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Knowledge Evolution in Construction Automation Research

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Abstract

Construction automation and robotics have been widely adopted in the construction industry as a promising solution to such issues like a shortage of skilled labor and the difficulties workers face in harsh working environments. The analysis of the knowledge structure and its evolution from the existing articles helps identify essential knowledge elements and possible future research directions. This study attempts to (1) construct keyword networks from the papers published in the International Symposium on Automation and Robotics in Construction (ISARC), (2) investigate how keywords and keyword communities are associated with each other, and (3) examine the changes in the crucial keywords over time. Through cluster analysis, 79 keywords were categorized into four groups (BIM, Building construction, Sensing, and GPS as representative keywords) with similar structural positions. Research trends show that research themes related to Infrastructure, Construction equipment, and 3D have consistently received a large amount of attention, regardless of geographical region. Research on as-built status model utilization through BIM and Laser scanning and improving Energy performance is taking place more frequently. In contrast, research studies related to problem-solving based on Neural networks are not as common as previously. This study provides useful insights into the construction automation field, at both the macro and micro levels.

Keywords : construction automation and robotics, knowledge evolution, keyword networks

1. Introduction

The construction industry is regarded as an industry with low productivity and efficiency because of its site-dependent, labor-intensive production system, supplier-oriented business structure, disconnection of information in the construction process, and many uncertainties associated with project implementation. Accordingly, in the construction industry, the use of technologies related to the fourth industrial revolution such as construction automation and robotics has emerged as a promising direction for the productivity of the industry and its continued growth, with advanced foreign countries such as the United States and Japan conducting national and industrial research and development[1]. This advancement of the world-class construction industry society and the development of advanced technologies is causing widespread changes and new technological

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information, making the network of information more complex. Because of these problems, many recent scientific and technological fields have scientifically identified network-specific relationships. They have actively utilized them through social network analysis that abstracts and analyzes network objects' connection relationships using a graph model[2].

To identify the knowledge structure and evolution in the construction automation and robotics field, we investigated (1) the correlations between keywords and their communities and (2) the changes in core topics over time through analyzing keyword networks constructed from existing articles. Keyword networks were made up of data from the International Symposium on Automation and Robotics in Construction (ISARC) over 17 years (2000 to 2016). The findings of this study provide useful insights into major issues and their relations in the construction automation field, as well as worthy reference information for preparation and prediction to address the large changes brought about by the 4th industrial revolution.

2. Theoretical Background

2.1 Knowledge Structure Analysis

There are qualitative and quantitative approaches to knowledge structure analysis. While the qualitative approach has the advantage of making it easier to grasp the knowledge structure by gaining input from a small number of experts in the research field, it has limitations of possible expert prejudice or subjective evaluation errors[3]. Recently, social network analysis, which is widely used as an analysis method of knowledge structure, has been used to construct a keyword network with keywords as an object to quantitatively analyze them and identify relationships among keywords[4]. Significantly, because the author carefully selected the keywords of the paper to express the thesis implicitly, keyword network analysis, which formed a network based on co-occurrence frequency between each keyword, is a good means to understand the structure of knowledge[5].

2.2 Network Analysis

A knowledge network analysis is a methodology for a quantitative analysis of topological structures and diffusion and evolution processes through modeling relationships between analysis objects as nodes and links[6]. Because the word for the analysis target becomes the network node and the relationships between the words become the network links, the overall structure can be identified by analyzing the relationship between the nodes. The connections between words can be visualized through the expressed links. The network analysis data expressed are ultimately investigated for connection relationships where all the words in the unit of analysis are connected through a one-mode matrix that ultimately consists of the same row and column[7]. Based on the frequency index at which two words appear simultaneously in one sentence, the words' structural equivalence is derived and clustered. The one-mode matrix shows what clusters of words are influential in a visualized network, how many words in a cluster are clustered, and the degree of concentration of words in the group[8]. Therefore, unlike content analysis, which considers only the frequency of the appearance of keywords, it is a useful method for understanding the meaning and flow of words by identifying the connection structure of a particular keyword[9].

Considering the rapid changes and expansion of technologies in the construction automation field, network analysis may help analyze relational patterns and trends based on quantitative methods from large datasets. However, previous studies[10-12] have applied questionnaire surveys or frequency analysis to identify the key topics and trends in this field.

