Exploring research trends and network characteristics in construction automation and robotics based on keyword network analysis

Taehoon Kim, Dongmin Lee, Hyunsu Lim, Ung-Kyun Lee, Hunhee Cho and Kyuman Cho

ABSTRACT
Over the past decades, automation and robotics have been widely adopted in the construction industry as a promising solution for troubleshooting issues. This field is highly interdisciplinary and rapidly changing, and new concepts and ideas are being actively introduced in association with the existing ones. To reveal new insights, the evolution of knowledge in this field needs to be characterized by identifying important knowledge elements and research trends from published data. This study investigated research trends and network characteristics in the field of construction automation and robotics by using a keyword network analysis based on published articles. We analyzed the structure of the keyword network and identified major research topics and their relationships. Notable findings of the research characteristics are as follows. 1) Popular research themes with a set of closely connected keywords continue to be selected and contribute to the evolution of the network. 2) As an interdisciplinary research area, popular keywords that actively interact with other keywords also bridge different clusters of related research concepts. This study could provide useful insights and a better understanding of the knowledge structure and research trends as well as information on future directions in the construction automation and robotics field.

1. Introduction
The application of automation and robotics technology (A&RT) has become one of the most promising solutions for troubleshooting issues in the construction industry. The construction industry faces an increasing shortage of skilled labor and low interest among younger generations, and productivity indicators in recent decades show that conventional construction methods have reached their limits (Bock 2015). Moreover, an increase in mega-projects involving tall building construction, and the development of space, deep sea, and artificial islands, requires more efficient construction processes and technologies. Research has demonstrated that changes in equipment technology to apply robotics and automation correlate positively with improvements in construction productivity (Construction Industry Institute 2008). State-of-the-art strategies from general manufacturing industries under the label “Industry 4.0” also promise to yield higher productivity in the construction industry.

However, until recently, the construction industry was one of the most unfamiliar fields for research and development (R&D) in A&RT. The main difficulties come from the unstructured and dynamic nature of the work environment, the involvement of numerous uncoordinated participants, and the reluctance to adopt new technologies (Bock 2015; Balaguer 2004). Despite these barriers, there have been some successful uses of A&RT in the construction field, and as a reaction to tight margins, engineering and construction firms have recently adopted automated and streamlined approaches over all phases of projects (Goetjen, Dann, and Berg 2016). Current trends clearly show an increased awareness of the potential benefits of A&RT development (Yamazaki 2004).

The analysis of the existing research trends and knowledge structure is useful for investigating where further R&D is needed, as well as identifying the likely directions of future research (Wong, Li, and Wang 2005). Previously, qualitative analysis methods such as literature surveys and expert evaluation have been used. However, these techniques are likely to reflect the expert’s or researcher’s subjectivity in producing and interpreting the results (Kim, Jo, and Shin 2015). The application of quantitative techniques such as bibliometrics to overcome these limitations has been gaining attention. The techniques involve not only frequency analysis of keywords and related literature but also network analysis, which is a rapidly growing field, thanks to the support of information processing as well as visualization methods for mapping the relationships among relevant factors based on the co-occurrence of citations, authors, keywords, etc. (Ding, Chowdhury, and Foo 2001; Cobo et al. 2011).
This study aims to investigate the research trends and network characteristics in the application of A&RT in the construction industry by using keyword network analysis. Keywords provide an adequate description of an article’s content, and the frequent co-occurrence of a pair of keywords within articles shows that they may be highly relevant to the topic that these articles address (Ding, Chowdhury, and Foo 2001). Therefore, keyword network analysis can effectively reveal the intellectual structure of a field, including information on core technologies and research in the areas of construction automation and robotics. In this study, keyword networks were constructed from papers published in the International Symposium on Automation and Robotics in Construction (ISARC). ISARC is the only conference devoted solely to the field of construction automation and robotics worldwide, and so it is the most appropriate choice for identifying emerging R&D areas. Next, we investigated the characteristics of the keyword network, major topics based on both node- and network-related measures, and meaningful relations between keywords from association rule analysis.

2. Literature review

Based on the adoption of A&RT, the construction industry has made continuous efforts to reduce its dependence on skilled labor, and also to improve the harsh working conditions and poor coordination among participants. In the past decades, many countries have focused on developing new robotic systems and automating existing machinery, called hard robotics (Balaguer 2004). They have tried to automate individual construction tasks and several processes, such as interior building finishing, bricklaying, infrastructure inspection, excavator control, etc. The Japanese construction industry has introduced fully automated construction systems (SMART, ABCS, Big Canopy, etc.) based on the concept of factory automation from the manufacturing industry (Tanijiri et al. 1997; Yamazaki and Maeda 1998; Ueno 1998). In hard robotics, the focus has been moved to remote-controlled or autonomous vehicles for safe construction and maintenance work in dangerous environments, and into wearable mechanical devices to augment the capabilities of the worker (Delgado et al. 2019). However, their high initial costs and inadequate performance can hinder effective use of the technologies for construction. Against this background, the recent R&D in this area has placed more emphasis on soft robotics, including sensory data acquisition, image processing, and chip-based process control (Balaguer 2004). The integration and effective coordination of hard and soft robotics could not only facilitate the development of advanced automation technologies, but also be the key research area in this field.

The trends in the A&RT field need to be analyzed to reveal new insights, given the rapid changes in technology development and the construction environment. For this purpose, a number of studies (Bock 2015; Balaguer 2004; Lee et al. 2011) have used representative examples developed by countries and companies. Lee et al. (2010) and Kim et al. (2008) applied experts’ evaluations through questionnaire surveys to develop a technology roadmap for construction automation. Son et al. (2010) investigated the contents of published papers based on frequency analysis to identify the key topics and subjects by countries, regions, and institutions. However, these approaches are likely to reflect the expert’s or researcher’s subjectivity. They also have limited ability to provide a clear picture of the interrelationships between key subjects and/or technology factors from the viewpoint of a network. To overcome this limitation, Lim and Kim (2016) used text mining techniques to investigate key research areas in construction automation based on information and communications technology in Korea. However, considering the scope, the cases, and the level of analysis, this study has limitations in providing a macroscopic view of the overall context and in providing detailed information on the A&RT field.

