A Research Roadmap for Off-Site Construction: Automation and Robotics

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ABSTRACT

The development of a research roadmap was undertaken to further the activities of a joint industry-university-government initiative in off-site construction research in Canada. The roadmap identifies the general research areas of structural design, construction materials, building science, advanced manufacturing, logistics and transportation, automation and robotics, and digitized construction. The development of the roadmap included a broad literature review of peer reviewed academic journals, select conference proceedings, and industry publications. The review of recent research in these areas was analyzed from the perspectives of application area, technology area and innovation phase. The purpose of the analysis was to identify the current activities and opportunities for further research. For example, in the area of automation and robotics, the results showed the majority of construction automation research relates to the actual production phase, as opposed to planning or operations. In terms of innovation maturity, little research is being undertaken with respect to the implementation and adoption of automation technologies, and very little research in technology development or prototyping. In addition, applied research is being conducted at approximately half the rate of basic research. A more recent trend has been greater research interest in industrial production technologies, particularly in additive manufacturing. Very little research is being conducted with respect to non-robotic cyber-physical systems including, IoT connectivity, drone technologies, or construction focused actuator and manipulator technologies. This paper will discuss the broader results of the research roadmap with a focus on automation and robotics.

KEYWORDS

Construction; Automation; Robotics; Research; Roadmap; Off-site

INTRODUCTION

According to Froese and Rankin (2009), there exists an "extensive body of knowledge surrounding the general topic of innovation in construction" and that innovation within the construction sector tends to follow the Complex Products and Systems (CoPS) model which is "highly reliant on knowledge transfer and the flow of information. However, much of the contemporary research on construction industry practice confirms that this business sector has been historically slower to adopt process and technology innovations with lower spending for Information and Communication Technology (ICT) and Research and Development (R&D) activities (Barbosa et al. 2017). Furthermore, global infrastructure deficits have been on the rise while construction productivity has been declining (Changali et al. 2015). Together, these trends suggest that information flow across the sector is restricted in a way that has stifled innovation.

This paper sets out to explore the research potential of a range of currently emerging technologies characterized by the Fourth Industrial Revolution (4IR) (also referred to as Industry 4.0) that are applied broadly across the construction sector; this subset of applied technologies is sometimes referred to as Construction 4.0. It begins with a look at current research interests at selected universities around the world with a focus on efforts at Canadian academic institutions. A literature search was conducted, and a classification scheme is introduced to limit the scope of technologies being explored. Subsequently, a multi-dimensional framework developed by Froese and Rankin (2009) to evaluate the innovation maturity of construction technologies was modified and applied to evaluate Cyber-Physical and Industrial Production technologies related to construction. An analysis of this data was used to determine potential research areas and activities, and the results are discussed in the context of a research roadmap.

METHODOLOGY

The goal of this work was to generate an academic research roadmap related to technological development in off-site construction products and processes by considering current research efforts with respect to technology innovation maturity. Research on technologies conducted through the years 2000-2018 provide the temporal bounds for the study while their maturity is evaluated through an innovation scale framework.

Research(er) Review

A review of current research activities was conducted by examining the research interests and activities as provided or described by faculty members on their department website biographies from a selection of Canadian, American, and other global academic institutions that have Architecture and/or Engineering faculties with Building Science; Civil, Industrial, Mechanical, Electrical, Computer, or Systems Engineering; and Engineering Science departments.

Literature Review

The literature review contained two aspects: (1) the technology inventory overview for classification and (2), a cursory review of recent international efforts with respect to research agendas and roadmaps to determine how and where other construction-focused researchers were looking at new technologies.

Inventory of Construction 4.0 Technology Research

A quasi-bibliometric analysis was conducted using the Scopus database. A generalized search was conducted across all source publications with the understanding that a high number of results for individual articles could be refined and filtered without excluding source publications. A basic top-level keyword search resulted in 9728 documents that were filtered for a final study of 217 documents. An internet search using both the Google and Google Scholar search engines with the keywords: ***construction, automation, robotics*** produced 45 articles which were cross-referenced with the Scopus results and then sorted. It should be noted that the definition of automation explores technologies that directly reduce human labour input.

Classifying Construction 4.0 Technologies

Several classification schemes were identified and examined through different perspectives: a technology perspective, a construction perspective, a research perspective, and others within each of those. A research perspective was chosen to consider the broader context while still maintaining specificity to construction as a discipline. The Construction 4.0 Framework proposed by Sawhney (2018) describes Construction 4.0 as a "confluence of three main, but broadly defined, themes: Industrial Production, Cyber-Physical Systems, and Digital & Computing Technologies". This classification system was used in this work and the technologies categorized by these themes are outlined in Table 1.