These approaches are prone to reflecting the subjectivity of the researchers or experts[13]. They can run into difficulty when it comes to identifying the interrelationships among relevant elements from the perspective of networks. To overcome these limitations, this study attempts to identify research trends related to construction automation by using network analysis that can identify the influence and flow between keywords based on quantitative measures.

3. Data Collection and Analysis Methods

A total of 9,067 keywords were collected from 2,073 research papers published in the ISARC between 2000 and 2016. Before constructing the keyword network, the keywords were refined through unifying synonyms, standardizing singular/plural forms, separating multiple terms into individual keywords, and integrating semantically related keywords. Based on the refined keywords, we generated a 2-mode matrix consisting of each article identifier-respective keyword and then converted it into a co-occurrence matrix consisting of keyword- keyword using NetMiner 4.0 software. In the matrix, a higher value in a cell means more frequent co-occurrence between keywords. Based on the co-occurrence matrix, each keyword pair's similarity was measured using the cosine similarity method that measures the similarity of two vectors by measuring the co-occurrence angle between the two vectors when converting to the network. A higher similarity index corresponds to a higher association between keywords[14].

First, we conduct a structural equivalence analysis to investigate connection relationship patterns among keywords and keyword communities. We reconstructed the keyword network for the structural equivalence analysis using 79 keywords with a frequency of appearance greater than 20. We also removed keyword pairs with a cosine similarity less than 0.1.

Second, we analyzed the change in important research topics over time. For the analysis, we divided the period into two sections: (1) first (2000 to 2009) and (2) second (2010 to 2016). Then, the top 50 keywords in each group were selected based on the frequency of keywords. Based on the change in the ratio of those keywords and the presence or absence status between the first and second periods, the keywords were categorized into three keyword groups: Concentrated, New, and Excluded. Besides, to investigate differences in important topics across geographical regions, we compared and analyzed the top 30 keywords over time by geographic regions.

4. Results and Discussions

4.1 Structural Equivalence Analysis

A structural equivalence analysis is a technique to identify the connection relationship pattern between keywords to find similar connections and identify similarities, with greater similarity in the connection relationship pattern. A greater structural equivalence score between two keywords did not directly relate to other nodes in the same network[15]. One of the most natural and useful methods here is cluster analysis, because it is a statistical technique that binds them into homogeneous groups based on interrelationships between nodes[16]. A structurally equivalent relationship is a group determined to have close similarity by performing correlation coefficient analyses repeatedly.

As a result of cluster analysis, 79 keywords were categorized into four groups (G1, G2, G3, and G4) with similar structural positions based on the corresponding eigenvector indexes (see Figure 1). For each cluster, a structural equivalence analysis was performed again to create subclusters. Consequently, nine subclusters in four groups were constructed (Table 1).