Network analysis facilitates the identification of relational patterns at the macro and micro levels by quantitatively analyzing the interactions between bits of information. In the area of text mining, network analysis is particularly useful for understanding the context of broad text clusters, through analysis of the positions and relationships between key selections of text and their visual representation (Kim 2016a). According to the target and object of the analysis, different approaches have been developed to construct networks, such as co-citation, bibliographic coupling, coauthor, and co-word analysis (Cobo et al. 2011). Among such approaches, keyword network analysis based on the co-occurrence of keywords is useful for understanding the conceptual structure and trends of a specific field by measuring the relationship intensity among representative keywords in relevant documents. In a research paper, the keywords selected by the authors directly express the themes and main ideas of that paper. Thus, the popularity of some keywords can serve as an indicator of the importance of the associated research themes, and a strong connection between keywords is regarded as indicating that they “belong to” the same research theme (Choi, Yi, and Lee 2011; Choi and Hwang 2014). With the aid of software for the analysis and visualization, this method of analysis has been used by numerous researchers to investigate the intellectual structure of different fields (Choi, Yi, and Lee 2011; Liu, Hu, and Wang 2012; Zhang and Hong 2014; Kim 2016b, 2015). In this study, keyword network analysis was applied to reveal useful insights in the field of construction automation and robotics at both the macro and micro levels.
3. Data collection and analytical methods

To achieve the goals of this study, we retrieved articles published in the ISARC proceedings, from which we could identify the latest research trends in the construction automation and robotics field. A database composed of 9,837 keywords from 2,080 articles (i.e., 4.7 keywords per an article on average) published between 2000 and 2016 was constructed. This is because the studies on trend analysis (Balaguer 2004; Lee et al. 2011; Son et al. 2010) in this field were mainly conducted based on the data before the early 2000s with qualitative techniques.

Before constructing the keyword network, refinement of the keywords was required, because individual keywords can be expressed in different ways by the authors; e.g. in abbreviated or singular/plural form. This process was performed with the assistance of experts and required a considerable investment of time and effort. The refining principles applied in this study were as follows:

(1) the unification of synonyms: e.g., BIM, BUILDING INFORMATION MODEL, and BUILDING INFORMATION MODELING were summarized under “BIM”;

(2) standardization into a singular or plural form based on keyword frequency: e.g., AGENT and AGENTS were summarized under “AGENT”;

(3) separation of multiple terms into individual keywords: e.g., COLLABORATION AND INTEGRATION was separated into “COLLABORATION” and “INTEGRATION”; (4) integration of semantically related keywords into a representative word based on a literature review and expert knowledge: e.g., CRACK DETECTION, FLAW DETECTION, and DEFECT RECOGNITION were summarized under “DEFECT DETECTION.” (see Appendix)

Based on the refined keywords, a keyword network was constructed by the following procedure: (1) the identifier and the refined keywords for each paper were put into the first and second column, respectively, in Excel; (2) the Excel data were converted into a (symmetric) keyword co-occurrence matrix using NetMiner 4.0 software (http://www.netminer.com), which has been widely used for exploratory network data analysis and visualization. In this study, the matrix was constructed using the cosine coefficient, which represents the similarity of each keyword pair (i.e., a greater value means a higher similarity between two subjects). In the matrix, the diagonal values represent the relationships between identical keywords, and thus they were replaced with missing values (blank cells). A portion of the matrix is shown in Figure 1.

The structure of keyword networks can be analyzed by various node- and network-level indexes. In this study, we used well-defined and widely used indexes for the analysis. The “density” of the network is the ratio of the actual number of links between nodes (keywords) to the maximum possible number of links. It ranges from 0 to 1, and a higher value indicates a denser and more cohesive network. The “clustering

|       | 1       | 2     | 3     | 4     | 5     | 6     | 7     | 8     |
|-------|---------|-------|-------|-------|-------|-------|-------|-------|
| 1     | AUTOMATION | 0.056 | 0.032 | 0.044 | 0.049 | 0.017 | 0.053 |
| 2     | INTEGRATION | 0.059 | 0.045 | 0.026 | 0.035 | 0.012 | 0.050 |
| 3     | STRUCTURAL DESIGN | 0.032 | 0.039 | 0.021 | 0.026 | 0.067 | 0.056 |
| 4     | COORDINATION | 0.044 | 0.026 | 0.148 | 0.154 | 0.034 |
| 5     | REINFORCEMENT | 0.069 | 0.136 | 0.236 | 0.156 | 0.037 |
| 6     | BUILDING CONSTRUCTION | 0.107 | 0.030 | 0.052 | 0.034 | 0.027 |
| 7     | ASSEMBLY PROCESS | 0.030 | 0.027 | 0.059 | 0.064 | 0.037 |
| 8     | CAD | 0.051 | 0.056 | 0.037 | 0.056 |
| 9     | KNOWLEDGE BASED SYSTEM | 0.017 | 0.120 | 0.041 | 0.105 |
| 10    | GENETIC ALGORITHM | 0.027 | 0.059 | 0.078 | 0.071 |
| 11    | WOOD STRUCTURE | 0.010 | 0.010 | 0.050 | 0.095 |
| 12    | VIRTUAL REALITY | 0.020 | 0.047 | 0.093 |
| 13    | SIMULATION | 0.059 | 0.012 |
| 14    | DEGREE | 0.040 |
| 15    | COMPACTION | 0.050 |
| 16    | SOIL | 0.017 |
| 17    | VIBRATION | 0.017 |
| 18    | JUMPING | 0.140 | 0.029 | 0.069 | 0.034 |
| 19    | CONSTRUCTION EQUIPMENT | 0.053 | 0.091 | 0.033 | 0.070 |
| 20    | REHABILITATION | 0.043 |
| 21    | INFRASTRUCTURE | 0.040 |
| 22    | DEFECT DETECTION | 0.040 |
| 23    | TRENCHLESS TECHNOLOGY | 0.045 |
| 24    | EARTHWORK | 0.012 |
| 25    | OBJECT ORIENTED | 0.051 |
| 26    | COST | 0.052 | 0.039 | 0.076 | 0.014 |
| 27    | OPTIMIZATION | 0.018 |
| 28    | DATABASE | 0.050 |
| 29    | SENSING | 0.075 |
| 30    | FORCE | 0.030 |
| 31    | HYDRAULIC CYLINDER | 0.011 |
| 32    | WORKING SYSTEM | 0.037 |
| 33    | DYNAMICS | 0.037 |
| 34    | CONSTRUCTION MANAGEMENT | 0.051 | 0.090 | 0.051 | 0.037 | 0.018 |

Figure 1. Keyword co-occurrence matrix using the cosine coefficient.
coefficient" is the ratio of the number of connections to a given node to the maximum possible number of connections between its neighbor nodes. The clustering coefficient of the entire network is the average of the clustering coefficients of all nodes. The “degree centrality” of a node is defined as the number of links incident upon that node (i.e., a node with a higher value has more direct links with other nodes). It indicates that the keyword actively interacts with many others to constitute the ideas of the papers. The “betweenness centrality” of a node represents the degree to which that node stands between other nodes. In other words, it quantifies the number of times the node acts as a bridge along the shortest path between two other nodes, indicating the importance of a keyword in bridging subsets of keywords belonging to different research themes.

