KSCE Journal of Civil Engineering (2010) 14(2):131-139
DOI 10.1007/s12205-010-0131-7

Trend Analysis of Research and Development on Automation and Robotics Technology in the Construction Industry

Hyojoo Son*, Changwan Kim, Hyoungkwan Kim***, Seung Heon Han****, and Moon Kyum Kim*****

Received June 16, 2009/Accepted July 27, 2009

Abstract

Attention to development of automation and robotics technology in the construction industry seems to have been growing and there has been an increased awareness of the potential benefits of automation and robotics technology development. Although research and development (R&D) facilitates progress in the state of technology and-in the long run-yields significant savings in time and money for companies that take advantage of it, the costs of R&D in the short term are high and resources are limited. Analysis of trends in existing research is helpful in identifying where further R&D is needed and in suggesting directions for future research. In addition, it can be used to help predict the return on investment in individual technologies. This study was to identify global trends and issues in automation and robotics technology in the construction industry by analyzing papers published in the proceedings of the International Symposium on Automation and Robotics in Construction (ISARC). The results of that analysis show that various research topics are actively researched from the viewpoint of automation in construction and contributed by different countries and regions as well as different types of research institutions.

Keywords: *automation technology, robotics technology, R&D investment, trend analysis*

1. Introduction

In the late quarter of the 20th century, the importance of automation and robotics technology development in the construction industry was conceived to be falling behind compared to that of other industries. This situation has continued, despite the undesirable impact on the industry. For example, within a fiercely competitive environment-with thin profit margins-individual firms, especially the smaller ones, simply cannot afford to engage in research and development (R&D) or to incur the added regulatory costs of introducing robotics and automation technologies (Bogdan, 2000). Many studies have shown that the construction industry is reluctant to apply robotics and automation technology, that it employs lower levels of technology than other industries, and that the low investment in R&D has resulted in higher than necessary construction costs (Tatum, 1986; Slaughter, 1993; CII, 2003). A nationwide survey conducted in the United States by the Civil Engineering Research Foundation (CERF) also indicated that the design and construction industry devotes only 0.5% of its total revenues on R&D (CERF, 1997; O'Connor and Yang, 2003).

In more recent years, attention to development of automation and robotics technology in the construction industry seems to have been growing, since the industry is becoming more complex and is facing new challenges (Raymond and Choy, 2005). In addition, analysis of current trends suggests that there has been an increased awareness of the potential benefits of automation and robotics technology development and that the industry has ramped up its level of R&D in order to sharpen its competitive position (Yamazaki, 2004). The advantages of automation and robotics technology include enhanced productivity, a reduced need for labor, benefits to society at large, and a lessening of harmful effects on the environment (Slaughter, 1998; Goodrum and Haas, 2002; CII, 2003).

Analysis of trends in existing research is helpful in identifying where further R&D is needed and in suggesting directions for future research (Wong *et al*., 2005). In addition, such analysis is useful in a practical sense, since it can be used to help predict the return on investment in individual automation and robotics technologies to predict the potential for investment in automation

*Research Assistant, Dept. of Architectural Engineering, Chung-Ang University, Seoul 156-756, Korea (E-mail: hjson0908@wm.cau.ac.kr)
**Member, Assistant Professor, Dept. of Architectural Engineering, Chung-Ang University, Seoul 156-756, Korea (Corresponding Author, E-mail: changwan@cau.ac.kr)
***Member, Associate Professor, Dept. of Civil Engineering, Yonsei University, Seoul 120-749, Korea (E-mail: hyoungkwan@yonsei.ac.kr)
****Member, Professor, Dept. of Civil Engineering, Yonsei University, Seoul 120-749, Korea (E-mail: shh6018@yonsei.ac.kr)
*****Member, Professor, Dept. of Civil Engineering, Yonsei University, Seoul 120-749, Korea (E-mail: applymkk@yonsei.ac.kr)

and robotics technology. The primary objective of this study was to identify global trends and issues in automation and robotics technology in the construction industry in the last two decades. To gain an understanding of trends in the development of automation and robotics technology in the global construction industry, we analyzed the content of papers that appeared in ISARC proceedings during the period 1990–2008 (except the year of 1998 when the publication is not available to authors). The ISARC is the only conference solely devoted to the area of robotics and automation in the construction industry and its proceedings constitute the largest output of the International Association for Automation and Robotics in Construction (IAARC). During the period covered by this study, a total of 1671 papers appeared in ISARC proceedings, representing 2,900 authors, 5,163 authorships, and 55 countries. Content analysis was used to create a classification framework for the published papers and analyze the material presented in them because keywords often do not reflect the entire substance of a paper or all the pertinent features discussed therein.