Table 1. Construction 4.0 – three major themes

Industrial Production	Cyber-Physical Systems	Digital & Computing Technologies
Additive Manufacturing (3d Printing)	Actuators	Digital Ecosystems/Platforms
Off-Site Digital Fabrication (Manufacturing)	Sensors	Data Standards & Interoperability
On-Site Digital Fabrication (Manufacturing)	Internet of Things (Iot)	BIM
General Digital Fabrication (Adv. Manufacturing)	Robots & Cobots for Repetitive & Dangerous Processes	Vertical & Horizontal Integration
On-Site Automated Assembly	Drones for Mapping	AI & Cloud Computing
	Progress Monitoring	Big Data & Data Analytics
	Safety & Quality Inspections	Reality Capture
	Lifting, Moving & Positioning	Blockchain
		Simulation
		VR/AR
		Video & Laser Scanning

Evaluating Construction 4.0 Technologies

Froese and Rankin (2009) proposed a multi-dimensional framework to evaluate the innovation maturity of construction technologies. The framework considers (1) Application Area, (2) Technology Area, (3) Innovation Process, (4) Scale, (5) Objectives and Drivers, and (6) Time and "provides a high-level conceptual model" and "illustrates how these different topics relate to each other and can be useful in structuring gap analysis".

Modifying the Framework

The Froese and Rankin (2009) framework required modification to be better suited for the Construction 4.0 classification scheme. While Froese and Rankin (2009) considered six dimensions, their published work only presented an analysis using three: Application Area, Technology Area, and Innovation Phase. This study follows that analysis and also uses publication dates to realize the Time dimension for a broad-spectrum trend analysis. The Objectives and Drivers, and Scale dimensions are not well defined in the original work and were excluded in this work as well. While these dimensions are pertinent to a deeper understanding of innovation in an applied context, they proved difficult to identify or quantify/qualify from the literature and typically require direct input from those conducting the research. The paragraphs below briefly describe how the framework was modified.

Application Areas

In the Application Area dimension, Management was subdivided into Construction Management applications encompassing operational technologies related to materials, labour, and safety on-site; and Project Management applications encompassing technologies related to quality, schedule and cost. Lifecycle Phase now includes Planning, Operations and Maintenance, and Decommissioning. Supporting Systems was reorganized to include system-wide ICT infrastructure, Safety Systems and Legal Infrastructure that could capture new systems of contracting.

Technology Areas

The Construction 4.0 technologies categorized in Table 1 define the Technology Areas for the modified framework. The Digital and Computational Technologies domain maintains the distinction between computational and non-computational technologies as defined by Froese and Rankin (2009). This work defines Industrial Production to include technologies being currently described as Digital Fabrication and relates to production methods composed of electro-mechanical systems driven by digital signals and data. Cyber-Physical Systems relate to mechanisms that are controlled or monitored by computer-based algorithms.

Innovation Phase

The Innovation Phase scheme used by Froese and Rankin (2009) was replaced through an iterative process that examined two other specific approaches: a commercialization approach and an academic approach. Innovation phases are defined in this study as: (1) Basic Research/Understanding; (2) Applied Research; (3) Development/Prototypes; (4) Implementation/Commercialization; and (5) Adoption/Application.

Applying the Modified Framework

Each article identified in the literature search was classified using the categorizations from the modified framework described above. An example is shown in Table 2. To analyze the data, pivot tables and plots were created to visualize the impact each dimension had on the others. This data is used to identify trends and gaps in the current research.

Table 2. Example of technology classification using the modified framework

		FRAMEWORK DIMENSION				
Article	Time	Appl'n Area	Appl'n Area	Tech. Area	Tech. Area	Innov'n Phase

	(year)	(main)	(sub)	(main)	(sub)	
Robot assembly system for computer-integrated construction	2000	Lifecycle Phase	Constr'n Prod/Assy	Industrial Prod'n	On-site Auto'd Assembly	Basic Research

RESULTS

Academic Research(er) Review

Of the 49 accredited engineering programs in Canada, 20 Architectural, Building Science, Civil, Mechanical, and Electrical engineering departments were reviewed providing an un-scientific, but reasonably good cross section of research activities. As a general conclusion, it was found that there is very little research being conducted, either basic or applied, specific to construction automation. It was also found that in North America, academic departments tend to silo research areas that, in practice, are multi-disciplinary, suggesting that construction technology research is being conducted independently of the foundational technologies. It is important to note that the goal of this work was to identify directed research specific to the discipline of construction and construction management in a civil engineering context. As such, it cannot be said that research as related to the three technology domains is being neglected at Canadian Schools. Furthermore, researchers in engineering departments outside of Civil are recognized to be engaged in examining these technologies in a more fundamental way.

