2023 European Conference on Computing in Construction
Heraklion, Crete, Greece
July 10-12, 2023

Enabling Intelligent Construction: Current Challenges and Considerations for the Connected Site

Kyle Morman[1], Aaron Costin[1], and Janise McNair[1]
[1]University of Florida, Gainesville, FL

Abstract

Technological advancements of Construction 4.0 are enabling the construction industry to become safer, more efficient, and higher quality. Industrial production, cyber-physical systems, and embedded microelectronics are a few technologies being integrated to enable intelligent job sites. Connectivity and real-time data are essential for these technologies to work properly. Unfortunately, the current dynamic and chaotic environment of the construction site presents less-than-ideal conditions for the successful implementation and operation of these enabling technologies. The aim of this paper is to present the current problems and solutions in establishing connected job sites, specifically focusing on network and device integration.

Introduction

The importance of enabling intelligent construction sites to mitigate industry challenges is becoming paramount. Safer sites, quicker schedules, and higher quality products are of the many demands on the industry. The future construction site, named Construction 4.0, is the new age of construction technology that utilizes the recent innovations in industrial production, cyber-physical systems (CPS), digital/computing technologies, big data analyses, and artificial intelligence (AI) (Sawhney et al. 2020). Industrial production includes prefabrication, 3D printing and additive manufacturing, and offsite assembly. Cyber-physical systems include physical objects (e.g., actuators, sensors, robots) that are controlled by computers producing a virtual-physical feedback system. Digital and computing technologies include building information modeling (BIM), Digital Twin, reality capture technology (e.g., laser scanners, drones, cameras), immersive realty technologies, and data standards. Big data analysis and AI provide the means to efficiently analyze the vast amounts of data for decision making and prediction. The essence of Construction 4.0 is the integration of all of these technologies into various interconnected and smart applications for construction, and the industry is already benefiting from the implementation of Construction 4.0 principles and technologies in different ways (Toca Perez et al. 2020). However, these scenarios will require a vast network of wireless communications with considerable computing power, in which the current conditions of the construction site does not offer a suitable environment.

Connectivity, bandwidth, cyber-security, and quality of service (QoS) are a few of the many challenges that will be faced with the dynamic and chaotic nature of the construction environment (Costin and McNair 2022). Further challenges also "require serious attention and consideration, such as interoperability and integration of devices, big data analysis... communication networks [and] congestion" (Saleem et al. 2019). Thus, as the high number of potential issues indicates, to enable intelligent jobs, the understanding of constraints and mitigation of obstacles are essential. The aim of this paper is to identify the current challenges and solutions towards establishing a connected active construction environment.

Overview of IoT and CPS in Construction

An essential component of Construction 4.0 is the connectivity of the physical devices and sensors, including across local area networks and the internet. Intelligent construction sites require a system architecture of wireless communications mechanisms in order to relay sensor information and device control. This system falls under the realm of internet of things (IoT): a communications paradigm where the internet is connected to the physical world via ubiquitous wireless sensor networks (WSN). World objects are known as physical things, and they perform near constant information exchange with one another. Their connection through a wireless network to a virtual environment creates a CPS, in which one significant feature is the creation of a virtual-physical feedback loop between device modification and human behavior. Figure 1 displays an abstraction on how the IoT components connect to one another as part of a CPS (Costin and McNair 2022).

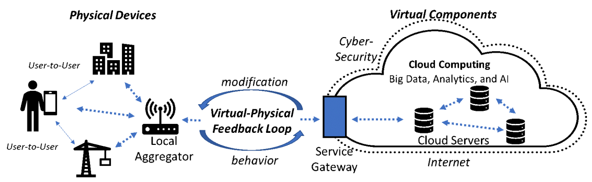

Figure 1: Abstraction of the IoT system for Construction (Costin and McNair 2022)

Furthermore, the large quantity of sensors in WSN and wide variety of types of CPS assist in the creation of Big Data. The idea is, since the internet is so spatially pervasive, virtually every physical thing in this world can also become a computer that is connected to the internet. Once the connections are established, "IoT not only enhances the digitalization, informationization, and cyberization in the construction domain, but it also provides the required technology and solutions for smart buildings, construction, and manufacturing" (Lin and Cheung 2020).