In addition, for the investigation of more specific research trends, the association rule learning method was applied. This method enables the discovery of meaningful relationships between variables in large datasets. Based on the concept of strong rules, three interestingness measures, namely “support,” “confidence,” and “lift,” were used to analyze the relationship between the construction engineering and management (CEM) category and the technology area and internal relevance in the technology area (Agrawal, Imaiński, and Swami 1993; Brin et al. 1997). If we have a rule AB, “support” is the probability that a record contains (A, B) of the total dataset, and “confidence” is the conditional probability that a dataset having A also contains B. “Lift” becomes an indicator of whether A and B are independent, and a value larger than 1 means that these two occurrences are dependent on each other. This study used R version 3.5.1 for the association rule analysis and visualization.

4. Analysis of results

4.1. Characteristics of the keyword network

First, we identified the basic characteristics of the keyword network constructed through the abovementioned process. As shown in Table 1, the keyword network in the study of construction automation and robotics showed a very low density and a high clustering coefficient. This implies that the entire keyword network consisted of individual communities for a wide range of research themes, while each community showed strong interconnection between highly related keywords internally. In addition, this was a small-world-type network characterized by short path lengths, with a mean distance of 2.983.

Another important feature of the keyword network was that the cumulative degree distribution clearly followed the power-law distribution that has been observed in various kinds of networks, including coauthor (Börner, Maru, and Goldstone 2004), citation (Wanga and Yua 2008), and patent networks (Choi and Hwang 2014). In Figure 2, the x-axis is the log scale of the degree for each keyword, and the y-axis is the proportion of keywords having a degree higher than the corresponding degree on the x-axis. In this network, only 10% of the keywords have more than 20 connections to other keywords. This implies that a small number of keywords play the role of core elements and are frequently used for research topics in this field. The most important feature of the power-law distribution is the “rich get richer and the poor get poorer” phenomenon (Buchanan 2002). This indicates that concepts with numerous connections that are actively studied continue to be selected by researchers, and this contributes to the evolution of the network based on constructing further new links.

The correlations between the indicators related to the importance of keywords are shown in Figure 3. This figure (Figure 3(a,b)) shows strong positive correlations between the frequency and the centrality of each keyword, implying that frequently used keywords also have structural importance in the network. The network also shows a strong correlation between the degree centrality and the betweenness centrality (see Figure 3(c)). In other words, the keywords that actively interact with other keywords also play a role in bridging the subsets of keywords that correspond to distinct research themes. Actually, in most networks, there is a significant difference in these keyword sets, because of their distinctive natures (Choi, Yi, and Lee 2011). Their similarity here is an unusual feature of the keyword network of the research field of construction automation and robotics.

4.2. Major research topics

4.2.1. Important keywords in the overall network

For the detailed investigation of important keywords and major topics in this field, we chose the top 20 keywords by different indicators (i.e., keyword frequency, degree centrality, and betweenness centrality). Before conducting the analysis, three keywords, namely, AUTOMATION, ROBOTICS, and CONSTRUCTION, were removed from the database because they directly represented the ISARC proceedings’ topic and the scope of our research. The top 20 keywords based on each measure were listed in the corresponding three columns, and the common keywords from the three top-20 lists were marked in the first column (see Table 2). Sixteen keywords were common to all three of the top-20 lists.
This implies that most keywords with high popularity also had high structural importance in the keyword network, as indicated in Figure 3. Of these, INFRASTRUCTURE showed the highest values for all three measures. In other words, the application of A&RT in infrastructure such as bridges, tunnels, etc. has been intensively studied in a wide range of subjects. In addition, research works on CONSTRUCTION EQUIPMENT have been widely implemented with related themes such as SAFETY and EARTHWORK. As general research topics related to construction engineering and management, OPTIMIZATION and MONITORING have received particular attention as well. In terms of technologies, including tools and techniques, the keywords BIM, SIMULATION, 3D (i.e., three-dimensional), SENSING, IT (information technology), LASER SCANNING, CAD (computer-aided design), and REAL-TIME are major focuses and the bridges connecting other topics. The underlining of a keyword in each column means that it is ranked in the top 20 only for the corresponding measure. For example, MAINTENANCE is very popular keyword used in many papers, as shown by the frequency measure. However, it is not in the top 20 keywords by either degree centrality or betweenness centrality, and thus its importance is relatively low in terms of connecting other keywords and bridging research topics. In contrast, POSITIONING has a relatively high level of connection with other keywords. In that sense, DESIGN, CRANE, NEURAL NETWORK, and PRODUCTIVITY play important roles in bridging separated keyword groups, in contrast to their relatively low frequency.

The changing trend of important keywords in the keyword network can be identified by comparing the keywords of different time periods (e.g., a short- and long-term period). Table 3 shows important keywords constructed from a short period of time covering the recent three years (2014–2016). When compared with the results in Table 2, BIM became the most important keyword both in terms of frequency and structural importance in the keyword network. As LASER SCANNING with BIM has received growing attention, VISUALIZATION and POINT CLOUD have been selected as important research concepts, while IT and CAD lost most interest in all three measures. The importance of safety-related keywords (SAFETY, CONTROL, and ACCIDENT) in all measures has also been substantially increased. Even though there is a certain level of change in important keywords between the short- and long-term periods, they showed very similar top-10 lists in all three measures. In other words, despite the passage of time, core concepts with high popularity and centrality continuously play a key role without being removed from the keyword network. In addition, the number of common keywords was increased in the short-term period network. This implies that new research concepts and ideas increasingly tend to be expanded from existing keywords with high popularity.

