technology-related content into their curriculum, little is known about what should be taught to students to prepare them for their future careers in this area. This can be identified by examining the sensing needs of the industry, how the construction industry is using and would like to use sensing technologies on construction projects, and the industry's perceived benefits of embarking on this transformational change. Thus, the objective of this study is to investigate the perceptions of construction industry practitioners of the knowledge and skills required of graduating students from construction-related disciplines for implementing sensing technologies on construction projects. To achieve this objective, this study aims to answer the following questions:

- What knowledge and skills are required to implement and advance sensing technologies on construction projects?
- What is the value and anticipated demand for these skills by prospective employers?

This paper is organized as follows: a literature review on sensing technologies in the construction industry and construction education is provided in the next section. The methodology is described in the following section. The results of the study are presented in the next section. Discussions of the findings and conclusions of the study are detailed in the last sections.

2 LITERATURE REVIEW

2.1 Sensing Technologies in the Construction Industry

Sensing technologies are technologies that extract information about the context and condition of construction resources and processes during the lifecycle of facilities to improve communication between project participants, enhance project safety and improve quality control (Akinci and Anumba 2008). Sensing technologies are broadly classified as image-based (Teizer 2008, Teizer 2015) and component-based technologies (Akanmu, Anumba et al. 2020, Rana and Baz 2020). Image-based sensors include laser scanners and cameras, while component-based sensors include radio frequency identification tags, global positioning tags, accelerometers, and temperature and humidity sensors. Over the past ten years, there has been an increase in the pace of the adoption of sensing technologies. For example, DPR Construction, a commercial general contracting firm, has been actively leveraging laser scanners for as-built documentation and quality control. In 2011, DPR Construction used laser scanners to capture existing wood trusses, and mechanical, electrical, and plumbing systems before renovating a highly themed building (DPRconstruction 2011). DPR Construction also used laser scanners for capturing constructed ornamental iron elements during construction. This was compared to shop drawings to detect deviations from the planned model (DPRconstruction 2011). The use of drones on construction sites has been reported by different companies like Bechtel, which claims to be one of the first construction companies licensed by the Federal Aviation Administration (FAA) to utilize Unmanned Aerial Vehicles (known as drones) on their job sites. Drones are remotely controlled systems that are equipped with sensors (e.g. vision sensors, ultrasonic sensors, etc.) and can also be equipped with more sensors for performing specific tasks e.g., thermal imaging. According to Bechtel (2015), the company utilized drones for capturing real-time aerial images of megaprojects. Skanska (2015) reported the adoption of drones on the Welsh Water Framework project for exploring water turbines and other features that were difficult and dangerous to assess on the project. Hensel Phelps in 2019 documented the use of drones for enhancing the virtual design and construction of a healthcare project challenged with limited access to the site. A drone was used to procure progress photos during the construction phase which reportedly improved the site logistics of the project (HenselPhelps 2020). The adoption of a radio frequency identification (RFID) system for tracking resources can also be seen across different construction companies (e.g., Skanska employed an RFID system for tracking precast concrete pieces of a stadium project located in New Meadowlands (Miller 2008)). In 2016, Balfour Beatty reportedly proposed the attachment of RFID tags in workers' hard hats for monitoring workforce safety (BalfourBeatty 2016). In order to further the adoption of sensing technologies in the construction industry, a critical next step is to understand how sensing technologies are integrated into construction education.

2.2 Sensing Technologies in the Construction Education

Despite the proliferation of sensing technologies in the construction industry as showcased above, few studies have investigated industry requirements of the future workforce, such as types of sensing technologies and applications that should be taught in order to prepare students for the workplace. Tang, Aktan et al. (2012) proposed a framework for integrating laser scanning and building information modeling into the construction engineering curriculum. Zhang and Lu (2008) described the course contents of smart structures technology in the civil engineering curriculum at Lehigh University. Similarly, Hurlebaus, Stocks et al. (2012) provided a comprehensive overview of smart structures as a course in civil engineering, at Texas A&M University. Hurlebaus, Stocks et al. (2012) described the course, course contents, learning outcomes, course activities, and other outdoor demonstrations. The authors described the inclusion of smart sensors such as optical fiber sensors, wireless sensors, and wavelength-based sensors, with a focus on smart materials for delivering high self-actuation, and efficient structures in engineering. The paucity of literature in this area is indicative of the low inclusion of sensing technologies in construction engineering education and/or the lack of research documenting the integration of these technologies in construction engineering education. This study contributes to closing the gap in incorporating sensing technologies into the construction education curriculum.

3 RESEARCH METHODOLOGY

To investigate the knowledge and skills required of graduating Construction Engineering and Management (CEM) students to implement sensing technologies on construction projects, this study adopted a mixed-method approach (Creswell, Hanson et al. 2007) to obtain qualitative and quantitative data (Fig. 1). The study was approved by the Institutional Review Board (IRB) of Virginia Tech under IRB# 18-847 to enable the ethical collection of human subjects' data. An online survey was developed to obtain quantitative data from industry practitioners on the required skills for deploying sensing technologies on construction projects. To validate the results from the survey, a focus group was conducted with selected industry practitioners identified from the survey to be knowledgeable about the potential of sensing technologies and their implementation on their projects. The survey and focus group data were bolstered with case studies on the applications of sensing technologies retrieved from the websites of construction companies.

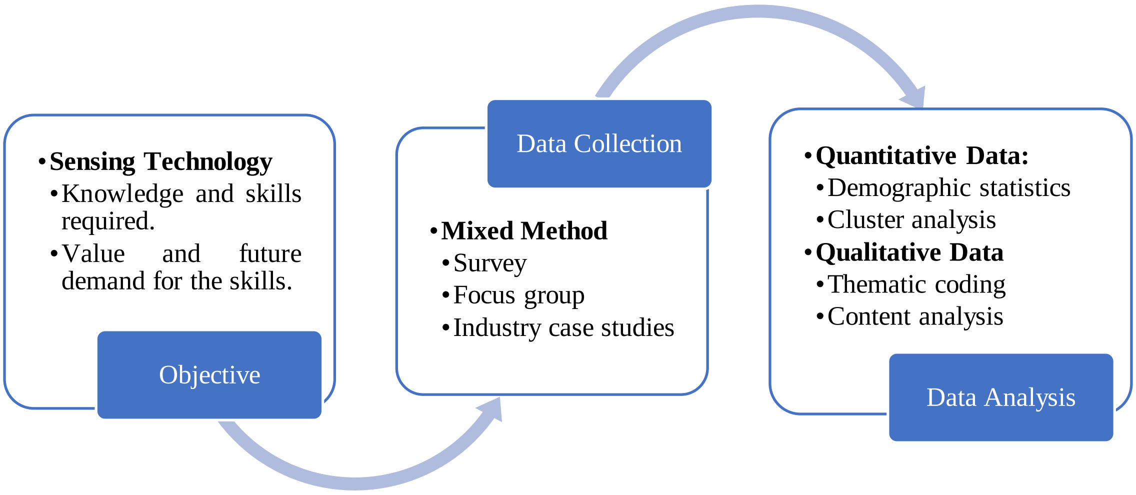

FIG. 1. Overview of the methodology.