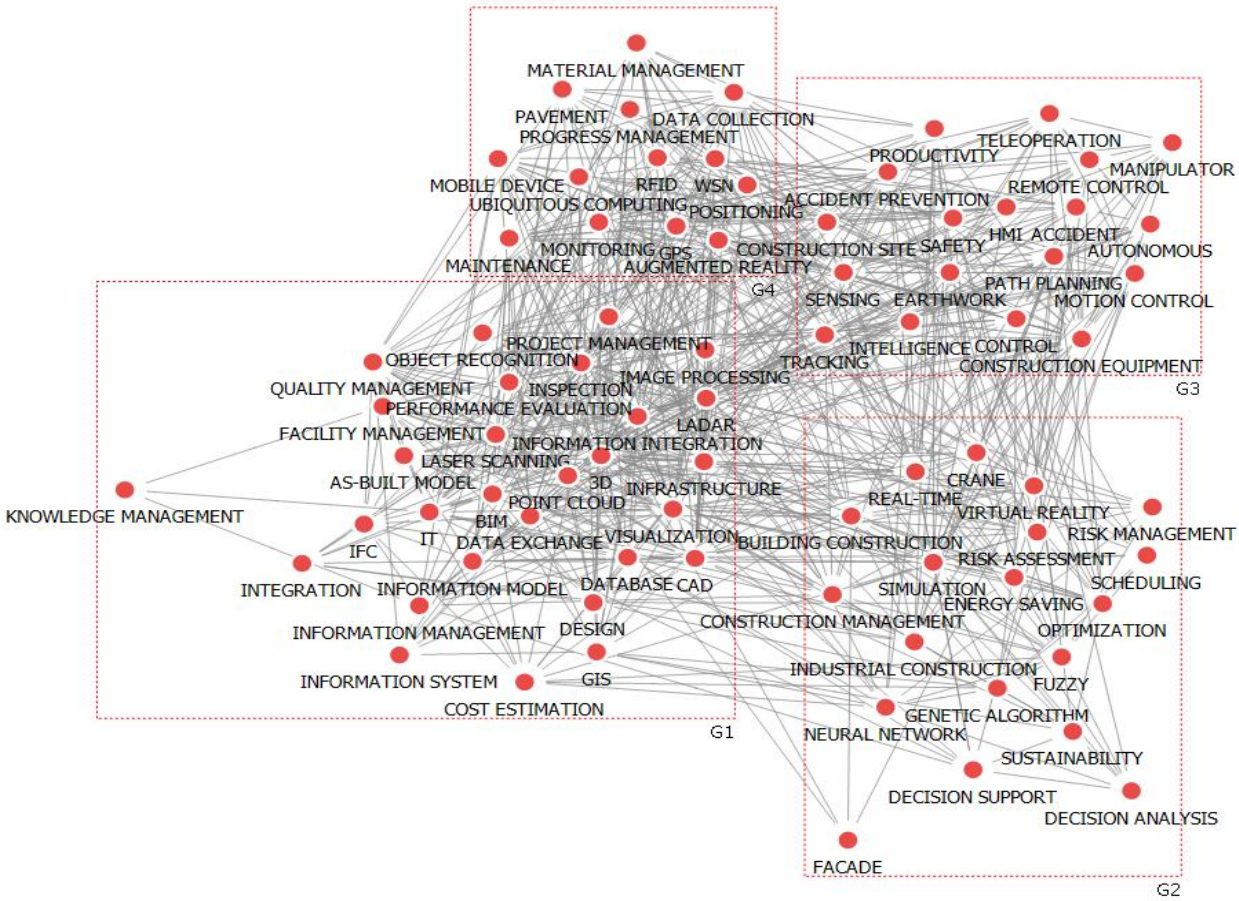

Figure 1. Visualization with structural equivalence analysis

Table 1. Keyword communities by structural equivalence analysis

Groups	Subgroups		
G1	(G11) **Laser scanning, Infrastructure, 3D**, Point cloud, Visualization, CAD, As-built model, Facility management, Performance evaluation, Object recognition, Inspection, Quality management, Image processing, Design	(G12) **Information integration, Database**, Information system, Information management, Information model, Data exchange, GIS, IFC	(G13) **IT, BIM**, Project management, Integration, Knowledge management, Cost estimation
G2	(G21) **Building construction**, Simulation, Optimization, Industrial construction, Virtual reality, Sustainability, Crane, Energy saving, Façade	(G22) **Real-Time**, Fuzzy, Neural network, Risk management, Decision analysis, Risk assessment, Scheduling, Decision support, Genetic algorithm	
G3	(G31) **Sensing, Safety**, Accident prevention, Construction site, Intelligence, Accident, Productivity, Tracking, HMI	(G32) **Construction equipment**, Teleoperation, Path planning, Remote control, Control, Earthwork, Manipulator, Motion control, Autonomous	
G4	(G41) **GPS**, Monitoring, Maintenance, Ubiquitous computing, Augmented reality, Mobile device, Pavement	(G42) **WSN, RFID, Progress management, Data collection**, Material management, Positioning	

Note: CAD(Computer Aided Design), GIS(Geographic Information System), IFC(Industry Foundation Classes), IT(Information Technology), BIM(Building Information Modeling), HMI(Human Machine Interface), GPS(Global Positioning System), WSN(Wireless Sensor Network), RFID(Radio Frequency IDentification)

In Table 1, the bold and underlined keywords have the highest value of betweenness centrality in each group, implying that they represent the corresponding community's representative keywords. Similarly, bold keywords indicate representative keywords of corresponding subclusters. In the G1 group with the most keywords, the first cluster (G11) is primarily networked with related research keywords for 3D visualization using surveying technology, such as laser scanning. The second cluster (G12) is related to database construction and information integration for information management, and the third cluster (G13) consists of keywords related to project management using technologies such as BIM (Building Information Modeling) and IT (Information Technology). This association indicates that the G1 group forms a group of studies to collect information using efficient surveying tools and visualize as-built status using BIM.