Mention should also be made that technological integration in the name of IoT are no longer purely academic endeavors. In 2015, the IoT worldwide energy market exceeded $6.8 billion USD and is projected to reach $26.5 billion USD by 2023, with a compound annual growth rate of 15.5 percent in 2016-23 (Ahmad and Zhang 2021). It is predicted that the quantity of active IoT devices worldwide will reach between 22-75 billion in 2025 with a market of $457 billion USD (Ahmad and Zhang 2021; Ali et al. 2022).

Literature review on IoT in Construction

Recent literature reviews have been conducted for IoT applications in construction (Tang et al. 2019), methods for interoperability (Costin and Eastman 2019), and construction safety sensors and technology (Thibaud et al. 2018; Costin et al. 2019; Awolusi et al. 2019). Ghosh et al. (2020) has found that key drivers for adoption in these domains include interoperability, data privacy, data security, flexible governance structures, and proper business planning and models. The mentioned key drivers are being utilized to mitigate the challenges faced in the construction industry including skilled labor shortage and low productivity. Furthermore, to assist the growth of these drivers, data streams that have been received through IoT devices and sensor networks could be integrated with BIM tools and make a paradigm shift in construction efficiency improvement (Tang et al. 2019). Such real-time sensor data integrated with BIM to reflect the current condition of the physical object enables the production of a digital twin (Adibfar and Costin 2022). IoT is an enabling technology for digital twin, but there have been various definitions and maturity levels of what digital twin is (which is not in the scope of this research). Enabling a smart worker is the most popular use of technology since it can prevent safety risks and increase performance. Thibaud et al. (2018) state that the use of IoT in construction is sky rocketing and emphasized that the IoT can significantly help in alleviating the high-risk concerns in construction industry. Dozens of technologies exist for location tracking, gait analysis, object detection, activity recognition, and ergonomic assessment (Asadzadeh et al. 2020). Two examples of smart-worker technology incorporation are as follows. First, Kanan et al. (2018) utilize an IoT architecture in proposal of an autonomous system for hazard recognition that sends safety notifications to site laborers. The validation of system results show that this new approach could be a cheap and effective system that has low operational costs that supports the feasibility of their further utilization. Second, Louis and Dunston (2018) provide a practical and sensor-agnostic implementation of operation-level decision-making by utilizing IoT networks along with advancements in modeling and simulation tools.

Some of the data on worker conditions, such as location, path, orientation, temperature, heart-rate, and blood-oxygen saturation, can be monitored via smart-phone or smart-watch. Other conditions require user-specific data generation, like typical pace of productivity, level-of-enthusiasm, and attended safety training inclusion. Yet, in still another category, some conditions will require application-specific devices to be developed, like repetitive strain gauges on a particular body part and augmented-reality incorporation mechanisms. These categories still do not encompass the other technology made for site connectivity that will be discussed shortly, which include but are not limited to, unmanned equipment, automated tools and machines, localization systems, video, point-cloud, and ambient environmental interaction mechanisms. Despite available sensing approaches and concerns on worker safety, there is a large gap among sensor data, modeling of safety issues, and individuals' safety performance (Park et al. 2018).

The consideration of the intelligent jobsite, as an expansion of the technologically assisted laborer, needs to be approached in an integrated and non-proprietary manner. As Jia et al. (2019) note, "integrating components among a project's entire life cycle should be studied to increase interoperability of IoT systems and give birth to industry-specific standards." This is because "isolated systems can result in significant increases in cost and resource consumption for actual practice" (Qi et al. 2021). Costin and McNair (2022) provide an overview of the integrated IoT system architecture on the construction site, considering state-of-the art technology and next generation IoT infrastructure, including software-defined networks (SDN), edge computing, cloud-based services, and machine learning techniques.

Figure 2 illustrates some typical applications of how Construction 4.0 exists within the active construction domain. Sensors can be allocated near waste stations on-site to ensure toxicity does not exceed environmental regulation. Automated verification methods can be used for laborer identification, PPE compliance, site access, and asset tracking. These can be further enhanced by the use of computer vision techniques (Paneru and Jeelani 2021). Further sensors can be embedded into materials or equipment for structural health monitoring (SHM), proximity detection, and environmental monitoring as liability safeguards. Finally, the necessary real-time assimilation to the cloud-based BIM is paramount to the success of AR/VR, clash detection, and future project planning methods. -

Research Methods

This research is motivated by the major challenges faced in the construction by enabling the current condition of the job site to adapt to the emerging wireless technologies. This work is part of a larger research project in the development of cyber-infrastructure (CI) service for construction research called IoT-ACRES (IoT-Applied Con-