3.1 Survey

A survey addressing the research questions was developed for this study. The survey was sent to 869 industry partners via the Myers Lawson School of Construction's listserv. The listserv comprises contact addresses of general and specialty contractors, construction managers, subcontractors, and construction technology consultants. A total of 105 surveys were received, out of which 19 survey responses were incomplete and excluded from the analysis. The survey was administered between August 2019 and September 2020. To answer the research questions, the survey investigated the level of adoption of sensing technologies in the construction industry as follows: To identify the specific knowledge and skills required to plan, implement, and advance sensing technologies in the construction industry, four questions were asked. Questions ranged from the applications of sensing technologies, the skills and knowledge of sensing technologies expected from graduating CEM students, and the required sensing technologies and applications to be included in the curriculum. The values and anticipated demand for these skills by prospective employers were also investigated. The survey questions in this section were categorized based on the duration of use of sensing technologies, the present and future demand for these technical skills, and the required industrial training. To explore the duration of use of sensing technologies by the practitioners, the survey asked how long they have been using each sensing technology in their company. To evaluate the present demand for technical skills, the practitioners' reasons for adopting sensing technologies, and the workforce requirements were captured. To explore if this demand is met, participants were asked if the employed graduate engineers possess the required skills to meet up the demand in the industry. The survey explored how, and to what extent recruited graduate engineers are trained to reinforce their skillset. To assess the future demand for technical skills for operating sensing technologies, participants were asked to provide the number of employees currently deploying sensing technologies in their organization. Participants who have not yet adopted sensing technologies were asked when and what prospective sensing technologies will be adopted in their companies. Prior to finalizing the questions in the survey, a pilot study was conducted with five industry practitioners, who have experience with sensing technologies and four instructors teaching and researching the applications of sensing technologies for construction companies. The pilot test was conducted to identify any flaws in the survey. A pilot test is an effective way of establishing the reliability of a questionnaire (Reynolds, Diamantopoulos et al. 1993, Kasunic 2005). Based on the feedback from the pilot test, the questions were revised before the dissemination of the survey.

The survey was disseminated via Qualtrics and had an average completion time of ten minutes. The survey data was analyzed using descriptive statistics, including response means and frequencies. Open-ended questions were analyzed using cluster analysis. Open-ended survey questions offer a good approach to obtaining honest and diverse responses from subjects (Erickson and Kaplan 2000). The use of cluster analysis encourages the classification of subjects into different categories. This helps to identify distinctive characteristics in a dataset (Battaglia, Di Paola et al. 2015).

3.2 Focus Group

Diverse views (group work) provide a rich source of information which is invaluable for grounded theory development (Kitzinger 1995). Focus groups are resourceful for accumulating data on collective views and the connotations behind those views (Gill, Stewart et al. 2008). The survey results were validated with a focus group comprising of five industry practitioners, creating a team setting for diverse data collection. Focus groups are small group interviews of people with similar backgrounds employed for collecting generalized opinions on collective views and meanings behind the views (Mishra 2016). The participants were identified from the survey as either adopting sensing technologies on their projects or knowledgeable about the potential of sensing technologies. The participants were from companies such as steel contractors, project managers, construction managers, mechanical and electrical contractors, and civil engineering contractors. The focus group protocol was approved by the IRB of Virginia Tech under (IRB No 19-488) and conducted as a single online session via Zoom video conferencing application. Questions regarding the required technical skills for operating sensing technologies, and the future of sensing technologies in the construction industry were discussed. The focus group discussion was audiotaped and later anonymized before being transcribed. Appropriate codes were assigned to the transcript using Dedoose, an application for analyzing qualitative data. Each code was classified based on the focus group questions. The coded data were compared with the original transcript to ensure consistency. Thereafter, similar themes were explored to further categorize the data. The codes were initially developed by the first author and verified by two researchers. Braun and Clarke (2018) did not recommend additional coding and inter-rater reliability to be undertaken in the data analysis because thematic analysis assumes a reflexive approach that isn't necessarily guided by positivist assumptions. However, to ensure the trustworthiness of data (Nowell, Norris et al. 2017), an inter-rater reliability test was conducted to assess the level of agreement between the researchers.

3.3 Industry Case Studies

To further corroborate the data from the survey and focus group discussion, industry case studies on the identified sensing technologies (from the survey) were obtained via content analysis of websites of construction companies. A total of 35 case studies were collected from different company websites and analyzed. The case studies were based on technologies such as laser scanners, drones, RFIDs, ground-penetrating radars (GPRs), and Global Positioning Systems (GPS). Next, a detailed web search of each sensing technology was conducted via Google search engine. For example, for laser scanners, the web search string used was "Laser scanner case studies in construction companies". Subsequently, "Laser scanner" was replaced in the search string with each sensing technology. The search was further filtered by omitting search results without the exact words "Sensing technologies", and "Construction". This step limited the results to sensing technologies in the construction industry. Results from marketers and developers of sensing technologies were excluded. The web search produced 18 case studies for laser scanners and 17 case studies for other sensing technologies such as drones, GPRs, GPS, and RFIDs.

4 RESULTS

4.1 Survey Results

4.1.1 Demographics

105 surveys were received from the participants, out of which only 86 were complete and included in the study. The participants were asked to state their years of experience, one participant did not respond, 42 participants had 0-5 years of experience, 18 participants had 5-10 years of experience, 5 participants had 10-15 years of experience, and 20 participants had over 15 years of experience. The respondents of the survey were grouped according to their companies; hence, data from 62 construction companies were represented in this study. Table 1 summarizes the demographics of the respondents' companies.