4.2.2. Important keywords across geographical regions

Table 4 shows comparison results for important keywords across the regions based on the country of affiliation of the primary author. Papers from Asia accounted for the largest portion, i.e., about 51% of the total, followed by Europe (25%), North and South America (20%), Oceania (4%), and Africa (0.4%). We excluded from the subsequent analysis the papers from Oceania and Africa, which each had only a small number of papers.

The number of common keywords was larger in America than in Asia and Europe. This means that, in America, the popular keywords also have many
connections with other keywords as well as playing a bridging role. In contrast, keyword networks for Europe showed a clear distinction between the frequency and centrality measures, which implied that there were a number of keywords with relatively low frequency but high centrality, or with low centrality but high frequency. The bold keywords in each region’s common-keyword list are unique to that region; the meaning of the underlined keywords is the same as in Table 2.

Regardless of region of origin, the keywords BIM, 3D, SIMULATION, INFRASTRUCTURE, CONSTRUCTION.
equipment, and monitoring were in the top 20 keywords for all three measures. In Asia, construction management, inspection, and database attracted more attention and had high structural importance. Optimization also had a higher rank for all measures in Asia compared with other regions. Similarly, genetic algorithm, which is commonly used in optimization problems, was ranked ninth in frequency and was unique to Asia (not appearing in any other regions). In America, research on image processing, visualization, and safety received more attention. As a related topic, tracking was also ranked in the top 20 keywords for all three measures and was unique to America. In Europe, research on sensing and real-time ranked higher for all measures. In each region, distinctive research topics that do not appear in the top-20 lists of other regions are as follows: 1) Asia: genetic algorithm-based optimization, maintenance, neural network, information integration, and quality management; 2) America: tracking and productivity analysis based on object recognition, and crane; 3) Europe: integrated construction and control in construction site, motion control-based kinematics, decision support and analysis, and virtual reality.

### 4.3. Analysis on research trends and associations of keywords

To investigate more specific research trends and relationships between keywords, we selected 35 representative keywords involved in the CEM area and divided them into eight categories (see Table 5). The “General” category was further classified into three subcategories because they are difficult to classify as a specific CEM category. In addition, we selected 63 technology-related keywords that had a frequency more than 10 times, to investigate the relationship between the CEM category and technology-related keywords.

Table 3. Important keywords from 2014 to 2016.

| Common (frequency) | Frequency | Degree centrality | Betweenness centrality |
|-------------------|-----------|-------------------|------------------------|
| BIM (85)          | POINT CLOUD INSPECTION | POINT CLOUD ACCIDENT | WSN PRODUCTIVITY       |
| INFRASTRUCTURE (33) | WSN INSPECTION | WSN ACCIDENT | WSN PRODUCTIVITY        |
| 3D (30)           | INSPECTION | INSPECTION | RFID | INSPECTION | RFID | INSPECTION | RFID |
| SIMULATION (27)   | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| OPTIMIZATION (27) | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| BUILDING CONSTRUCTION (27) | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| SAFETY (24)       | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| LASER SCANNING (24) | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| CONSTRUCTION EQUIPMENT (22) | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| MONITORING (21)   | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| SENSING (16)      | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| REAL-TIME (16)    | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| VISUALIZATION (14) | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| CONSTRUCTION MANAGEMENT (14) | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| CRANE (13)        | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| CONTROL (12)      | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| EARTHWORK (12)    | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| IMAGE PROCESSING (11) | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |

RFID, radio-frequency identification.

Table 2. Important keywords in the field of construction automation and robotics.

| Common (frequency) | Frequency | Degree centrality | Betweenness centrality |
|-------------------|-----------|-------------------|------------------------|
| INFRASTRUCTURE (186) | INSPECTION | INSPECTION | DESIGN | RFID | RFID | RFID | RFID |
| BIM (175)         | IMAGE PROCESSING MAINTENANCE | IMAGE PROCESSING RFID | RFID | RFID | RFID | PRODUCTIVITY | RFID |
| CONSTRUCTION EQUIPMENT (145) | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| SIMULATION (131)  | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| 3D (130)          | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| BUILDING CONSTRUCTION (121) | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| OPTIMIZATION (92) | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| MONITORING (91)   | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| SENSING (81)      | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| SAFETY (79)       | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| IT (69)           | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| LASER SCANNING (63) | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| CONSTRUCTION MANAGEMENT (55) | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| CAD (54)          | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| REAL-TIME (51)    | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |

Table 5. Important keywords from 2014 to 2016.

| Common (frequency) | Frequency | Degree centrality | Betweenness centrality |
|-------------------|-----------|-------------------|------------------------|
| RFID              | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| real-time         | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| system            | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| security          | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| protection        | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| technology        | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| engineering       | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| automation        | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| research          | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| development       | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| innovation        | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| application       | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| application       | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| application       | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
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| application       | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| application       | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| application       | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| application       | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| application       | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| application       | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| application       | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| application       | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| application       | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| application       | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
| application       | RFID | RFID | RFID | RFID | RFID | RFID | RFID | RFID |
Table 4. Comparison of important keywords by region.