In the G2 group, the first cluster (G21) consisted of research topics on operation optimization through simulation using a virtual reality technique. In contrast, the second cluster (G22) consisted of artificial intelligence solutions for real-time decision support and risk control. The first cluster (G31) of the G3 group consisted of keywords related to accident prevention and safety management in construction sites based on sensing technology. The second cluster (G32) was formed by technologies related to the teleoperation of construction equipment for earthwork. That is, this research area (G3) is focused on enhancing safety performance through remote operation and motion control of construction equipment and tracking using advanced sensing technology.

Finally, the first cluster (G41) in the G4 group is related to monitoring or maintenance using GPS and augmented reality technology. The second cluster (G42) is focused on progress and material management by collecting data based on RFID(Radio Frequency IDentification) and WSN(Wireless Sensor Network). Overall, this community is associated with progress monitoring and resource management using positioning technologies such as GPS(Global Positioning System) and RFID.

4.2 Research Trend Analysis

As described, we analyzed the changes in important research topics by comparing top 50 keywords with high frequency between the first (2000-2009) and second (2010-2016) periods. After extracting the top 50 keywords in each period, we categorized the keywords into three groups: (1) Concentrated: keywords appearing in both periods; (2) New: keywords appearing only in the second period; and (3) Excluded: keywords appearing only in the first period (Table 2).

Table 2. Research trend analysis based on the top 50 keywords

Category	Keywords
Concentrated	Safety / Infrastructure / Optimization / Building construction / Monitoring / Real-Time / Visualization / Crane / Inspection / Construction management / Earthwork / 3D / Decision support / Object recognition / Positioning / Image processing / Tracking / Cost estimation / Motion control / Scheduling / Data collection / Virtual reality / Construction equipment / Sensing / Simulation / IT / RFID / CAD
New	BIM / Laser scanning / Maintenance / Point cloud / WSN / Accident / IFC / Energy efficiency / Energy saving / Control / As-Built model / Augmented reality / Information integration / Productivity / Accident prevention / Energy consumption / Quality management / Sustainability / Facility management / HMI / Information model / Performance evaluation / Risk assessment
Excluded	Genetic algorithm / Neural network / Database / Fuzzy / GPS / Information management / Manipulator / GIS / Information system / Mobile device / Construction planning / Construction site / Data exchange / Decision analysis / Design / Kinematics / Knowledge management / Project management / Integration / LADAR / Path planning / Remote control

Table 3. Analysis of research trends across the regions

Category	Region	Keywords
Concentrated	All	3D / Building construction / Construction equipment / Infrastructure / IT / Monitoring / Optimization / Sensing / Simulation
	Am/As	Earthwork / Image processing
	Am/Eu	Real-Time / Safety
	As/Eu	Inspection
	Am	Data collection / Laser scanning / Object recognition / Positioning / RFID / Tracking / Visualization
	As	CAD / Construction management / Cost estimation / Database
	Eu	Control
New	All	BIM
	Am/As	Crane / IFC / WSN
	Am/Eu	Construction management / Point cloud
	As/Eu	Laser scanning / Maintenance
	Am	Accident prevention / As-Built model / Cameras / Facility management / Industrial Construction / Inspection / Productivity
	As	Accident / Augmented reality / Energy efficiency / Performance evaluation / Positioning / Quality management / Safety / Visualization
	Eu	Ambient assisted living / Construction process / Elderly / Energy saving Health / HMI / Image processing / Information model / Mechatronics / Supply chain / Ubiquitous computing
Excluded	Am/As	Information management / Mobile device / Neural network
	Am/Eu	CAD / Integration
	As/Eu	GPS
	Am	Information model / LADAR / Material management
	As	Autonomous / Construction planning / Data exchange / Fuzzy / Genetic algorithm / GIS / Information system Knowledge management / RFID / Risk management / Scheduling / Virtual reality
	Eu	Assembly / Civil engineering / Computer integrated construction / Construction site / Crane / Data collection / Decision analysis / Decision support / Design / Façade / Kinematics / Manipulator / Motion control / Positioning / Quality management / Remote control