2. Development of Automation and Robotics Technology in the Construction Industry

New construction projects tend to pose complex problems that require innovative solutions (Tatum, 1989; Nam and Tatum, 1992; CII, 2003). The use of automation and robotics technology becomes essential to the success of a construction project and also creates possibilities for the construction company to realize a competitive advantage (Pries and Janszen, 1995; Slaughter, 1998). It has been demonstrated that the development of automation and robotics technology is a promising approach to satisfying the needs of the construction industry (NRC, 1988; Tatum, 1989; Laborde and Sanvido, 1994). However, people with expertise in any given discipline are limited in their ability to come up with new ideas for automation and robotics technology technologies in their specialties (Han *et al*., 2006).

The term robotics and automation technology construction technology refers to generation, development, and implementation of ideas and also encompasses adoption and implementation of products or processes developed outside the industry in order to enhance the efficiency of a standard operation and/or to yield a better product (Laborde and Sanvido, 1994; Tatum, 1989; Park *et al*., 2004). Robotics and automation technology has brought many intangible benefits that cannot be adequately measured in terms of direct monetary savings and gain but can add to a company's competitive position in the long run. In a recent study that examined trends in productivity over a 30-year period, it was found that employment of various robotics and automation technologies can improve construction productivity and efficiency and result in cost savings (Slaughter, 1998; Goodrum and Haas, 2002; CII, 2003). In addition, there is a general consensus that mechanization of construction tasks has reduced the cost of construction by decreasing the number of hours of labor required to complete a project (Slaughter, 1998).

Construction-related automation and robotics technology can also provide multiple social benefits (Seaden, 1996; Slaughter, 1998). Improved productivity and efficiency make construction more affordable. In addition, use of automation and robotics technology spurs market growth through the provision of new or improved products and services as well as reductions in the cost of production (Slaughter, 1998; CII, 2003). In addition, the extent of harmful environmental effects of construction-related activities is reduced by adoption of improved components and technologies (Slaughter, 1998; CII, 2003). Moreover, the construction industry has historically suffered from a poor image, so that young people and newcomers to the workforce do not want to serve in an industry that has been known for hard work and long hours in a hazardous and dirty environment. Automation and robotics technology could help to solve this problem by making construction work easier, safer, and more attractive (Slaughter, 1998; CII, 2003).

In the mid 1980s, many large construction companies in Japan as well as in other countries started to make huge investments in automation and robotics technologies in order to deal with the growing construction market and to reduce the cost and duration of a project (Hardie *et al*., 2005; Kangari and Miyatake, 1997; Pries and Janszen, 1995; Slaughter, 1998). In addition, there has been a change in focus of the technology development environment, in the direction of using more effective technology and pooling the knowledge of different companies and industries, since the construction industry recognizes that there is a high degree of risk-and a potentially low rate of return-on investment in indigenous technology development (Yang, 2003; Yamazaki, 2004).

3. Research and Development Trends on Automation and Robotics Technology

In the construction industry, it is customary to assess the effectiveness of automation and robotics technology in terms of value chains, i.e., the values added in the different phases of a construction project, beginning with the initial concept and design, followed by the actual construction, the operation and maintenance of the built environment over the course of its useful life, and the eventual demolition (APCC, 2000; FIATECH, 2004). In this study, the areas of research on automation and robotics technology were classified along roughly those same lines and were organized into five major categories: 1) Planning and Design, 2) Construction Robotics, 3) Intelligent Job-Site Management, 4) Operation and Maintenance, and 5) Others. Planning and Design focuses on the pre-construction phase, Construction Robotics and Intelligent Job-Site Management deal with issues related to the construction phase, and Operation and Maintenance focuses on the post-construction phase. The others category encompasses papers that either overlap two or more of the other four categories or otherwise do not belong in any of them. For the analysis, each paper was assigned to just one of the five major categories.