| Region   | Common                        | Frequency          | Degree centrality | Betweenness centrality |
|----------|-------------------------------|--------------------|-------------------|------------------------|
| Asia     | INFRASTRUCTURE                | GENETIC ALGORITHM  | IMAGE PROCESSING  | NEURAL NETWORK         |
|          | BIM                           | MAINTENANCE        | INFORMATION       | VISUALIZATION          |
|          | CONSTRUCTION EQUIPMENT        | NEURAL NETWORK     | INTEGRATION       | POSITIONING            |
|          | BUILDING CONSTRUCTION 3D     | IMAGE PROCESSING   | POSITIONING       | QUALITY MANAGEMENT     |
|          | SIMULATION                   |                   |                   |                        |
|          | MONITORING                   |                   |                   |                        |
|          | OPTIMIZATION                 |                   |                   |                        |
|          | IT                           |                   |                   |                        |
|          | CONSTRUCTION MANAGEMENT      |                   |                   |                        |
|          | INSPECTION                   |                   |                   |                        |
|          | SENSING                      |                   |                   |                        |
|          | DATABASE                      |                   |                   |                        |
|          | EARTHWORK                    | OBJECT RECOGNITION |                  | CONSTRUCTION MANAGEMENT|
|          | RFID                         | POINT CLOUD        | CRANE             |                       |
|          | CAD                           |                  | PRODUCTIVITY      |                        |
|          |                               |                    | POSITIONING       |                        |
|          |                               |                    |                   |                        |
| America  | BIM                           |                   |                   |                        |
|          | 3D                            |                   |                   |                        |
|          | SIMULATION                   |                   |                   |                        |
|          | SAFETY                        |                   |                   |                        |
|          | INFRASTRUCTURE               |                   |                   |                        |
|          | CONSTRUCTION EQUIPMENT       |                   |                   |                        |
|          | IMAGE PROCESSING             |                   |                   |                        |
|          | LASER SCANNING               |                   |                   |                        |
|          | MONITORING                   |                   |                   |                        |
|          | TRACKING                     |                   |                   |                        |
|          | VISUALIZATION                |                   |                   |                        |
|          | SENSING                      |                   |                   |                        |
|          | BUILDING CONSTRUCTION        |                   |                   |                        |
|          | REAL-TIME                    |                   |                   |                        |
|          | EARTHWORK                    |                   |                   |                        |
|          | IT                           |                   |                   |                        |
|          | OPTIMIZATION                 |                   |                   |                        |
|          | RFID                         |                   |                   |                        |
| Europe   | INFRASTRUCTURE               | OBJECT RECOGNITION |                   | CONSTRUCTION MANAGEMENT|
|          | BIM                           | INSPECTION         | INTEGRATION       |                       |
|          | CONSTRUCTION EQUIPMENT       | DESIGN             | COMPUTER INTEGRATED|                       |
|          | BUILDING CONSTRUCTION 3D     | DECISION ANALYSIS  | CONSTRUCTION      |                       |
|          | SENSING                      | MOTION CONTROL     | SUPPORT           |                       |
|          | MONITORING                   |                            | CONSTRUCTION PROCESS | |
|          | SAFETY                        |                            |                      |                        |
|          | LASER SCANNING               |                            |                      |                        |
|          | REAL-TIME                    |                            |                      |                        |
|          | OPTIMIZATION                 |                            |                      |                        |
|          | CAD                           |                            |                      |                        |
|          | IT                           |                            |                      |                        |
|          | CONSTRUCTION SITE CONTROL    |                            |                      |                        |

**GPS**, global positioning system.

(G2), **SUSTAINABILITY**, and **SAFETY MANAGEMENT** increased steadily over time. In particular, **SUSTAINABILITY** showed a significant increase from 1.3% to 10.1% between the first and third periods, and **SAFETY MANAGEMENT** accounted for the highest share (16.3% on average) during the total time period. In contrast, the proportion of papers on **GENERAL CEM** (G1), **COST**, and **INFORMATION MANAGEMENT** steadily decreased over time. In particular, the field of **INFORMATION MANAGEMENT** showed a dramatic decrease from 13.9% in the first period to 2.8% in the third period. Overall, the analysis showed that studies on establishing a sustainable and safe construction environment have become the main topic in the field of construction automation and robotics, whereas papers on **COST** and **INFORMATION MANAGEMENT** have become less common.

**Figure 5** shows the change in the proportion of papers that addressed technology-related keywords over time. **GROUP I** and **GROUP II** (**Figure 5(a,b)**, respectively) include the keywords that have shown a steady increase and decrease over time, respectively (i.e., a change of more than 1.5% between first and third periods). **BIM**, which appeared from 2006, showed the most significant increase while the proportion of papers on **CAD** steadily decreased over time. In addition, as efficient surveying tools, **UAV with LASER SCANNING** has come into focus recently. **GROUP III** (**Figure 5(c)**) includes the steadily appearing keywords, accounting for more than 1.5% in every period. In other words, research themes by using **SIMULATION**, 3D, **SENSING**, etc. have received relatively consistent attention in the construction automation and robotics field since 2000.
Table 5. Classification of CEM categories and their representative keywords.

| Category | Representative keywords | Frequency |
|----------|-------------------------|-----------|
| General (G1) | CONSTRUCTION MANAGEMENT, PROJECT MANAGEMENT, CONSTRUCTION PLANNING | 97 |
| (G2) Optimization | OPTIMIZATION | 92 |
| (G3) Monitoring | MONITORING | 91 |
| Time | SCHEDULING, PRODUCTIVITY, PROGRESS MANAGEMENT, SCHEDULE MANAGEMENT | 94 |
| Cost | COST MANAGEMENT, COST ESTIMATION, COST | 56 |
| Quality | QUALITY MANAGEMENT, INSPECTION, DEFECT DETECTION, STRUCTURAL HEALTH | 119 |
| Safety | SAFETY MANAGEMENT, RISK MANAGEMENT, RISK ASSESSMENT, DISASTER MANAGEMENT, ACCIDENT PREVENTION, SAFETY, ACCIDENT, RISK | 184 |
| Resource | SUPPLY CHAIN MANAGEMENT, MATERIAL MANAGEMENT, PATH PLANNING, TRACKING, POSITIONING, EQUIPMENT MANAGEMENT, LIFT PLANNING, SUPPLY CHAIN | 158 |
| Information | INFORMATION MANAGEMENT, KNOWLEDGE MANAGEMENT, DATABASE | 91 |
| Maintenance | MAINTENANCE, FACILITY MANAGEMENT, LIFECYCLE MANAGEMENT | 77 |
| Sustainability | ENERGY SAVING, ENERGY CONSUMPTION, ENERGY EFFICIENCY, SUSTAINABILITY | 73 |

Figure 4. Changes in CEM research based on A&RT over time.

We applied association rule analysis to discover interesting relations between each CEM area and the technology-related keywords. To select meaningful rules, the minimum thresholds in this study were set at 0.002 for support (having more than four co-occurrences) and 0.02 for confidence, with regard to the number of CEM categories and the selected technology-related keywords. In addition, only the rules having a lift value greater than 1 were selected for the analysis. Visualization of the derived association rules is shown in Figure 6. In this figure, a larger circle size between keyword pairs indicates a higher support value, and a darker color indicates a higher lift value.