Note: Am(America), As(Asia), Eu(Europe)

Keywords in the Concentrated group mean that they have been studied steadily in the construction automation field. In this group, research themes related to Infrastructure, Construction equipment, 3D, and Simulation have received more attention (their ratio of frequency accounts for more than 5% in both periods) than other themes. Research topics related to Safety and Optimization have also been getting more attention recently (their frequency ratio is much higher in the second period compared to the first period), while research using CAD has decreased gradually.

The topics presented in the New group implies to be recently studied much more frequently compared to in the past, while the topics presented in the Excluded group implies the opposite. Thus, the topics of as-built status model utilization through BIM and Laser scanning and improving Energy performance are being researched more frequently. In contrast, the topics related to problem-solving based on the Genetic algorithm and the Neural network are not being studied as much as possible.

To identify the research trends by region, we classified the body of papers across geographical regions based on the country of affiliation of the first author. Excluding the papers from Oceania and Africa, which were fewer, we used 1,801 papers from Asia, the Americas, and Europe for the comparison. Using the method mentioned above, we extracted the top 30 keywords in the first and second periods and categorized them into three groups (Table 3).

In line with the overall trends in the Concentrated group, research themes related to Infrastructure, Construction equipment, and 3D have received a

large amount of attention (their ratio of frequency accounts for more than 5% in both periods) in all regions. However, in Europe, research themes on Construction equipment show a significant decline, although they still account for a high percentage. Safety research has been getting more attention in all regions. Tracking and Laser scanning research are some of the popular subjects in the Americas, unlike in other regions. In each region, the following distinctive research topics have significantly increased in recent years compared to other regions: 1) Asia: Building construction and Optimization, 2) The Americas: Safety, 3) Europe: Monitoring and 3D.

In the New group, regardless of region, studies related to BIM have increased dramatically in recent years, while topics related to Point cloud, IFC, and Laser scanning connected with BIM have received much more attention than in the past in most regions. In this group, distinctive themes in each region are as follows:

1) Asia: Positioning, Performance evaluation, and Visualization
2) The Americas: Productivity
3) Europe: Ambient assisted living, Health, and Supply chain

In the Exclude group, problem-solving studies based on Neural networks have lost much popularity in most regions. There has been a sharp decline in studies using CAD in the Americas and Europe, while still popular topics in Asia. Distinctive themes with declining popularity in each region are as follows:

1) Asia: Genetic algorithm, RFID, Scheduling, Fuzzy, and GIS
2) The Americas: Information model and Material management
3) Europe: Kinematics, Decision support, and Computer-integrated construction

This shows that the keywords with high popularity are similar, regardless of the region. In other words, they continuously play a key role in the keyword network of the construction automation field. There was a relatively small change in the research trends in the Americas compared to other regions. Thus, new research concepts in the American region tend to be expanded from existing popular keywords.

5. Conclusion

This study analyzed the major keywords related to construction automation to understand related research's relevance and trends. The following conclusion was reached by extracting keywords with a certain frequency or higher, performing structural equivalence analysis with the correlation of keywords and analyzing the keyword changes in each country over time.

Previously, some studies used keywords to compile trends in research on construction projects. However, most studies using keywords used frequency analysis or centrality analysis of keyword network analysis methods. Using structural equivalence analysis, this study was an opportunity to determine the kinds of groups the research keywords in construction automation formed, and by analyzing the trends of the keywords in the relevant research, the meaningful differences and similarities in research interests by country could be identified. Consequently, the findings of this study can provide a useful grasp on key research themes and their connectivity, and on the changes in the intellectual structure of the construction automation field at both the macro and micro levels. Thus, it can be utilized as a meaningful reference for determining the future R&D directions and contribute to facilitating relevant research in this field. This study's limitations are that the collected keywords were studied in a limited number of papers published in one international journal; as such, if future research considers all future international journals on construction automation, we believe that this will help generalize the arguments of this study.

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