Figure 2: Typical Smart Construction Site Applications (Morman 2021)

struction Research and Education Services), which is a central, interoperable framework hub that can incorporate a variety of heterogeneous sensors, technology, software, managed by a software-defined network infrastructure and optimized by ML and AI techniques. A systematic literature review of both the construction industry and advancements of wireless technology has been performed, further elaborated upon in Morman (2021). Specifically, 33 keywords relating to low-power wireless communications and construction were run through search engines in Springer Link, Wiley, MDPI, Elsevier, and other popular publisher sites. Compositions were collected from 128 different journals and conferences. Additionally, the equipment from 40 different experimental prototypes, found during the literature review, were compared via experimentation. The resulting device data sheets were downloaded from each respective manufacturer. Each data sheet was searched for processor architecture, energy characteristics (like power consumed or generated), cost, availability, and capabilities. Finally, the data was tabulated for observation. The aim of this paper is to present the findings, challenges and considerations, for the integration of wireless networks and sensors on the construction job site. In enabling a intelligent job site, the following evaluation criteria and questions were asked:

- Device Hardware- *Do we have the right devices to deploy?*
- Device Software - *Can we operate the devices?*
- System Architecture - *Do we have the capability to deploy the devices?*
- Usability - *Are the end users able to use the devices?*
- Acceptability - *Are the end users willing to use the devices?*

The specific scope of this paper is the evaluation and considerations of the devices, namely the hardware and software. The specific consideration of the hardware and software include:

- Site Connectivity: wireless capability, network type, and existing infrastructure.
- Energy Usage: power consumption, power generation, battery life, and energy harvesting.
- Software: low-power operating system, interoperability, and open source code.
- Hardware: packages, cost, and durability.
- User Elements: technical proficiency, adaptability, usability, acceptance, and ethics.

Findings

Site Connectivity

Unlike a building or facility, a construction site is dynamic and has many more considerations that prohibit an off-the-shelf or plug-and-play IoT solution. Environmental stressors, equipment movement, limited power, and inadequate internet connectivity are major barriers in successful IoT deployment. "These issues are a result of the location, a harsh natural environment of civil infrastructure, large sensing scope of wireless monitoring system, a generation and transmission of huge amount of data in each data sensing period, and complexity of... algorithms, which were also developed to be processed at a centralized station" (Abdulkarem et al. 2020).

System architecture is a critical piece of the IoT network, and can become very complex. When setting up a network, there is a big difference between devices being integrated into an existing system and new system creation. For construction, the majority of projects will be new systems' development. There are many questions that need to be asked, whether new or existing, in the deployment of the system architect: *What devices are needing to connect to the wireless/wired and need to communicate back to a service or server? How many number of end devices will there be? What is the required size of the sub-net? Will the end devices need to communicate to each other on a local network? Will the end devices need to communicate to a wired device, gateway, or route? If there is a wired device, where will it be located? Are there multiple rooms or locations?* The solutions to these questions will be different for each construction project and there is difficulty for a one-fits all solution. Furthermore, setting up a network requires a full time information technology (IT) personnel to ensure smooth operation, and this is not a typical position on the job site.

Energy Focuses

Power on construction sites can be a challenge, especially during project initiation or projects that are located in remote areas. Generators are common on site, and when these are in use, only critical tasks are allowed power for use. Every node in an IoT network requires power, from routers and access points to the sensors and devices. Yet, even when power is accessible, running electrical wiring from device to device around the job presents major safety hazards, such as tripping, electric shock, and equipment interference.

The sensor layer of IoT is hindered by power needs. The nodes must be either grid connected, which creates unnecessary infrastructure costs to hard wire and reduces the flexibility and mobility of node placement, or remotely powered and wirelessly connected, which hosts another plethora of issues worth discussion. Early IoT experiments quickly showed the impracticality of attempting to hard wire billions of electronic sensors into construction infrastructure. The safety hazards and material cost of wire alone made the idea completely impractical. When researchers tried using simple battery-powered systems, they found that "the battery-powered sensor nodes are not feasible as the battery needs to be replaced or recharged" (Al-Kaseem et al. 2020). The nodes would last only weeks or months at best before needing physical replacement (Hu et al. 2013).