First, the GENERAL CEM (G1) area showed the highest support value with SIMULATION (0.0062), while it had the lowest lift value (1.27) of the total valid rules in this category. This means that the simulation technique has been frequently used not only in the general CEM area but also in other CEM areas. In the G1 area, the simulation technique has mainly been applied for the efficient design and planning of the construction process in the preconstruction phase. UBIQUITOUS COMPUTING (3.62) and MOBILE DEVICE (2.89) showed the highest lift values, which means that they had a higher correlation with the GENERAL CEM area than other technology keywords. They have been introduced to enhance the CEM process on site, through setting up a ubiquitous computing environment using mobile devices such as personal digital assistants and smartphones.

Second, the OPTIMIZATION (G2) area has a close connection with PARTICLE SWARM, GENETIC ALGORITHM, and SIMULATION. The PARTICLE SWARM and GENETIC ALGORITHM, which are commonly used to generate high-quality solutions to optimization and search problems, showed very high lift values (>6). These algorithms have mainly been applied to optimize construction schedules, resource allocation, and site layout plans. In addition, they have been used for optimization problems in path planning and for the formation control of construction equipment or robots. Similarly, the simulation technique has been adopted to seek optimized solutions for earthmoving fleet composition and allocation and for site layout planning.

Third, in the MONITORING (G3) area, keywords such as REAL-TIME, WSN, SENSING, DATA COLLECTION, etc., showed a high co-occurrence frequency (>10). Of these, WSN had the highest lift value (6.26) and has been mostly introduced to monitor the structural behavior and condition of infrastructure, particularly bridges. The REAL-TIME keyword also showed a close
association with G3 in terms of both support (0.0093) and lift (5.21). It has focused on progress monitoring and accident prevention on construction sites through real-time location sensing and resource tracking. This data collection technique is aimed at automating project performance control.

The TIME MANAGEMENT category has a close connection with DATA COLLECTION, RFID, GENETIC ALGORITHM, SIMULATION, etc. The studies were mainly conducted on automated data acquisition systems using RFID technology for progress measurement and management. The category COST MANAGEMENT
yielded valid rules with the keywords FUZZY, SIMULATION, NEURAL NETWORK, and SVM (support vector machine). In particular, SVM showed the highest lift value (10.47), meaning that this technique has become a core research method in the COST MANAGEMENT area. SVMs, which have excellent performance in classification and regression analysis in the machine learning field, have mainly been used in the prediction of project cash flow or prices by using a refined version such as least-squares SVM (LS-SVM). Fuzzy systems combined with neural networks (i.e., fuzzy neural networks) have been widely used for conceptual cost estimates in construction projects.

The QUALITY MANAGEMENT category showed a strong relationship with NONDESTRUCTIVE METHODS, UAV, COMPUTER VISION, IMAGE PROCESSING, etc. Nondestructive methods (which had the highest lift value, 8.34), such as GPR (ground penetrating radar), have been applied for robotic inspections of infrastructure, such as bridges and pipelines. Similarly, COMPUTER VISION and UAV combined with image processing solutions have been actively introduced for the safer and more efficient visual inspection of high-rise structures or infrastructure. The SAFETY MANAGEMENT category showed higher support values (>0.01) with REAL-TIME and SENSING. Real-time object detection and location sensing solutions involving ultra-wide band technology have been widely adopted for the proximity detection of equipment and workers and for hazard warnings. In addition, REMOTE CONTROL technology (which showed the highest lift value, 3.85) has been applied for remotely operated machines or robots in disaster areas and for unmanned construction.

The RESOURCE MANAGEMENT category yielded the largest number of rules (13), with the technologies involving RFID, CAMERAS, REAL-TIME, WSN, etc. Among them, RFID showed the highest values for both support (0.014) and lift (4.60). RFID with real-time and WSN technology has been actively introduced in the areas of material tracking and construction logistics management. 3D tracking using networks of calibrated cameras has also been studied.

The INFORMATION MANAGEMENT category showed a close connection with DATA MINING, INFORMATION MODEL, INFORMATION SYSTEM, MOBILE DEVICE, etc. Advanced data mining techniques have been used for effective knowledge discovery from construction databases. Moreover, information management systems using mobile devices, and web-based management information systems, have been applied to allow for easy information access and project control.

In the MAINTENANCE category, BIM had the highest frequency, with a lift value of 1.92, whereas HMI (human–machine interaction) had the highest dependency (a lift value of 2.99). BIM has been utilized for facility maintenance and the lifecycle management of building components using 3D information models, instead of the traditional two-dimensional CAD-based illustrations. It can contribute to enhancing the effectiveness of tracking and managing the related maintenance information. HMI has mainly been applied in the operation of haptic-based robots for infrastructure inspection and maintenance.

The SUSTAINABILITY category only yielded two valid rules, with SIMULATION and 3D. Simulation has been widely used to assess building energy
performance, and 3D as-built models have been applied for building energy analysis. Through more accurate modeling and simulation, this aims at improving building energy efficiency and reducing the environmental impact of the built environment.

In terms of the technologies, several keywords, such as REAL-TIME, SENSING, SIMULATION, RFID, and WSN, yielded valid rules across multiple CEM categories. Real-time sensing based on various sensors and WSN technology for data communication have mainly been applied in monitoring, safety, and resource management, whereas simulation techniques have been used for optimization, general CEM, and cost and time management. Applications of RFID technology have centered on resource management but have also been in maintenance and in time and information management.

To investigate the main relationships between the technologies, we performed association rule analysis on 63 technology-related keywords and visualized the top 100 keyword pairs by the support value (Figure 7). BIM as an effective information integration tool has a strong connection with the IFC (industry foundation classes) data model to facilitate interoperability. BIM also showed high dependency with constructing an AS-BUILT MODEL based on LASER SCANNING technology to capture accurate geometric information. In addition, there is a keyword group associated with the extraction of useful information and the registration of POINT CLOUDS data produced by 3D laser scanning. As mentioned above, SENSING technology has a close relationship with the keyword REAL-TIME, to enable immediate actions based on continuous data acquisition in a dynamic construction environment. Moreover, it has been used in adaptive MOTION CONTROL in robotic systems. VISUALIZATION and SIMULATION of the VIRTUAL REALITY environment based on n-dimensional CAD formed another group of keywords for efficient preplanning or training. Finally, it was shown that hybrid approaches combining NEURAL NETWORKS with FUZZY systems or GENETIC ALGORITHMS have been actively applied to enhance the applicability of neural networks and their performance in problem solving.

5. Discussion

The implications of this study are summarized as follows.