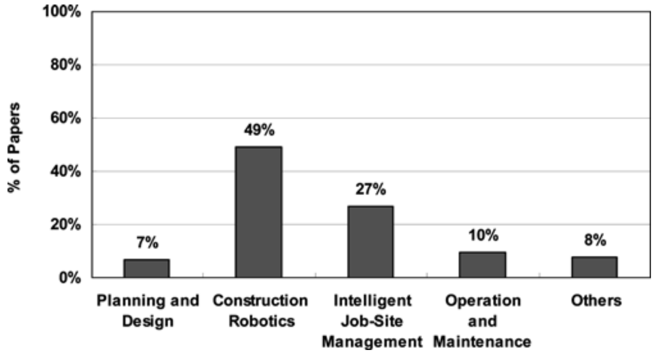

Fig. 1. Distribution of Papers by Category

3.1 Distribution of Research and Development by Category

For purposes of discussion of trends in construction research, the 18-year period covered by this study was divided into three-year periods. Within each period, statistical data for the various topics were compiled, and the period totals were analyzed and compared to identify changes and trends over time. Fig. 1 shows the percentage of ISARC papers in each of the five major categories. Research in the top category, Construction Robotics, accounts for approximately 50% of all the ISARC papers, and research in the second-highest category, Intelligent Job-Site Management category, accounts for another 27%, so that 77% of ISARC papers in the period covered by this study focus on those two categories, which are also the ones most closely aligned with the construction phase.

Table 1 shows the distribution of papers published over the five categories during the period 1990-2008 (except 1998). Several notable findings were found in the distribution of papers among the five categories over the period covered by this study. The relative amount of research on Construction Robotics has undergone a net decrease, from 71% of ISARC papers in the period of 1990-1992 to 33% in the period of 2006-2008, while the relative amount of research on Intelligent Job-Site Management has seen a net incline, from 17% of ISARC papers in the period of 1990-1992 to 29% in the period 2006-2008. The Planning and Design category is the comparatively low portion of research, while increasing in the 21st century. And the relative amount of research on Operation and Maintenance has undergone a net increase, from 5% of ISARC papers in the period of 1990-1992 to 14% in the period of 2006-2008.

3.2 Country and Regional Differences

The 2,900 authors of ISARC papers published during the period 1990-2008 represent five continents and 55 countries. For each country, the adjusted number of papers was computed according to the Eq. (1):

$$C_j = \sum_i \frac{N_{ij}}{M_i} \tag{1}$$

where C_j is the adjusted number of papers for country *j*, is the total number of authors of paper *i*, and M_{ij} is the number of authors of paper *i* who are from country *j* (Lakmazageri and Rasdorf, 1998; Abudayyeh *et al*., 2006). For example, if a paper had two authors and they are from different countries, then each of those countries was given 1/2 point for that paper. If three authors contributed to a paper, two from one country and one from another, then the first country was given 2/3 point and the second country was given 1/3.

The countries with an adjusted number of papers greater than 37.5 are Japan, the U.S., Taiwan, the U.K., South Korea, Germany, Poland, Spain, Netherlands, and India. Fig. 2 shows the adjusted percentage of papers for each of the top ten countries. As shown in the figure, the research contributions of Japan, the U.S., and Taiwan combined make up approximately 50% of the whole.

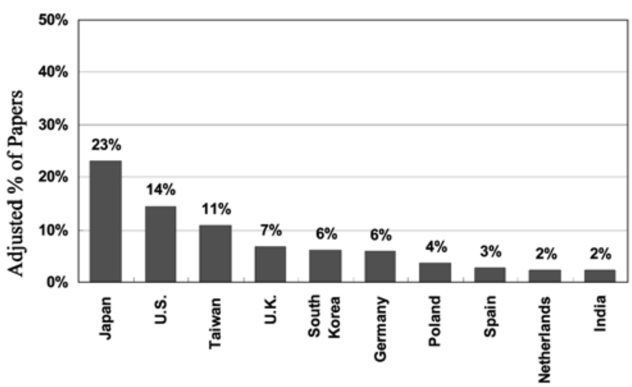

Fig. 2. Total Contribution by Country

Table 1. Distribution of Papers by Category

Category	1990-1992 (%)	1993-1995 (%)	1996-1999* (%)	2000-2002 (%)	2003-2005 (%)	2006-2008 (%)
Planning and Design	2	3	2	11	10	10
Construction Robotics	71	68	66	33	37	33
Intelligent Job-Site Management	17	19	20	35	36	29
Operation and Maintenance	5	8	7	12	9	14
Others	5	3	5	8	8	14

* Except the year of 1998 when the publication is not available to authors
Note: Percentages may not add up to exactly 100% due to rounding