Table 1. Company Demographics.

Company size	Frequency	Percentage
10-50 employees	14	22%
50-100 employees	6	10%
100-500 employees	21	34%
More than 500 employees	21	34%
Total	62	100%

Company size	Frequency	Percentage
Construction trades/types		
General contractors	45	73%
Professional consultants	5	8%
Civil engineering contractors	3	5%
Site development contractors	1	2%
Electrical contractors	2	3%
Department of Transportation	1	2%
Metals contractors	1	2%
Construction technology consultants	1	2%
No response	3	5%
Total	62	100%

4.1.2 Knowledge and skills required to plan, implement, and advance sensing technologies on construction projects

This study investigates the knowledge and skills required to plan, implement, and advance sensing technologies on construction projects. As explained by Adepoju, Aigbavboa et al. (2022), skills are defined as the competencies required to execute a job in the best possible way successfully. Skills entail applying explicit and tacit knowledge, adopting tools and technologies, implementing cognitive and practical applications, and understanding appropriate approaches and procedures (Adepoju, Aigbavboa et al. 2022). Hence, this study investigates the required skills and knowledge of sensing technologies by understanding the adopted sensing technologies and current and anticipated construction applications of sensing technologies. Participants in this study were surveyed on the current level of adoption of sensing technologies, construction applications of sensing technologies, and the expected skills and knowledge of sensing technologies from graduating students. The survey also obtained the industry's perception of the required sensing technologies and the construction applications to be included in CEM curriculum.

Adoption of sensing technologies in the industry: The current and future adoption of sensing technologies were investigated. Participants were asked if they have adopted sensing technologies for their projects. 85% of the respondents indicated that they are adopting sensing technologies. These participants are general contractors, civil engineering contractors, electrical contractors, professional consultants, construction technology consultants, and metals contractors. Furthermore, the participants adopting sensing technologies were asked about the types of sensing technologies they adopt. Results reveal the top four sensing technologies with a high rate of adoption in the industry as cameras, laser scanners, drones, and GPS, while RFIDs, gyroscopes, accelerometers, GPRs, Electroencephalography (EEGs), electromyography (EMGs), and thermal imaging sensors have lower rates of adoption in the industry (Fig. 2).

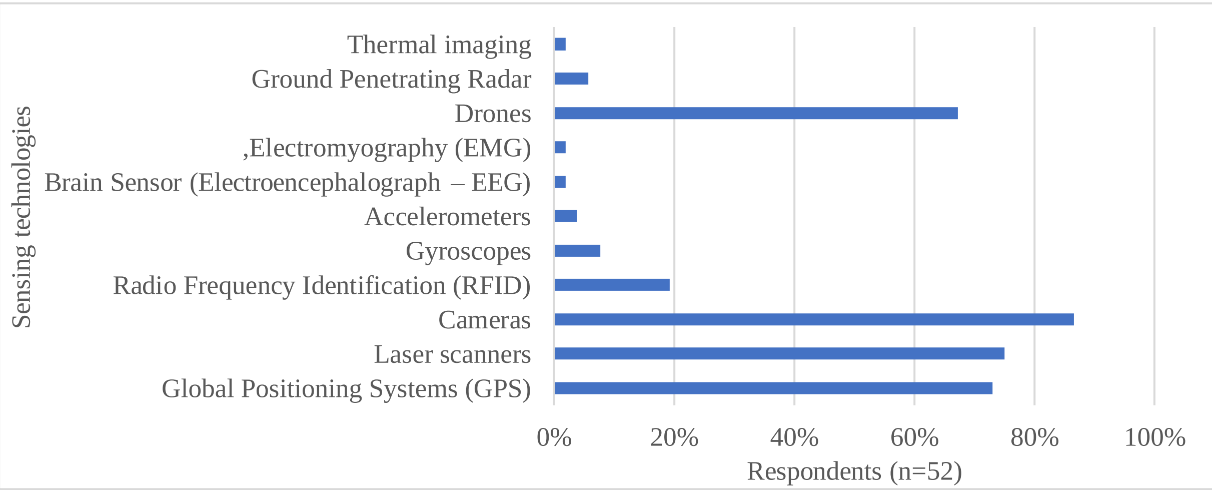

FIG. 2. Adopted sensing technologies in the industry.

Current applications of sensing technologies: Participants were asked about the construction applications of each class of sensing technologies e.g., image-based (Table 2) and component-based (Table 3) sensing technologies.

From Table 2, laser scanners were revealed to have vast applications in the construction industry. It is also observed that laser scanners are employed during the preconstruction stage (e.g., for three-dimensional (3D) coordination) through to the maintenance stage (e.g., for documenting existing conditions). Furthermore, a prominent application of component-based sensing technologies is for health and safety practices, and resource management. For example, tracking workers, detecting falls and injuries, material management, and locating equipment and vehicles.

TABLE 2. Applications of image-based sensing technologies in the industry.

Sensors	**Applications**
Laser scanner	As-built conditions, 3D coordination, floor flatness, deck pre-pour, field conditions, beam plumpness, pipe slopes, grade and levels, insulation thickness, existing conditions, mechanical shop drawing, clash detection, utility location, wall roughing, progress and quality checks, structural element location, mechanical spaces, and verifying mechanical, electrical, and plumbing (MEP) layout
Cameras	Progress documentation, safety, quality checks, laser scans supplement, security, and material management
GPR	Utility location and rebar location
Drones	Stockpile quantification, site inspections, progress monitoring, existing conditions review, and quality checks
Thermal imaging	Roof leaks detection

TABLE 3. Applications of component-based sensing technologies in the industry.

Sensors	**Applications**
GPS	Equipment location, building layouts, vehicle guidance, surveys, grades, documentation
RFID	Tracking workers, managing materials, tracking equipment
Gyroscope	Prefab bridge movement
Accelerometer	Detecting falls and injuries, supporting excavation
EMG	Detecting ergonomic risks
EEG	Assessing mental fatigue for accident prevention

Anticipated applications of sensing technologies: To further investigate the future applications of sensing technologies, participants that are yet to adopt sensing technologies were asked how they would apply each prospective sensing technology. While the stated applications of laser scanners, RFIDs, cameras, and GPSs (Table 4) are similar to the current applications (Table 3), some respondents mentioned that they would use EEGs to obtain data for simulation within virtual reality and building information models.