Upon realization of the early trial shortcomings, developers came to realization that "the minimization of energy consumption in IoT devices is a crucial target, i.e. reduction of energy supply" (Nizetic et al. 2020). One of the "essential concerns in the deployment of WSN is how to balance between network connectivity and network lifetime" (Nguyen and Kim 2021). As an example, "up to 500mA of current is required for data transmission via WiFi, which is too much for an extended battery-powered operation" (Benjamin et al. 2022). One method to "further reduce power consumption of a WSN" is standardizing "the combination of more advanced sensors and a carefully designed algorithm for system operations" (Nguyen and Kim 2021). Algorithmic development for power consumption seems insufficiently explored thus far in IoT however, because as Han et al. (2021) state, "future energy prediction and its appropriate management using IoT devices is rarely studied."

Sustainability, in general, is also on the rise. Academics frequently cite that "electronic waste will become one of the major issues caused with the planned rise of IoT products" (Nizetic et al. 2020). Similarly, "the sustainability aspect and long-term effects of IoT technologies are not clear and insufficiently investigated" (Nizetic et al. 2020). As proof, Benjamin et al. (2022) demand "the focus of further research should be the lowest possible power consumption." Beside the frequently unaddressed solutions throughout the remainder of this article however, there is a positive light in that, power consumption is being addressed via alternate energy storage and harvesting mechanisms via microelectromechanical systems (MEMS) (Eshaghi 2018).

Considering energy further, there is also a trade-off between the user interface and user experience with power consumption and data requirements. The more bare-bones an interface is, then naturally the less power consuming it will be. Unfortunately, creating sparsity in the interface will come at the cost of the back-end functions, which make the software enjoyable, because intuitive software is reliant upon the last few decades of behind-the-scenes engineering innovations in code development.

Software

Some modern energy improvements are resultant of low-power operating system (LP-OS) developments. However, LP-OS, like TinyOS Contiki, and FreeRTOS, have not yet acquired the same proprietary traction that low-power hardware has. It may be unlikely that we ever see commercial low-power operating systems, and this is again because of the nature of IoT: in order to make each device function a simply as possible, yet correctly for its application, it will need to be built specifically for that application, which requires systems that allow much freedom for alteration. Github and Open-source coding, which have been a growing source for computer developers, prove the likelihood that proprietary influence remains minimal.

Physical microelectronic limitations are another key consideration to recognize. Because of the open-source paradigm, there exists a lot of basic code upon which to develop WSN for IoT applications. Within open-source codes exist libraries and algorithms that can be used simply by copying freely available scripts from GitHub or a similar coding repository. However, without proper knowledge of the coding language, utilized libraries, and operation of the scripts, there can be extensive and unnecessary overhead irrelevant to the operation of the system as a whole. This overhead consumes the entire available memory on the device and causes the battery to deplete quickly, thereby rendering the usage of many freely available scripts moot.

As an example of the physical limitations just mentioned, although one of the most popular and user friendly development platforms available worldwide, "the Arduino Uno board may draw a significant amount of current compared to other existing platforms" (Al-Kaseem et al. 2020). The power consumption is caused by the size of the Arduino libraries, expanded at the cost of power and price for the sake of user-friendliness. As such, the Uno is relatively expensive, which makes it fun for prototypical experimentation, but impractical for full scale Construction 4.0 rollout. Thus, an intelligent IoT designer must be present to prevent the accidental overuse of one, or many, of the highly constrained variables involved. The trade-off between variable constraints is represented in Figure 3.

Hardware

The basic hardware that create 'intelligent' devices are microcomputers, micro electronics (transistors, relays, capacitors etc.), conductor-wires, adapters, sensors, an energy-storage mechanism, and some type of mechanical feature (motor, actuator, lights, etc.). As with all electronics, the development of the device is a combination of all of these spliced together. The cost of each of these components are fairly inexpensive, and there are kits that can be purchased to assist in the creations. For example, a 35 piece IoT development kit costs less than $50 USD.

In deploying highly application-specific electronics, the cost-power-usability-communicability trade-off described in Figure 3 is more likely to be satisfied, because the