1. The keyword network of this field is very sparse because the field has changed quickly, adopting many new technologies and concepts. However, the keyword network also shows a high clustering coefficient and power-law distribution. This implies that research themes with a set of closely related keywords continue to be selected by researchers and contribute to the evolution of the network.

2. The keyword frequency, degree centrality, and betweenness centrality indicators show a strong positive correlation. An unusual feature of the keyword network is the positive correlation between the degree centrality and the betweenness centrality. This means that popular keywords that actively interact with other keywords also bridge keyword clusters corresponding to distinct research topics, implying that this is an interdisciplinary research area.

3. Based on keyword popularity and network features, major research topics were identified both in the overall network and across regions. The research has been implemented more actively in Asia. The structure of the keyword network for America can be regarded as consistently increasing shapes, which have fewer distinctive keywords (i.e., new research topics are more likely to evolve from existing popular keywords),

Figure 7. Major association rules between technology-related keywords.
whereas the network for Europe shows clear distinction between the frequency and centrality measures. This implies that research themes in Europe have expanded through wide-ranging, distinct keywords.

(4) The main research concern in this field is establishing a more sustainable and safer construction environment. In terms of safety, the focus has been more on hardware solutions for real-time monitoring of construction equipment and sites, while improving building energy performance in the operation stage using modeling and simulation techniques has been a main focus in the sustainability category. There is much less interest in the development of effective systems for cost and information management.

(5) Major technologies and their application in each CEM area were investigated in detail based on association rule analysis. Real-time sensing technology with a WSN environment has been widely applied in multiple areas such as safety (more focus on proximity detection and hazard warnings on construction sites), resource management (for material tracking), and monitoring (on structural behavior and condition, and progress), while simulation techniques have mainly been used in optimization (for equipment and site layout planning) and in time and cost management. The relationship between technology-related keywords was analyzed as well, and BIM, 3D, SIMULATION, and SENSING comprised major technology-related keyword groups. This shows that corresponding keyword pairs and groups are used together more frequently and contribute greatly to facilitating expansion of research themes in this field.

The results of this study can be differentiated from those of previous studies that analyzed research trends in the field of construction automation and robotics in the following respects. 1) To our knowledge, this is the first study investigating the characteristics of the keyword network in the research field of construction automation and robotics. 2) Although the refinement of keywords was performed with the assistance of experts, the results and their interpretation were derived based on quantitative measures from large datasets, which enables providing more meaningful and objective information than the qualitative analysis methods. Major research topics and the relationships between them were provided based on well-defined and widely used indicators at different levels and perspectives. This enables providing a useful grasp on expandability of and connectivity between related research themes from specific keywords in overall and partial networks. 3) The representative keywords based on integration of semantically related keywords (presented in the Appendix) can also be helpful in conducting relevant research in the future, even though there would be some ambiguous classifications.

However, this study has the following limitations. The dataset was constructed on a limited number of papers published in one international journal, which could lead to biased results to a certain degree. Although the number of data is sufficient to conduct the network analysis compared with similar studies, additional data extension in terms of duration and target journal will be required to help verification and augmentation of the results of this study. The refinement process of keywords required a considerable investment of time and effort, and researchers’ and experts’ subjectivity was somewhat reflected. Thus, better structured and automated techniques need to be introduced to improve the efficiency and objectivity of this process as well as the quality of the results.

6. Conclusion

This study investigated the structure of keyword networks as well as major issues and relationships in the field of construction automation and robotics research. For identifying the existing trends and relational patterns in a vast field, the methodology used in this study can effectively help gain meaningful information at various levels and perspectives based on quantitative indicators. Consequently, the results of this study can provide not only useful insights through which to better understand the knowledge structure and research trends, but also information on likely future directions of R&D in the field of construction automation and robotics.

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Notes on contributors

Taehoon Kim is an assistant professor in the Department of Architectural Engineering at Chosun University. He received Ph.D. in Civil, Environmental and Architectural Engineering from the Korea University. His research interests are focused on introducing advanced construction methods and technologies for improving construction productivity.

Dongmin Lee is a post-doctoral research fellow in the Department of Civil, Environmental Engineering at the University of Michigan. He got a BS and Ph.D. from Korea University. His research focuses on productivity improvement of building construction with the aid of recent AI techniques.

Hyunsu Lim is an assistant professor at the Department of Architecture in Soochunhyang University. He got a B.S. and
Ph.D from Korea University. He was a manager in Samsung Construction and Trading. He has participated in the research project for high-rise building construction technology supported by the government for 7 years. His main research area is construction technology for high-rise building projects based on automation and ICT.

Ung-Kyun Lee received a doctorate from Korea University and worked as a post-doctoral researcher at Oklahoma State University in the United States. He is currently a professor at Catholic Kwandong University. The main area of interest in research is construction management using IT. He is currently developing smart balls for pipeline management with support from the Korea Research Foundation.

Hunhee Cho is a professor at the School of Civil, Environmental and Architectural Engineering of the Korea University. His research interests are focused on enhancing construction performance by applying state-of-the-art technologies such as 3D printing, image processing, etc. He has been also participated in many R&D projects on construction cost, policy, law and regulations supported by the government.

Kyuman Cho is an Associate Professor in the Department of Architectural Engineering at Chosun University. Before joining Chosun University, he was a Post-doctoral research fellow at Purdue University in USA and was working as a Practicing engineer in construction industry. He has published about 80 journal papers and peer-reviewed conference papers, related to Construction Engineering and Management. His primary research areas include Economic analysis on construction systems, Building renovation techniques, and Automation in construction operation.