TABLE 4. Anticipated Applications of Sensing Technologies.

Sensors	**Applications**
Laser scanner	Scanning existing conditions, as-built scans, documenting final space conditions for clients
RFID	Material tracking
GPS	Site logistics, position validations, point extractions from models
EEG	Data source for virtual reality and BIM
Camera	Security, project documentation, progress monitoring, virtual walkthroughs, monitoring construction speed, a data source for BIM

Suggested sensing technologies: Participants were probed on the types of sensing technologies that should be taught in CEM programs. The top three sensing technologies proposed by the respondents were laser scanners, GPS, and cameras, with more than 90% of the respondents indicating that laser scanners should be taught in CEM programs (Fig. 3).

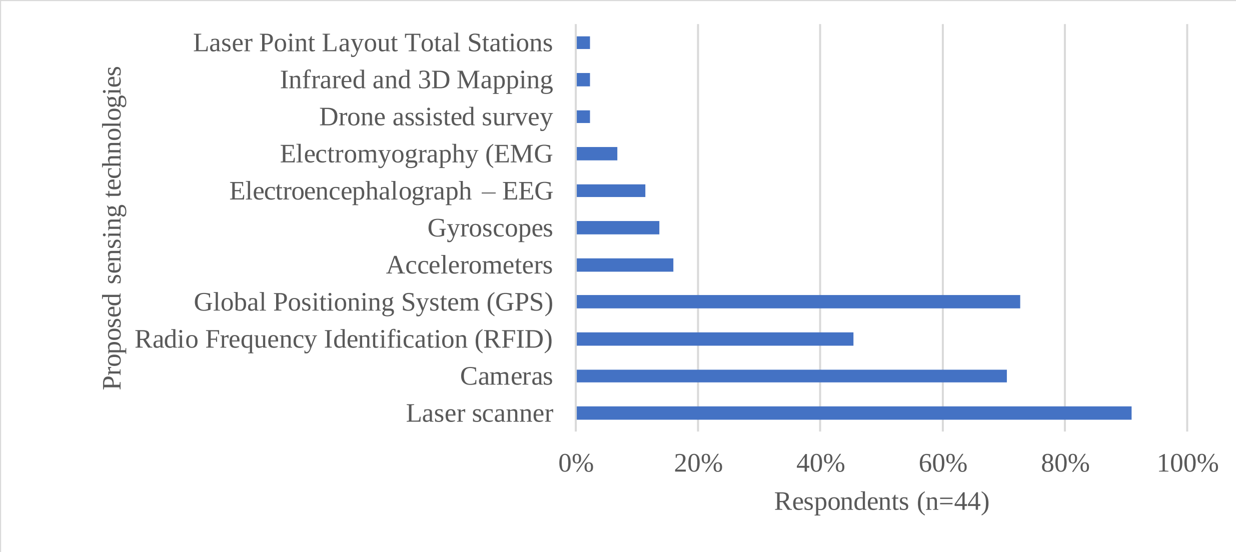

FIG. 3. Proposed sensing technologies.

Suggested applications: The survey asked participants "what specific construction applications of sensing technologies should be taught in CEM programs?". The responses suggest that only six sensing technologies, namely, laser scanners, cameras, EEGs, accelerometers, GPS, and RFIDs, should be integrated into curriculums. In addition to the applications, the participants suggested the potential construction applications indicated in Table 5.

TABLE 5. Proposed sensing technologies applications to CEM programs

Sensors	**Applications/Knowledge**
Laser scanner	As-built survey for different construction phases, procuring building scans, existing conditions mapping, resource tracking, CAD development, Matterport, site setup, laser scanner setup, eliminating over-scanning, data collection, and visualization, concrete work, high-resolution imaging, integration of laser scanner data with Autodesk Recap and Leica software's, and development of use cases and benefits
Camera	Types of cameras, uses and benefits, progress documentation, integration with drone deploy, holo-builder, and Smartvid.io, generating 360 degrees photos, artificial intelligence-imagery analysis, machine learning-object detection, and workers detection, and existing conditions review
EEG	Workers' behaviors, empathy, and decisions
Accelerometer	Unintended movement and lack of movement by workers
GPS	Resource and progress tracking, surveying, existing elevation data, localizing, site logistics, and integrating with shared global coordinate in Revit
RFID	Resource and data tracking, inventory controls, equipment operations, equipment, and material tracking, site access, and personnel tracking

Skills to implement sensing technologies for CEM programs: Participants were asked about the skillsets for implementing sensing technologies on construction projects. Data visualization, data extraction, data storage, and programming were selected by 76%, 71%, 63%, and 20%, respectively, of the respondents. While data visualization entails skills (like visual analytics and information visualization skills) required to understand the resulting outputs from sensing technologies (Ryan, Silver et al. 2019), data extraction is a comprehensive skill entailing the understanding of the nature of data generated from sensing technologies and data storage skills are the expertise required to retain digital information from sensing technologies using computers and other devices (Byrd 2019). Since sensing technologies often capture extensive digital information, including personal, classified, and critical business data, employers value and rely on data storage skills to preserve such information obtained from sensing technologies (Chukuigwe 2022).

4.1.3 Value and anticipated demand for the required skills by the prospective employers

The value and anticipated demand for the required skills by the industry was identified by capturing how long the companies have been implementing sensing technologies, the present and future demand for skills for implementing sensing technologies, and the required training. Similarly, the reasons behind adopting sensing technologies, the workforce classifications (e.g., employees, consultants, and subcontractors) required for implementing the technologies, and the employees dedicated to implementing sensing technologies were also captured.

Duration of use of different sensing technologies: To assess the extent to which construction practitioners deploy the sensing technologies, the survey asked participants, who are already adopting sensing technologies, how long they have been using sensing technologies. The participants provided the duration of adoption of each sensing technology in the industry. As indicated in Fig. 4, a total of 32, 45, and 30 responses were retrieved for laser scanners, cameras, and GPS respectively. Similarly, a total of 9 and 35 responses were retrieved for RFID and Drones, respectively. While more than 50% of companies have been adopting laser scanners and drones for 2-5 years, more than 50% have adopted RFID for 5-10 years.