Construction Technology Innovation Evaluation

The abstracts from the 217 articles identified through the SCOPUS search were manually read to determine, based on the content, how each article best fit within the six dimensions of the framework. The subjective nature of the classification, especially at this cursory level using only the abstracts, should give the reader some pause. With that in mind, the data were analyzed categorically, and the results emphasize trends in innovation maturity while other trends are summarized.

Trends in Innovation Maturity

Adding the Time dimension to the innovation maturity analysis for both the Cyber-Physical Systems and the Industrial Production Technology Areas indicates slow technological development of mobile platforms applied to industry and the lack of research into the application of sensor networks in the field. As well, Figure 1 indicates a significant increase in applied research related to on-site automation systems and an overall increase in Basic research related to digital fabrication in general. Research is needed at all levels related to on-site digital fabrication as a means to disrupt the current industry.

Innovation Maturity in Application Area

When looking at Innovation Maturity with respect to Application Area, it appears that very little research in Management or Supporting Process automation technologies is being done. This result is likely due to the influence of the original search criteria used for the literature review. If we look at this data over time, it appears that research in general has increased significantly in the last five years. However, it also shows that the construction industry could benefit from more Applied and Technology Development research on technologies for all lifecycle phases.

Innovation Maturity by Technology Area

The data show there is a research gap in applied research related to Industrial Production systems. An overall increase in basic research for both Cyber-Physical systems and Industrial Production technologies was identified, while until 2018, overall applied research in both technology areas had been trending negatively. The data also show a need for more applied research for sensor technologies and IoT Connectivity and presumably both of those together. Most of the research in Cyber-Physical systems is directly related to robotics either as a use-case or for discrete applications and rarely for systems of robotics. Some basic research, particularly from institutions outside Canada, report on the concept of the construction factory as an on-site assembly facility. Interestingly, no research was identified related to this concept with respect to standardization or construction workflows. If research on the topic of General Digital Fabrication is not considered, Figure 1 reiterates a gap in applied research related to Industrial Production systems, as well as basic research related to different types of systems like off-site digital fabrication or on-site automated assembly systems.

While robotics is being used to construct components, there is a potential gap in research related to wide-scale, integrated automation throughout the construction lifecycle. The analysis suggests that while research in being done with respect to advanced manufacturing processes for construction production, there is a gap in research related to prefabrication/off-site digital fabrication.

Trends in Application Area

With respect to the Time dimension, most automation and robotics research is occurring within the Production phase of the construction lifecycle. This result is unremarkable since this literature search was defined using keywords that would produce these results. Interestingly, trends show a waning interest in automated construction equipment and vehicle systems similar to those developed for the mining industry but an uptick in production or assembly technology research. There appears to be a gap in research related to automating the construction site as a work-center.

Trends in Technology Area

It was found that, in general, from 2015 to 2018, there has been an increase in the overall amount of research in both Industrial Production and Cyber-physical systems equally. This could be due to the increased understanding of cyber-physical systems and their need to be integrated into Industrial Production systems. In the last decade there has been less focus on mobile robots while research pertaining to production robots has remained reasonably consistent. One reason may be due to differences in classification. New mobile platforms may be classified as Unmanned Aerial Vehicles (UAV's) or Unmanned Ground Vehicles (UGV's). Two areas requiring more research in the context of construction are; IoT connectivity and actuators with respect to exoskeleton integration and deployment; i.e. task-specific, human assist wearables.

There are indications of a spike in research in 2016 in Additive Manufacturing for the construction industry but also a decline over the last two years. One reason for this may be due to the maturity of mechanical processes required to produce viable products, especially with respect to concrete extrusion. While there is significant opportunity to advance this research, it may be more related to supporting systems such as BIM or other computational technologies that enable design-driven products as well as in advanced materials. It also appears that research in prefabrication is slowing. This may be a contextual error where prefabrication is being classified as off-site digital fabrication. Regardless, this is an area that could benefit from more research but would require large-scale facilities and an interdisciplinary program. Also, many research papers that addressed automation and robotics for the construction industry in the holistic sense could be classified as general Digital Fabrication (DFab) or Advanced Manufacturing.