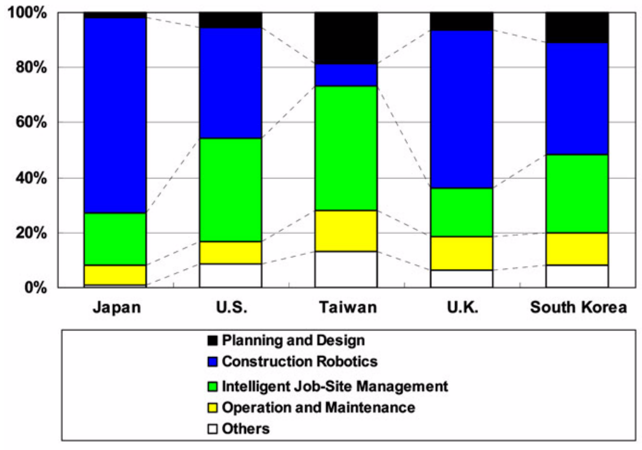

Fig. 3. Relative Contributions in Individual Categories: Top Five Countries

For each of the top five countries, Fig. 3 shows the distribution of its research contributions over the five categories. In Japan, the top country, about 90% of the research contribution of Japan, the highest country, was performed in the Construction Robotics and Intelligent Job-Site Management categories combined. It appears that Japan has concentrated on site-centered robots for industrialization of the construction industry. In the U.S., the second-highest country, more than three-fourths of the research was done on Construction Robotics and Intelligent Job-Site Management combined. In Taiwan, the third-highest country, an especially large percentage of research was devoted to Intelligent Job-Site Management, and considerable contributions were made in three of the other four categories (all but Construction Robotics). In each of the two remaining countries among the top five (the U.K. and South Korea), more than 70% of the research was done on Construction Robotics and Intelligent Job-Site Management combined. In an earlier study of research on advanced construction technology (Haas *et al.*, 1995), the ISARC papers published during the period 1987-1993 were analyzed. In that study, it was found that Japan had the highest contribution, followed by the U.S., the U.K., Germany, and France, in that order.

3.3 Differences by the Type of Institute

Research on automation and robotics technology which is applicable to the construction industry is performed by educational institutions, research institutes, the private sector, and government agencies. Within education, research is performed at colleges and universities by professors, visiting faculty, postdoctoral fellows, research personnel, and students. Research institutes include autonomous research units (including entities that serve as the research arm of a private corporation) which are affiliated with neither an educational organization nor a government agency. In the private sector, research contributions are made by personnel of civil engineering and construction firms and by consultants. Finally, the contributions of government agencies involve personnel at state transportation agencies, municipalities, and branches of the military.

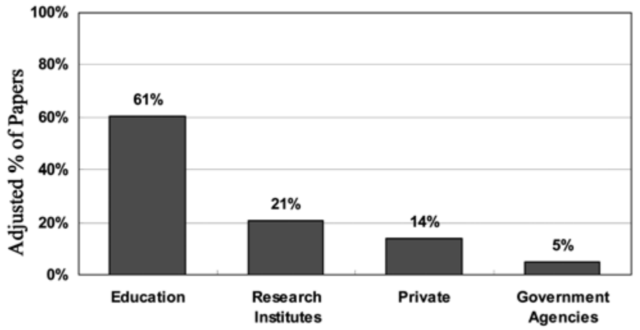

Fig. 4. Total Contribution by Type of Institution

For each of the four types of institutions, the adjusted number of papers was computed (using a formula which is analogous to the one used in computing the adjusted number of papers for each country). Fig. 4 shows the adjusted percentage of papers for each of the four contributing sectors. Educational institutions, which play an important role in research, account for about 60% of the total research reported in ISARC papers during the period under study. The research institutes, the private sector, and government agencies account for approximately 21%, 14%, and 5% of total research, respectively.

For each of the four sectors, Fig. 5 shows the distribution of its research contributions over the five categories. As expected, most of the research sponsored by research institutes and the private sector focused on issues pertinent to Construction Robotics and Intelligent Job-Site Management, while the interests of academicians are more evenly distributed over the various categories. Government agencies tend to concentrate more heavily on Construction Robotics relative to the other four categories. Research in that category is by no means limited to robotics; in fact, it covers a wide range of applications and technological aspects (Gambao and Balaguer, 2002). Robot technology has far-reaching effects on technology development,

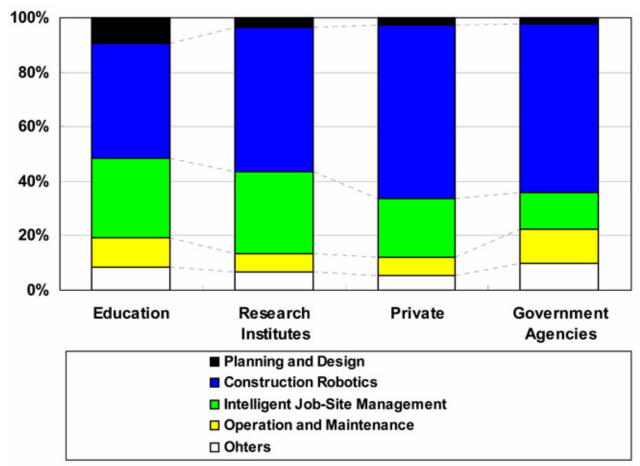

Fig. 5. Relative Contributions in Individual Categories, by Type of Institution

but most of the research in that area is conducted by the government, since the development costs are high. As can be seen in Fig. 5, in each of the three types of non-governmental institutions, there is indeed fairly little research in the "Operation and Maintenance", and "Others" categories, and (except for academia) very little research in the "Planning and Design" category.