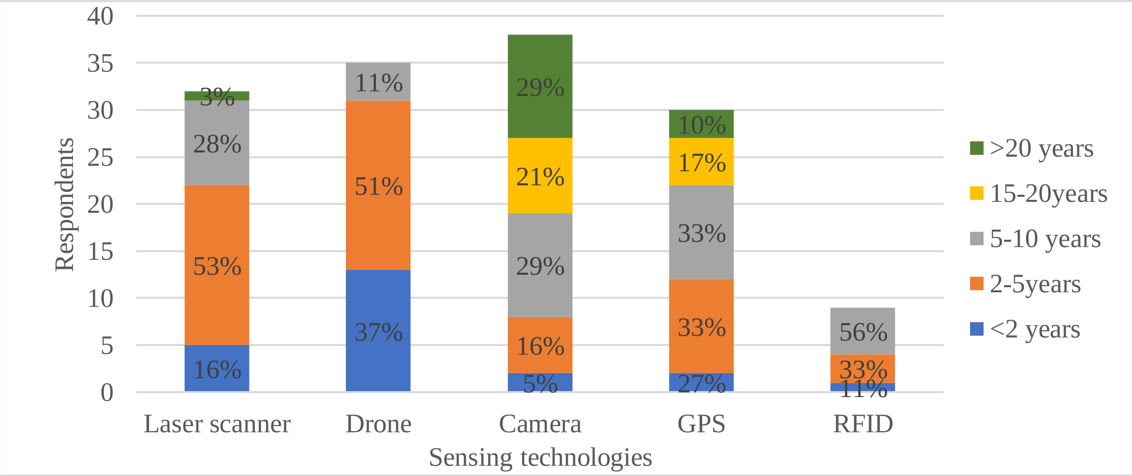

FIG. 4. Duration of adoption of sensing technologies.

The duration of use of cameras and GPS varied amongst the companies. Results revealed that cameras have long been used in the construction industry, with more than 25% of the respondents adopting them for over 20 years and about 10% adopting them for less than two years. Although the adoption of GPS varied, over 60% of the respondents have been using GPS for 2-10 years, while 27% have been using GPS on their projects for over 15 years.

Participants provided additional sensing technologies that were not listed in the survey questions. This includes concrete temperature and strength sensors. Gyroscopes, EMGs, EEGs, and concrete temperature and strength sensors are gradually evolving, as respondents have used them for less than 2years. Similarly, concrete deck scanners and thermal imaging have been adopted for 2-5 years, while infrared sensors have been used for 5-10 years. Lastly, GPR has been adopted by three companies for less than 2 years, 2-5 years, and 5-10years.

Present demands for sensing technologies: To establish the demand for sensing technologies, participants were surveyed on the reasons behind the adoption of each sensing technology, the current workforce for implementing sensing technologies, and the employees dedicated to implementing sensing technologies in the industry.

Participants specified factors such as cost and time-savings, efficient management, documentation, predictive analysis, accuracy, productivity, technological advancement, field quality, and schedule control as reasons behind the adoption of sensing technologies. For each factor, Table 6 further expands on the reasons for the adoption of sensing technologies.

Participants were asked to identify the personnel who implement sensing technologies for the companies. Results reveal that 67% of the respondents (n = 48) use in-house employees for implementing sensing technologies on their projects. These respondents were general contractors, civil engineering contractors, site developers, professional consultants, construction technology experts. 6% of the respondents use the services of subcontractors, and 10% employ both employees and subcontractors for implementing sensing technologies. The results further revealed that consultants and contractors are employed by 2% of the respondents and 15% employ other professionals to implement sensing technologies on their projects.

TABLE 6. Motivation behind the adoption of sensing technologies.

Factors	**Motivation for adoption**
Time savings	Better results in less time, convenience, increased construction speed
Predictive analysis	Early detection of potential problems on the site
Management	Efficient management and better project management experience
Competitive advantage and client's demands	Provide sensing technologies services to clients and security
Cost savings	Saves cost of rework and reduces project costs
Accuracy	Reliability, improved precision, and improved accuracy when measuring complex items
Productivity	Better understanding of work challenges, reduction of risks to workers, and reduction of highly manual tasks
Technological advancement	Keeping up with current trends and industry standards, envisaged as the standard in the future
Field quality	Construction progress measurement, site-work measurement, better jobsite supervision
Schedule control	Clash prevention

Participants were also asked to provide the number of employees that are dedicated to deploying sensing technologies on their projects. A total of 36 companies responded, with 50% of the companies stating that they dedicate more than 10 employees to implementing sensing technologies (Fig. 5).

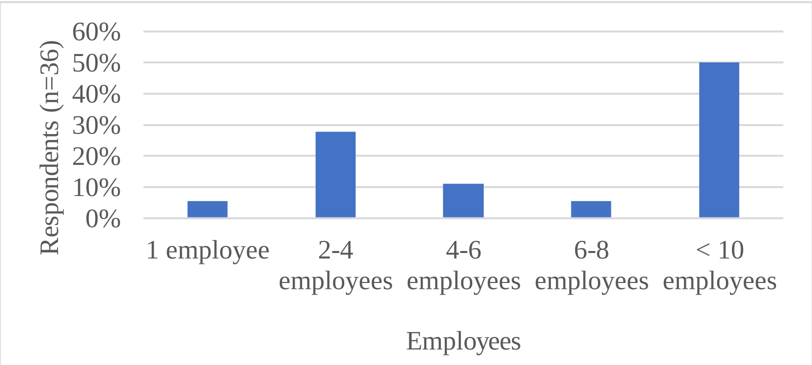

FIG. 5. Employees dedicated to sensing technologies.

Training needs of the recruited workforce: training needs are the expressed level of training employers need on the employees' required practices (Jacob and George 2013). They also reveal the recruited workforce's shortage of skills or abilities that can be mitigated through training (Khan and Al Zubaidy 2016). To assess the training needs of the recruited workforce, participants were asked about the educational background and formal training programs that the workforce (e.g., workers who implement sensing technologies) are required from, the need for training, and the duration of the training. The study also investigated how industry practitioners recruit graduating engineers to deploy sensing technologies on their projects by inquiring about the availability of on-campus recruitment, the type of graduate engineers considered for employment, the availability of required technical skills possessed by graduate engineers, and the duration of the training provided. Fig. 6 reveals that more than 72% of recruited graduates are from civil engineering and CEM programs.