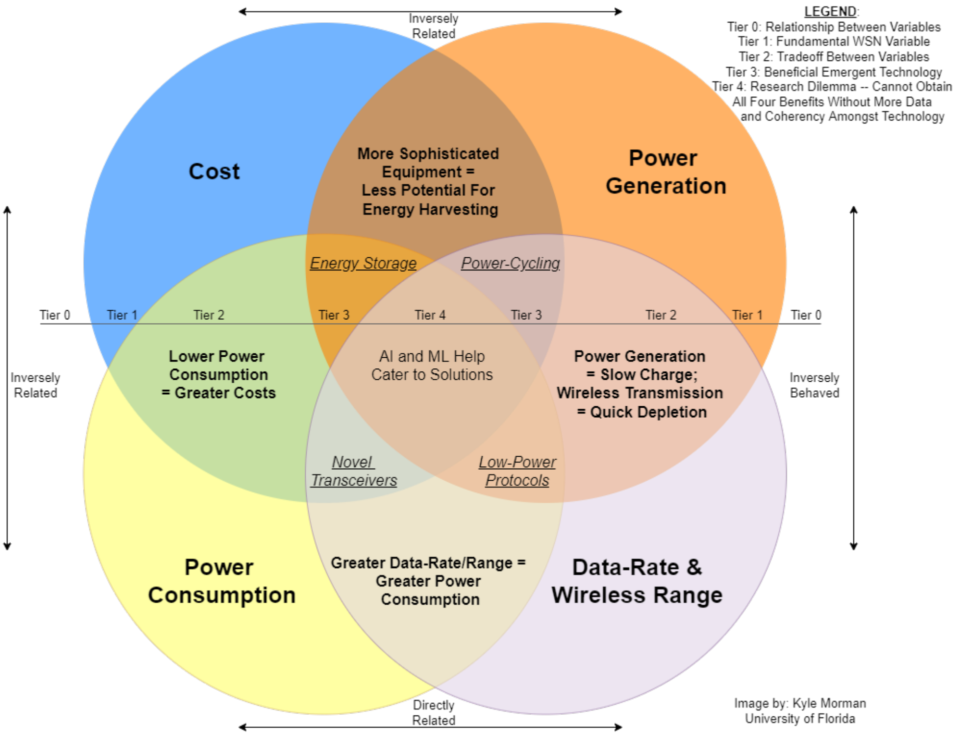

Figure 3: IoT Device Trade-offs (Morman 2021)

product developers and end-users can focus more intently on a subset of desired variables, rather than attempting to meet the often contradictory needs of low-power embedded wireless deployments. Additionally, available resources, such as time and memory, need to be considered more carefully, as some micro-controllers have such limited memory that more extensive libraries could not be used, as mentioned previously (Benjamin et al. 2022).

More often than not, however, construction practitioners find it easier and more viable to provide additional funds, energy, and time to job-site training and personnel briefings rather than technological incorporation for the sake of accident prevention. Also, near-miss events are important safety-leading indicators, but are are often left unreported and undocumented (Asadzadeh et al. 2020). Thus, in the domain of technologically-assisted safety and active-leading-indication for accident prevention, there remains much room for improvement. The technology does exists, but perhaps due to a lack of existing data-driven business models, it does not yet possess the successful commercial footing necessary for widespread adaptation.

Finally, and perhaps the biggest downside of the device hardware remains the lack of ruggedness. Custom coverings and housings, whether 3D printed or injected molded, are required to be able to use these devices outdoors. Most of the commercially available routers and sensors can go more than 3 times the cost of indoor ones.

User Elements

Human interactions are essential for technology; if humans don't accept the technology, it won't be used. Another element of technological inter-connectivity that is currently lacking in literature is the future need for an IoT-specific workforce. The current state-of-the-art, amidst the generational integration of BIM into practice, is to have an informational technology (IT) specialist working in the contractor's office, and who oversees the updating, assimilating, and purchasing of new software and hardware tools.

However, there are also already currently dozens of hardware and software tools already in consistent need of fixing and updating. On the software side, this includes "CoConstruct, PlanGrid, Autodesk BIM 360, Procore, e-builder and Aconex" (Dawood and Rahimian 2021). As for hardware, some leaders in construction technology include Trimble laser scanners and autostations, Boston Dynamics robots, and the various drone manufacturers. Thereby, recognition should be made that accommodating the technical needs of the numerous tools yet to be developed will likely transcend the capabilities of the current IT workforce within construction companies.

In continuation, the IT workforce will further be hindered by transitions from traditional call-in computing customer service assistance to the meticulous combing of the unvetted, free-to-use software development world. As such, considering the involvement of the open-source community mentioned previously in the success of the ubiquitous computing of IoT, there are no currently solution providers. No solution providers means no permanently funded troubleshooting and debugging customer service teams. In result, there is no customer support. In conclusion, the future connected building environments are going to require teams of dedicated IoT specialists to test and calibrate the numerously deployed device for accuracy and operability.