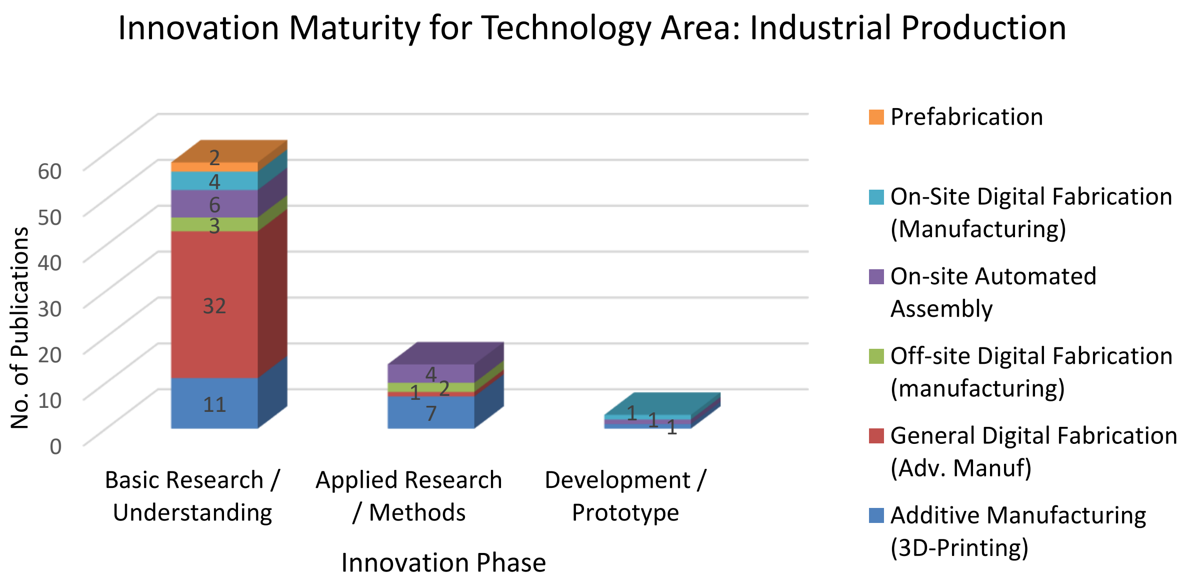

Figure 1. Innovation Maturity for Technology Area: Industrial Production

CONCLUSION

From the research(er) review, it appears that, in Canada, relatively little construction-based research is being conducted with respect to automation and robotics. In the US, larger civil engineering or dedicated construction engineering departments are beginning to take a more focused approach to basic research with respect to Construction 4.0 technologies. Some technical European institutions have taken a more inter-disciplinary approach and have advanced applied research programs that bring expertise from architectural, civil, mechanical and electrical departments together.

From the literature review, there appears to be a research gap, especially in applied research or prototype development in cyber-physical systems related to navigation and positioning systems during both the construction phase, and operations and maintenance phase as well as nascent research into drones and sensor/actuator technologies during the O&M phase. It is our opinion that these technologies should be considered in the planning and design phase to provide better integration into BIM extensions and deliver real-time information about the structural performance of a project. Moreover, the decommission or demolition phase is lacking in research across all phases of innovation and could present major opportunities for automation.

In terms of technologies, additive manufacturing (3D printing) technology is one area that spans manufacturing disciplines and has significant interdisciplinary research potential. As a construction technology however, the use-case must be clearly defined. For example, printing as a total process, a component process, or on-site vs. off-site. Additionally, there are aspects of the technology as a product that need to come together, including the machine-operator interface, the data interface, extrusion materials, constructability, structural integrity, etc.

Interestingly, there is a sense that research into digital fabrication more often refers to off-site or prefabrication processes and there appears to be scant research into on-site or in-situ technologies. This is possibly due to materials handling and supply-chain management rather than technological capability. Also, with respect to on-site technologies, there appears to be a gap in research related to wearable technologies either for safety aspects or enhanced productivity such as exoskeletons that have a large potential to reduce human work-load and workplace injury.

The results showed that the majority of construction automation research relates to the actual production phase as opposed to planning or operations. In terms of innovation maturity, no research is being done with respect to the implementation and adoption of automation technologies, with very little research in technology development or prototyping. Applied research is being conducted at half the rate of basic research. Since 2015, there has been greater research interest in Industrial Production technologies, particularly in additive manufacturing, although, very little research is being conducted with respect to non-robotic cyber-physical systems including, IoT connectivity, drone technologies, or construction focused actuator and manipulator technologies.

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Note: A complete listing of the references used in the article for analysis is not included due to space limitations but are available by contacting the authors.