The survey asked participants if they do on-campus recruitment for graduating engineers with skills for implementing sensing technologies. 46% of the respondents recruit on campus while 54% do not. Participants were further asked about the type of graduating engineers they recruit to implement sensing technologies in their company. The data suggest that 79% of the respondents recruit undergraduate students while 21% recruit graduate students. The participants responded to questions inquiring if the recruited graduates have the required skills and knowledge to implement sensing technologies or if they require training and the length of the training. The question regarding the length of training is open-ended. While 50% of the respondents stated that the recruited students are usually technically skilled, more than 80% feel that the recruited students still require training. Similar responses on the duration of the training were clustered together and represented in Fig. 7.

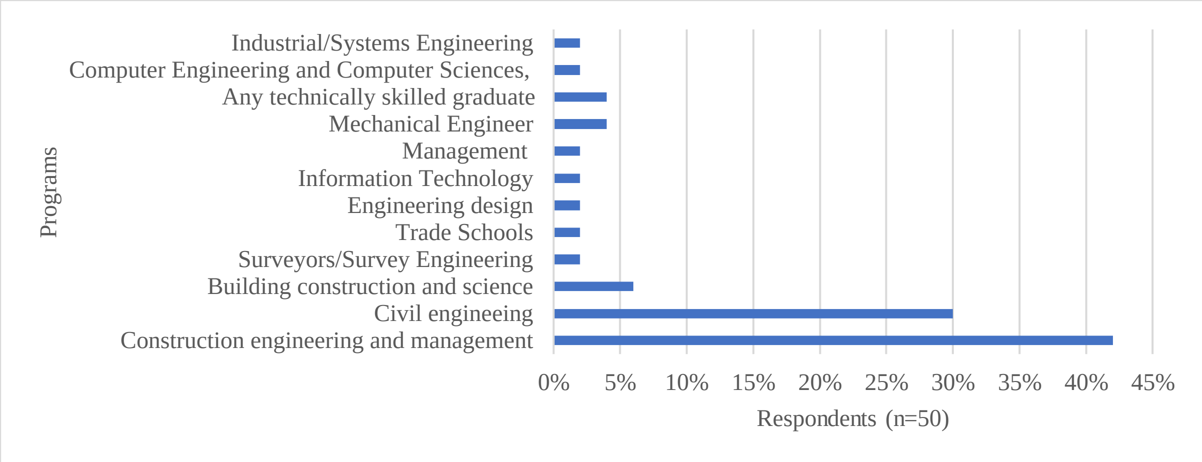

FIG. 6. Recruited educational programs.

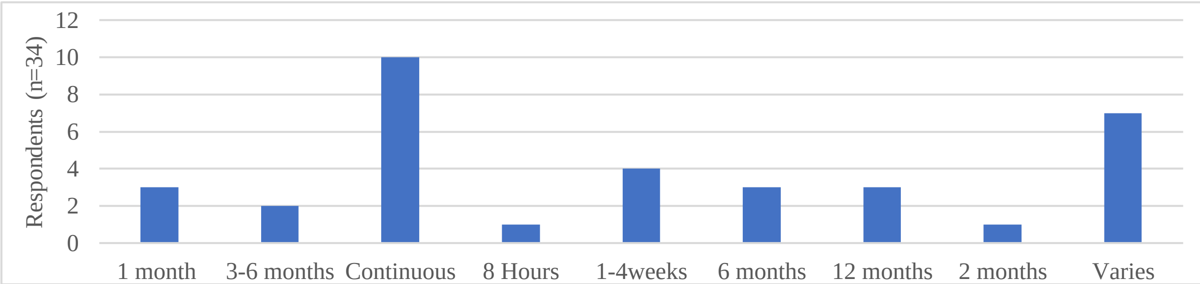

FIG. 7. Training duration.

Future demands of sensing technologies: To answer questions relating to the future demands of sensing technologies, participants who have not deployed and who are currently deploying sensing technologies were targeted. Participants who have not deployed sensing technologies on their projects were asked if they would adopt the technologies in the future, the timeline of adoption, and the types of sensing technologies they would adopt. The participants, who are currently adopting sensing technologies, were also asked if they anticipate future demand for more personnel to implement sensing technologies in the industry. Those that are yet to integrate sensing technologies (17% = 19 respondents from 10 companies) were asked if they foresee their company adopting sensing technologies in the future, and when they see their companies adopting sensing technologies. Result reveals that 89% propose to adopt sensing technologies in the future, out of which 67% and 33% foresee adoption in less than and beyond 5 years respectively.

As shown in Fig. 8, the top three sensing technologies that the participants plan to deploy in the future are cameras, laser scanners, and GPS.

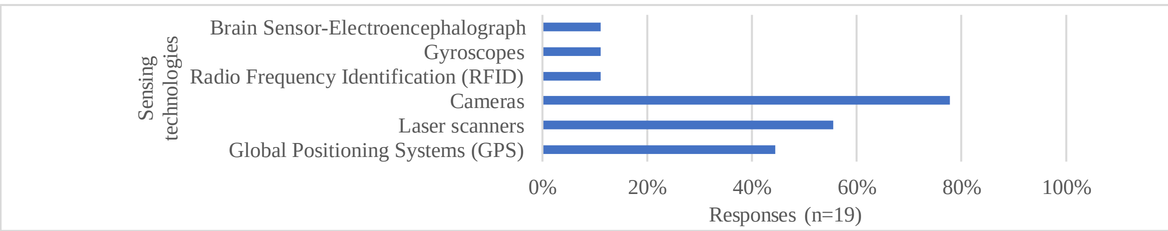

FIG. 8. Prospective adoption of different sensing technologies.

The participants that have already adopted sensing technologies were asked if they anticipate future demand for more personnel with skills for deploying sensing technologies. Results reveal that more than 60% of the respondents plan to recruit more graduating engineers to deploy sensing technologies on their projects.

4.2 Focus Group

The focus group discussion validated the results of the survey e.g., the applications of sensing technologies, the technical workforce for implementing sensing technologies, and the expected skill set of recruited graduate engineers. The following questions were asked in the focus group discussion:

1. What construction activities/ tasks do you adopt sensing systems on?
2. Who implements sensing technologies on your projects?
3. What are the skills required for implementing the sensing technologies on your project?