Usability is yet another important aspect of the system. If a system is not user friendly or fails to provide a good user experience, it will be abandoned. A simple, yet aggravating issue, is the glare on tablet and phones screens when out doors. Another screen issue is inadequate back lighting. These are common occurrences on construction sites. There is additionally the issue of push-back from the laborers in which is the targeted benefactors of the developed technologies. Research has already stated that additional research is required in the understanding the resistance of construction employees to the latest technologies (Sabu and Kumar 2022; Costin et al. 2012). The acknowledgement of this resistance places another constraint on IoT deployment: intuitiveness in application breeds success, but any fault in the application will be expounded by those resistant to its usage. Finally, with all technologies, ethics must be at the forefront when deploying the IoT system. Several researchers have sounded the alarm on the corresponding ethical and moral predicaments that often come with implementing these technologies (Hamzeh et al. 2021; Karmakar and Delhi 2021). Nizetic et al. (2020) also agree, in which they state that "IoT technologies can cause social impacts in specific industrial branches or businesses since working labour could be reduced and direct social contacts have also been reduced." As such, "more research is deemed necessary to clarify how Construction 4.0 is being implemented in each country considering also the local regulatory framework and the practices of the construction industry" (Forcael et al. 2020). Furthermore, Sherratt et al. (2020) claim that "future work should more clearly acknowledge the influence of technique within the change process, *the wider political and economic contexts* in which this revolution is occurring, and the potential power imbalances inherent in Construction 4.0." Amidst the design and implementation of new technology and integration, the potential power imbalances must always remain in-consideration because, as IoT evolves, "professionals may find their roles within the design, engineering and construction processes become more heavily influenced and shaped by the technologies themselves. Indeed, the role of the 'technology owner' may become more powerful than any traditional profession in the future, as they become dominant actors within the construction industry space" (Sherratt et al. 2020).

Discussion

Readiness: Very close, still not there

To date, abandonware and proprietary restrictions have impeded IoT rollout via interoperability issues and supply-chain bottlenecks. Since 2020, there have considerable supply chain hindrances in both the electronics and building domains. The inability to acquire sensing devices, microprocessors, and transceivers shuts down prototypical experimentation to all except for a lucky few. In result to supply-and-demand, costs rise and subsequently inhibit the ability of constrained systems' development. Also inhibiting the rollout of IoT, and embedded microelectronic systems in general, (up until recently) has been the proprietary mindset of the manufacturers involved in component development and distribution. However, as Morman (2021) shows, there are many connectivity standards bodies now integrating the works of previously competitive producers for the sake of heightened interoperability and device usability.

Beyond supply, cost, and interoperability, the power consumption of the subsystems within the IoT network have also already been discussed. 20th century wired and battery-oriented networks were incapable of feasibly deploying the mass number of devices associated with successful IoT integration and Big Data generation. With the advent of MEMS, researchers focused on ambient energy harvesting, and constant development of ever-improved energy storage mechanisms though, the power consumption issues of Construction 4.0 are likely to be near conclusion. Thereby, thanks to connectivity standards and MEMS, the potential for connected construction sites is very close... but still not quite ready.

A double-edged sword lies in the simplicity of devices deployed for the sake of Big Data via site connectivity. First, because the sensors are small, inexpensive, and functionally simple, they are often disregarded as the means-to-the-end. In reality, the practitioners of the IoT must consider the analog sensing, digital information relay, wireless transmission, data storage, and physical housing all as components to a temperamental WSN. In response to the many focuses previously mentioned, one final discussion point must be stated: to properly deploy smart construction systems, a new department with full-time positions must created (similar to BIM and VDC) that include team members who understand the protocols, devices, and languages used in package development. This department will be able to create the individual network applications, adjust the system to project conditions, and provide customer support.

Gaps and Future Research

Even with a viable IoT solution, these new technologies will create new issues and unintended consequence. "Lean Construction 4.0 should look behind the direct efficiency of operations and aspire towards systems efficiency. This entails a harmony between 1) human needs, 2) technology, 3) construction processes, and human values of free will, peace, and sustainability" (Hamzeh et al. 2021).

Inclusion, accessibility, and economic impact are critical considerations when developing and deploying these systems. Risk of job loss due to technology and automation currently does and will continue to happened. Those that have access to and can afford these technologies will have an economic advantage, thus widening inequality gap. The simple concept of internet access is an important issue many people face, as well as access to affordable training. Currently, there are no mechanism to reduce the technology-induced the economic inequality.

The technical gaps of construction is a major research area with many aspects. Connectivity, quality of service, and lack of durability prevent deployable and scalable solutions. Device consumption versus power generation will continue to be a literal power struggle.