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Appendix.

| Representative keyword | Original keyword |
|-------------------------|------------------|
| POSITIONING             | POSITION MEASUREMENT, LOCALIZATION, OCCUPANCY DETECTION, LOCATION SYSTEM |
| OBJECT RECOGNITION      | OBJECT/HUMAN/DOOR/CORNER/SHAPE/IMAGE (DETECTION) |
| COST ESTIMATION         | (COST) PREDICTION/PLANNING/FORECASTING |
| MOTION CONTROL          | (MOTION) ANALYSIS/PLANNING/TRACKING, SKELETAL TRACKING |
| TRACKING                | LOCATION/POSITION/ASSET/MATERIAL/OBJECT (TRACKING) |
| INFORMATION MANAGEMENT  | DATA/CONTENT/DOCUMENT (MANAGEMENT), (INFORMATION) PROCESSING/PULLING |
| QUALITY MANAGEMENT      | (QUALITY) ASSESSMENT/ASSURANCE/CONTROL/INSPECTION, CURING MANAGEMENT |
| PROJECT MANAGEMENT      | PROJECT CONTROL |
| PATH PLANNING           | ROUTING SCHEME, PATH FINDING, PATH CHECKING |
| RISK MANAGEMENT         | (RISK) CONTROL/ALLOCATION/MITIGATION/TREATMENT/SHARING/COMMUNICATION, (HAZARD) MITIGATION/PREVENTION |
| PERFORMANCE EVALUATION  | (PERFORMANCE) COMPARISON/Criteria/INDEX/VERIFICATION |
| ACCIDENT PREVENTION     | (ACCIDENT) DETECTION/WARNING/AVOIDANCE/PROTECTION |
| ENERGY SAVING           | (ENERGY) CONSERVATION MEASURES/RETROFIT/MINIMIZATION/MANAGEMENT |
| PROGRESS MANAGEMENT     | (PROGRESS) CONTROL/MONITORING/REPORTING/MEASUREMENT |
| MATERIAL MANAGEMENT     | (MATERIAL) SUPPLY/HANDLING/PLANNING/TRACKING, INVENTORY MANAGEMENT |
| RISK ASSESSMENT         | (RISK) IDENTIFICATION/MEASUREMENT/QUANTIFICATION/EVALUATION, HAZARD RECOGNITION |
| DISASTER MANAGEMENT     | (DISASTER) MITIGATION/PREVENTION/RESPONSE/RESTORATION/COUNTERMEASURE, (EMERGENCY) MANAGEMENT/REPAIR/RESPONSE/COMMUNICATION |
| STRUCTURAL HEALTH       | DAMAGE DETECTION |
| ENERGY CONSUMPTION      | (ENERGY) PREDICTION/USE BEHAVIOR |
| PATTERN RECOGNITION     | (PATTERN) CLASSIFICATION/MATCHING/MINING, SPEECH/IRIS (RECOGNITION), TEMPLATE MATCHING, EYE TRACKING |
| DEFECT DETECTION        | CRACK/FLAW/WATER LEAK/PATCHING (DETECTION), (DEFECT) RECOGNITION/CLASSIFICATION |
| SAFETY MANAGEMENT       | SAFETY MONITORING |
| EQUIPMENT MANAGEMENT    | EQUIPMENT MONITORING, FLEET MANAGEMENT |
| COST MANAGEMENT         | (COST) CONTROL/SAVING/SUCCESS |
| SCHEDULE MANAGEMENT     | (SCHEDULE) CONTROL/SUCCESS/MODIFICATION/UPDATING |
| IMAGE PROCESSING        | (IMAGE) THRESHOLDING/SEGMENTATION/STITCHING/ANALYSIS/REGISTRATION, IMAGING, RANGE IMAGING |
| FUZZY                   | (FUZZY) ADJUSTMENT/DATA/LOGIC/PREFERENCE/THEORY |
| WSN                     | USN, SENSOR NETWORK |
| VIRTUAL REALITY         | (VIRTUAL) ENVIRONMENT, INTERFACE |
| DATA COLLECTION         | DATA ACQUISITION, DATA IDENTIFICATION, INFORMATION GAIN |

(Continued)
| Representative keyword | Original keyword |
|------------------------|-----------------|
| HMI                    | HUMAN COMPUTER INTERACTION, HUMAN MACHINE COOPERATION, HUMAN MACHINE INTERFACE, HUMAN ROBOT COOPERATION, HUMAN ROBOT INTERACTION |
| DATA EXCHANGE          | DATA TRANSFER, INFORMATION EXCHANGE, INFORMATION SHARING |
| INFORMATION INTEGRATION | DATA MERGING, SENSOR FUSION, DATA FUSION, INFORMATION MANIPULATION |
| INFORMATION MODEL      | DATA MODEL, PRODUCT DATA MODEL |
| MOBILE DEVICE          | SMARTPHONE, WEARABLE COMPUTER, PDA, PALM PC, TABLET PC |
| UBQUITOUS COMPUTING    | PERVERSE/MOBILE (COMPUTING) |
| DECISION ANALYSIS      | DECISION MAKING |
| HAPTICS                | (HAPTIC) DEVICE/PERCEPTION/IMAGE/INTERFACE |
| CONSTRUCTION EQUIPMENT | EARTHMOVING/EARTHWORK/HEAVY/MINING (EQUIPMENT), DOZER, EXCAVATOR, GRADER, TRACTOR, LOADER, SHOVEL, TRUCK, COMPACTOR, PAVEMENT REPAIR MACHINE, SELF DRIVING MACHINE, TUNNEL BORING MACHINE, DRILL RIG, VEHICLE |
| EARTHWORK              | EARTHMOVING OPERATION, EXCAVATION, SCOOPING |
| DATABASE               | METADATA REGISTRY, DATA WAREHOUSE |
| ACCIDENT               | COLLAPSE, CRASH, DISASTER, FALL, FIRE, FLOOD, PROXIMITY |
| SUSTAINABILITY         | (SUSTAINABLE) BUILDING/CONSTRUCTION/ARCHITECTURE/ENVIRONMENT |
| ENERGY EFFICIENCY      | (ENERGY) PERFORMANCE/LOSS |
| RISK                   | HAZARD |
| IMAGE                  | PHOTOGRAPH |
| INFRASTRUCTURE         | BRIDGE, ROAD CONSTRUCTION, ROAD, TUNNEL, SEWER, BREAKWATER CONSTRUCTION, PIPELINE, IN-PIPE, DAM, CITY GAS NETWORK, HEAVY CONSTRUCTION, HIGHWAY CONSTRUCTION, METRO CONSTRUCTION, UTILITY, RAILWAY |
| BUILDING CONSTRUCTION  | BUILDING, SCHOOL, UNIVERSITY, HOUSE, HOUSING, HOUSEHOLD, WAREHOUSE |
| INDUSTRIAL CONSTRUCTION| NUCLEAR POWER PLANT, NUCLEAR FACILITY |
| CIVIL ENGINEERING      | BUILDING/CONSTRUCTION (ENGINEERING) |

In the original keywords, the words in parentheses include all words separated by diagonal lines (e.g., COST ESTIMATION as a representative keyword includes (COST) PREDICTION, (COST) PLANNING, and (COST) FORECASTING).