After the focus group discussion, the data was analyzed using thematic coding. To confirm the trustworthiness of the findings, inter-coder reliability testing was conducted using Cohen-kappa coefficient. The assessment showed a percentage agreement of 97% between the two coders. A Cohen-kappa coefficient of 0.5 was obtained, showing moderate agreement.

4.2.1 Applications of sensing technologies

As reported in Table 7, the application of sensing technologies is quite similar to those extracted from the survey results with laser scanners having the most application in the construction industry. Other data acquisition technologies that were not captured in the survey such as robotics total stations and concrete maturity meter were provided during the focus group discussion (Table 7).

TABLE 7. Applications of sensing technologies.

Sensors/Data Acquisition Technologies	Applications
Drone	Site mapping during preconstruction, site images for preconstruction estimating, safety coordination, site logistics
GPS	Tracking yard delivery trucks, locating or positioning equipment
Robotic total station	Layout slab edges, walls, and doorways; in-bed building layout; foundation layout
QR code	Tracking ducts from fabrication to installation; tracking equipment for maintenance and appraisal
Laser scanner	QA/QC applications, measurement of concrete for foundation work, quality control of placed concrete structural element, stub-ups checks before deck pre-pour, scanning joist for renovation work, locating wood knocker for hangers
Concrete maturity meter	Detecting concrete temperature and strength

4.2.2 Technical workforce for implementing sensing technologies

When participants were asked to provide the workforce within their organizations that implement sensing technologies, consultants, employees, subcontractors, and third parties were identified (Table 8). Contrary to the findings from the survey, the results revealed that construction companies do not often engage in-house employees in implementing sensing technologies due to the high risks and cost of operating sensing technologies. However, when they do, employees that are technically inclined are tasked with the implementation of sensing technologies in these companies.

TABLE 8. Technical workforce implementing sensing technologies

Technical Workforce	Reasons
Consultants	QA/QC is subcontracted to reduce risk to the company
Third-party	Risk shifted to the third party
Subcontractors	Laser scanning is often subcontracted due to the cost of acquiring a laser scanner
Employees	Technically inclined employees

4.2.3 Expected skill set

Participants further discussed the expected skillsets of graduate CEM students for deploying sensing technologies. Results revealed that the participants would like students to have prerequisite knowledge (i.e., functions), applications, and operations of sensing technologies. For example, comments such as "*I think that it is better if we can get the students to understand applications",* and another participant said *"So, the students have to have a basic understanding of how it is used, and how we are going to use it",* while another participant explained that students should have *"some generic exposure to it.".* The focus group further revealed the need to have general knowledge of these sensing technologies, as a participant stated *"What they just need to know is the generic knowledge, so they can be pretty sure of their skills when they come in to learn from whoever their Mentor is".* Furthermore, participants suggested that it is expected that graduate CEM students can model scans from laser scanners. For example, the participant stated, *"...So I guess the real skill is in dealing with the software that works from the scanner to get it into our model for people who will do the drafting for what we are using it for."*

4.3 Industry Case studies

Industry case studies on the application of sensing technologies were explored. A total of 35 case studies on the use of laser scanners, GPS, RFIDs, Drones, and GPRs were retrieved (Fig. 9), with laser scanners having 57% of the total case studies. The construction applications of these case studies were clustered and represented in Table 9. As shown in Table 9, the case studies are similar to the results from the survey and focus group, which further validates the results of this study.

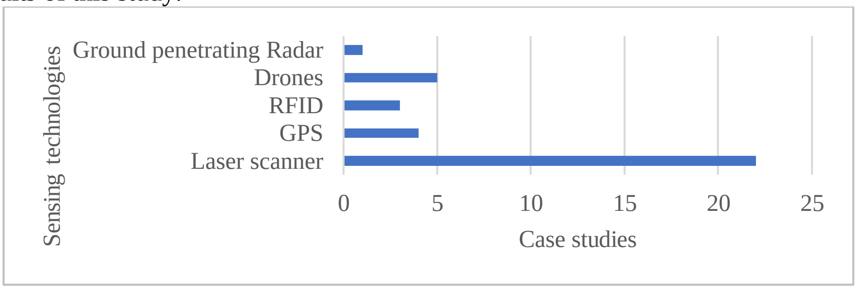

FIG. 9. Case studies of sensing technologies.

TABLE 9. Construction applications of sensing technologies

Sensors	Case studies
Laser scanner	Capturing existing conditions
	Capturing scans for complete 3D or 4D modeling
	As-built information for a medical building project
	Concrete floor flatness for a medical project that required installation of sensitive equipment
	Stockpile quantification for auditing purposes
	In-wall scans for detecting potential modifications
Drone	Site progress monitoring using drone images and videos
	Inspect difficult-to-reach areas on the jobsite
	Tracking structural changes of an abandoned tunnel for renovation work
	Procurement of images for advanced digital modeling
	Documentation of structural fills for a health care project
GPR	Wall deviation and issues hidden behind wall surfaces for renovation purposes.
RFID	Attached to workers' hardhats to track safety
	Track precast concrete from design, detailing, fabrication, and production, up till the installation phase
GPS	Locate electrical components in precast concrete
	Earthwork equipment navigation
	Location of stormwater, sewer, and telephone lines for HVAC systems renovation

5 DISCUSSION

This study investigated the required skills of graduating CEM students for deploying sensing technologies in the construction industry. A mixed-methods approach entailing surveys and a focus group discussion with practitioners to elucidate their perceptions on the knowledge and skills required, and the extent to which they are required to implement and advance the sensing technologies on construction projects was employed. The value and anticipated demand for these skills by the prospective employers were also presented. Results from the focus group discussion and industry case studies validated the survey results and are discussed below. The following section compares the study's results with previous work.

5.1 Knowledge and skills required to plan, implement, and advance sensing technologies on construction projects

As a first step to assessing the required skills for implementing sensing technologies, this study explored the level of adoption of sensing technologies in the industry. A high rate of adoption of sensing technologies, particularly image-based sensing technologies such as cameras, laser scanners, and drones, was observed in the surveys and validated from the case studies. Although GPS is increasingly being adopted, compared with image-based sensors, this study showed that other component-based sensors, such as RFIDs, accelerometers, gyroscopes, and EEGs, are gradually being embraced in the industry. The study reveals that these technologies are implemented for diverse applications at different project lifecycle phases, such as preconstruction, construction, and post-construction phases. The applications further reinforce the importance of the technologies in the construction industry.