Human behavior issues, such as lack of adoption and resistance to change, are still prevalent. And the use of integrated wireless automation systems can potentially have the risk of deskilling users who develop an over reliance on these technologies. Over-reliance on the systems may also result in unsafe behaviors that could actually potentially increase safety incidents. Finally, the increase in ubiquitous sensors that connect to the internet create huge opportunities for malware and hacking. Having the vast amounts of data, some often private and confidential, may expose personal and companies to compromised situations.

Conclusions

Technological advancements of Construction 4.0 are enabling the construction industry to become safer, more efficient, and higher quality, but there are many barriers and challenges that impede full integration of the technologies. This paper discusses the current challenges and solutions of establishing a connected job site, specifically focusing on the network and device integration. The main topics include site connectivity, energy factors, hardware, software, and human interactions. Future research is required to evaluate systems as a whole, including the accuracy, costs, bandwidth and data load requirements, and scale.

Based on the results, it was found that current IoT systems are currently not ready for full commercial deployment and most applications are small scale. However, large exponential growth is expected to occur within the next few years. A major recommendation to enable the implementation of IoT networks now is the creation of new department that include team members who understand the protocols, devices, and languages used in package development. This department will be able to create the individual network applications, adjust the system to project conditions, and provide customer support.

Ultimately, establishing an intelligent job site that integrates Construction 4.0 devices requires both multidisciplinary collaboration among researcher and construction stakeholders. The construction industry involves many stakeholders, and without everybody embracing and accepting the technology, full deployment of the system will be futile. There needs to be an low cost, open and accessible, yet secure solution that can capitalize on the human machine relationship: where the workers can improve their abilities, while the systems improves its capabilities to assist the workers. The future of the intelligent site is here, and the expansion is promising.

Acknowledgments

This research was funded by the National Science Foundation, grant number 2004544. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

References

Abdulkarem, M., Samsudin, K., Rokhani, F. Z., and Rasid, M. F. A. (2020). Wireless sensor network for structural health monitoring: A contemporary review of technologies, challenges, and future direction. Structural Health Monitoring, 19(3):693–735.

Adibfar, A. and Costin, A. M. (2022). Creation of a mock-up bridge digital twin by fusing intelligent transportation systems (its) data into bridge information model (brim). Journal of Construction Engineering and Management, 148(9):04022094.

Ahmad, T. and Zhang, D. (2021). Using the internet of things in smart energy systems and networks. Sustainable Cities and Society, 68.

Al-Kaseem, B. R., Ahmed, A. F., Abdullah, A. M., Azouz, T. Z., Al-Majidi, S. D., and Al-Raweshidy, H. S. (2020). Self-powered 6lowpan sensor node for green iot edge devices. In 2nd International Scientific Conference of Al-Ayen University (ISCAU-2020), volume 928. IOP Publishing Ltd.

Ali, O., Ishak, M. K., Bhatti, M. K. L., Khan, I., and Kim, K.-I. (2022). A comprehensive review of internet of things: Technology stack, middlewares, and fog/edge computing interface. Sensors, 22(3):995.

Asadzadeh, A., Arashpour, M., Li, H., Ngo, T. D., Bab-Hadiashar, A., and Rashidi, A. (2020). Sensor-based safety management. Automation in Construction, 113:103128.

Awolusi, I., Nnaji, C., Marks, E., and Hallowell, M. (2019). Enhancing construction safety monitoring through the application of internet of things and wearable sensing devices: A review. Computing in civil engineering 2019: Data, sensing, and analytics, pages 530–538.

Benjamin, B., Kristina, D., Andreas, A., and Christian, W. (2022). Evaluation of low-cost microcontroller-based electronic systems for simple sensor node applications.

Costin, A. and Eastman, C. (2019). Need for interoperability to enable seamless information exchanges in smart and sustainable urban systems. Journal of Computing in Civil Engineering, 33(3):04019008.

Costin, A. and McNair, J. (2022). IoT and Edge Computing in the Construction Site, chapter 10. CRC Press.

Costin, A., Pradhananga, N., and Teizer, J. (2012). Leveraging passive rfid technology for construction resource field mobility and status monitoring in a high-rise renovation project. Automation in Construction, 24:1–15.

Costin, A., Wehle, A., and Adibfar, A. (2019). Leading indicators—a conceptual iot-based framework to produce active leading indicators for construction safety. Safety, 5(4):86.