From the focus group results, it can be implied that students need to acquire generic and prerequisite knowledge on the types and functionality of sensors and operational knowledge of sensing technologies for diverse applications. While this study emphasized the need for students to be skillful in operating different sensing technologies for the construction industry, the study equally highlighted the importance of obtaining software skills. This is supported by Farooqui and Ahmed (2009), where students' proficiency in software skills was highly ranked amongst other skills. The software skills, which include data visualization, data storage, and data extraction skills, are needed for processing and interpreting data from sensing technologies. This implies that the ability to extract meaningful information from construction data obtained from sensing technologies is a top priority in the construction industry. This particularly entails the use of software such as Autodesk Recap, Laser scanner proprietary software, Holo-builder, Revit, CAD, and drone deploy. For example, the results show that teaching students how to collect and process laser scans using different proprietary software and processing data from image sensors such as cameras and drones is important.

This study also reveals the importance of preparing students for the era of automation in construction. The results show that CEM students are expected to acquire skills in the adoption of artificial intelligence for understanding data from different sensing technologies. These findings complement other studies (Abioye, Oyedele et al. 2021, Baduge, Thilakarathna et al. 2022) emphasizing that automation is the future of the construction industry. For example, the survey results highlight the necessity for students to acquire machine learning skills for imagery analysis, workers and object detection, and workers' behavioral analysis. Another example is the highlighted need for students to acquire knowledge on Smartvid.io, a software that adopts artificial intelligence for improving safety on construction jobsite. This signifies the potential demand for the future workforce to be technically skilled in the construction industry.

5.2 Value and anticipated demand for these skills by the prospective employers

The study further assessed the value of sensing technologies by exploring how long the industry has been implementing sensing technologies, the present and future demand of the construction industry, and the motivation for adopting sensing technologies. Results reveal that the adoption of some sensing technologies e.g., cameras, GPS, and laser scanners can be traced back to over 20 years ago. In recent times, and over the past 5 years, there has been a rise in the adoption of other sensing technologies like RFIDs, drones, EMGs, EEG, thermal imaging sensors, concrete deck scanners, gyroscopes, and infrared mapping, hence suggesting the technological advancement in the construction industry and a need for the inclusion of sensing technologies-related courses in construction education.

The present demand for sensing technologies was then assessed by exploring the number of employees dedicated to implementing sensing technologies, and the future recruitment plans of companies for such skillsets. The results reveal that companies employ the services of subcontractors, consultants, and in-house employees for deploying sensing technologies on their projects, and companies utilizing in-house employees often have more than 10 employees dedicated to deploying sensing technologies. These employees are usually recruited from a variety of backgrounds, with about 40% of the surveyed companies recruiting from CEM programs.

However, sometimes, the recruited students do not possess the required technical skills, and usually require training on the job. These construction companies are often dedicated to training the recruited workforce which often comes with cost and time implications. As highlighted by McGraw-Hill and Construction (2012), this is a challenge faced by construction companies in recruiting a technically skilled workforce. Despite the training costs, these companies still anticipate the recruitment of more technically skilled employees which further reveals the need for a technically equipped workforce for deploying sensing technologies in the construction industry. This may be driven by existing evidence of the benefits derived from sensing technologies (Taneja, Akinci et al. 2011, Akanmu and Anumba 2015, Li, Chan et al. 2015). Besides the benefits derived from the adoption of sensing technologies such as time and cost savings, increased accuracy and productivity, schedule control, and predictive analysis, companies are motivated by their clients to adopt sensing technologies on their projects. Likewise, companies are motivated by the desire to advance technologically and develop a competitive advantage over other companies as also supported by (Flanagan 2002). Furthermore, the future demand for sensing technologies was assessed by companies yet to adopt these technologies. Findings from this study show that in the next five years, there will be a continuous demand for sensing technologies, particularly cameras, laser scanners, GPS, RFID, gyroscopes, and EEGs.

6 CONCLUSIONS, LIMITATIONS, AND FUTURE WORK

The adoption of sensing technologies in the industry is gradually gaining momentum, and this has prompted the need for a workforce with the required skills and knowledge for deploying the technologies in the industry. This study investigated the adoption of sensing technologies in the construction industry, and the industry’s perceptions of the knowledge and skills required for deploying the technologies on construction projects. The sensing technologies currently adopted in the construction industry include cameras, laser scanners, drones, global positioning systems, radio frequency identification systems, gyroscopes, accelerometers, ground penetrating radars, electroencephalography, electromyography, and thermal imaging sensors. From this study, the vast application of sensing technologies across the lifecycle of projects further emphasizes their importance in the construction industry. As the rate of adoption of sensing technologies continues to increase, there will be a complementary increase in the demand for a workforce with the requisite skills in the industry. The study reveals that the top sensing technologies to be taught in CEM education include cameras, laser scanners, and global positioning systems and the required skillsets for implementing these sensing technologies on construction projects include data visualization, data extraction, data storage, and programming. In addition to these, this study emphasizes the need to equip students with operational skills of sensing technologies. This study also signals the era of automation in construction and the need to equip students with the required data computation skills to advance these technological innovations in the construction industry. This study contributes to the existing scarce literature on the knowledge and skill demands of the industry to implement sensing technologies. With the current workforce requiring training on the job, the future construction workforce will need to be equipped with the skills to ease their transition to the workforce. Hence, this study provides learning content for curriculum developers to prepare the future workforce with relevant technical skills in the industry.

However, this study has some limitations which should be addressed in future studies. Firstly, this study focuses on primarily identifying the knowledge and technological skills, and highlights the future demand for sensing technologies but did not investigate the type of training that are provided in construction companies for equipping new hires with the required skill sets. Secondly, although the duration of training to skill new hires on the use sensing technologies was investigated, the duration of training for each sensing technology is unknown. Future studies could explore the required training contents and duration for each sensing technology. Future studies will also investigate the extent to which sensing technology-related education is currently taught in CEM programs and how the CEM curriculum can be expanded to meet industry workforce needs. It is also necessary to investigate the non-technological skills needed for deploying sensing technologies in the construction industry. Furthermore, there is a need to explore how the inclusion of sensing technology-related education will meet current accreditation requirements and how it will be assessed.

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