Dawood, N. and Rahimian, F. P. (2021). Special issue editorial - construction 4.0: Established and emerging digital technologies within the construction industry. J. Inf. Technol. Constr., 26:758–762.

Eshaghi, M. (2018). An energy harvesting solution for iot sensors using mems technology. Thesis, University of Windsor.

Forcael, E., Ferrari, I., Opazo-Vega, A., and Pulido-Arcas, J. A. (2020). Construction 4.0: A literature review.

Ghosh, A., Edwards, D. J., and Hosseini, M. R. (2020). Patterns and trends in internet of things (iot) research: future applications in the construction industry. Engineering, Construction and Architectural Management.

Hamzeh, F., González, V. A., Alarcon, L. F., and Khalife, S. (2021). Lean construction 4.0: Exploring the challenges of development in the aec industry. In Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC), pages 207–216, Lima, Peru. Export Date: 27 January 2023.

Han, T., Muhammad, K., Hussain, T., Lloret, J., and Baik, S. W. (2021). An efficient deep learning framework for intelligent energy management in iot networks. IEEE Internet of Things Journal, 8(5):11.

Hu, X., Wang, B., and Ji, H. (2013). A wireless sensor network-based structural health monitoring system for highway bridges. Computer-Aided Civil and Infrastructure Engineering, 28(3):193–209. https://doi.org/10.1111/j.1467-8667.2012.00781.x.

Jia, M., Komeily, A., Wang, Y., and Srinivasan, R. S. (2019). Adopting internet of things for the development of smart buildings: A review of enabling technologies and applications. Automation in Construction, 101:16.

Kanan, R., Elhassan, O., and Bensalem, R. (2018). An iot-based autonomous system for workers' safety in construction sites with real-time alarming, monitoring, and positioning strategies. Automation in Construction, 88:73–86.

Karmakar, A. and Delhi, V. S. K. (2021). Construction 4.0: what we know and where we are headed?

Lin, Y.-C. and Cheung, W.-F. (2020). Internet of things (iot) and internet enabled physical devices for construction 4.0.

Louis, J. and Dunston, P. S. (2018). Integrating iot into operational workflows for real-time and automated decision-making in repetitive construction operations. Automation in Construction, 94:317–327.

Morman, K. (2021). Wireless sensor networks, internet of things, and construction 4.0. thesis, University of Florida, M.E. Rinker School of Construction Management.

Nguyen, P. D. and Kim, L.-W. (2021). Sensor system: A survey of sensor type, ad hoc network topology, and energy harvesting techniques. Electronics, 10(2):20.

Nizetic, S., Solic, P., and Lopez-de-Ipina Gonzalez-de Artaza, D. (2020). Internet of things (iot): Opportunities, issues and challenges towards a smart and sustainable future.

Paneru, S. and Jeelani, I. (2021). Computer vision applications in construction: Current state, opportunities & challenges. Automation in Construction, 132:103940.

Park, J., Cho, Y. K., and Khodabandelu, A. (2018). Sensor-based safety performance assessment of individual construction workers.

Qi, B., Razkenari, M., Costin, A., Kibert, C., and Fu, M. (2021). A systematic review of emerging technologies in industrialized construction. Journal of Building Engineering, 39:102265.

Sabu, J. and Kumar, D. D. R. (2022). A review of iot based construction site and labour safety monitoring systems. International Journal of Engineering Research and Technology (IJERT) ICART, 10(6).

Saleem, Y., Crespi, N., Rehmani, M. H., and Copeland, R. (2019). Internet of things-aided smart grid: Technologies, architectures, applications, prototypes, and future research directions. IEEE Access, 7:62962–63003.

Sawhney, A., Riley, M., Irizarry, J., and Riley, M. (2020). Construction 4.0. Sawhney, A., Riley, M., Irizarry, J., Eds.

Sherratt, F., Dowsett, R., and Sherratt, S. (2020). Construction 4.0 and its potential impact on people working in the construction industry.

Tang, S., Shelden, D. R., Eastman, C. M., Pishdad-Bozorgi, P., and Gao, X. (2019). A review of building information modeling (bim) and the internet of things (iot) devices integration: Present status and future trends. Automation in Construction, 101:127–139.

Thibaud, M., Chi, H., Zhou, W., and Piramuthu, S. (2018). Internet of things (iot) in high-risk environment, health and safety (ehs) industries: A comprehensive review. Decision Support Systems, 108:79–95.

Toca Perez, C., Bastos Costa, D., and Farragher, M. (2020). Construction 4.0 case studies.