4. Key Research Areas on Automation and Robotics Technology

To get a handle on key research areas on automation and robotics technology in the construction industry, the ISARC papers were further classified according to topics within each category. Each topic in turn comprises several specific subjects. In what follows, we describe the research topics in each category, tabulate the numbers and percentages of papers on those topics which were published in ISARC proceedings during the period under study, and discuss the types of technology that have been the subject of research on those topics.

4.1 Planning and Design

The planning and design phase is considered to be one of the most significant and cost-driving stages in a construction project (Ragusa and Bochenek, 1996). Therefore, the construction industry puts a great deal of effort into improvements in efficiency, and most research on this phase deals with how to use computer technology to enhance the efficiency of work done in the planning and design phase. In recent decades, computer hardware and software have been used for the purpose of improving the efficiency of project planning and design, and developments in technology have enabled design tasks to be computerized (Gardner, 2003). These developments have facilitated the optimization of the planning and design process.

The topics of research within the Planning and Design category, along with the number and percentage of ISARC papers on each topic, are listed in Table 2. More than 60% of the papers in this category focus on one of four topics: design assistance tools, estimation tools, visualization tools, or procurement systems.

The research on design assistance tools, which are used in performing design tasks more effectively and efficiently, covers a wide range of areas, including automated design systems, decision-making/support tools for design, design media, drafting management systems, and reasoning systems/knowledge-based expert systems for use in design. The subjects of research on estimation tools, which focus on enhancing the accuracy of cost estimates and reducing the time needed to produce them, include automated estimation systems, task-based cost estimation tools, Web-based estimation systems, and others. The research on visualization tools, which serve as a comprehensive aid in the design process and use 3D modeling technology and virtual reality technology, deals with issues such as concept modeling technology, tools that generate digital 3D models from a sketch, auto-stereoscopic display (ASD), augmented reality systems, tangible media, and user-oriented interactive design systems. The subjects of research on procurement systems, which are used for more proficient management of the various stages in the procurement process, include contract management systems, and decision-support systems for bidding, subcontracting systems, among others.

The remaining research in the Planning and Design category (which is classified as "Other" in Table 2) deals with issues such as collaborative design systems, design review tools, design knowledge management tools, evaluation of project risk, and analysis of design.

Table 2. Category 1: Planning and Design

Topic	No. of papers	Percentage in category	Percentage of all ISARC papers
Design assistance tools	31	27%	2%
Estimation tools	17	15%	1%
Visualization tools	16	14%	1%
Procurement systems	13	12%	1%
Others	36	32%	2%
Total	113	100%	7%

4.2 Construction Robotics

The nature of robotics used in the construction industry has progressed during the past few decades. Robotics technologies are now widely used in various aspects of construction in order to achieve greater efficiency in the performance of construction tasks and to improve working conditions in the construction phase. This category covers the latest construction technologies, such as robots, sensors, control devices, human interfaces, and manipulation techniques. Research in this category has concentrated on how to improve productivity of construction tasks and how to promote safety on construction sites. The robotics technologies that have been developed as a result of this research help human workers on construction sites and optimize the construction process, in that they reduce labor requirements,

Table 3. Category 2: Construction Robotics

Topic	No. of papers	Percentage in category	Percentage of all ISARC papers
Control systems	133	16%	8%
Automated systems	88	11%	5%
Earth-working equipment	82	10%	5%
Sensor systems	66	8%	4%
Heavy-lifting equipment	56	7%	3%
Path planning systems	33	4%	2%
Other	361	44%	22%
Total	819	100%	49%

improve safety, enhance emissions control, raise productivity, and allow for a greater degree of flexibility in the construction enterprise (Haas *et al*., 1995).

The topics of research within the Construction Robotics category, along with the number and percentage of ISARC papers on each topic, are listed in Table 3. More than 50% of the ISARC papers in this category focus on one of six topics: control systems, automated systems, earth-working equipment, sensor systems, heavy lifting equipment, or path planning systems.

The subjects of research on control systems, which are devices or sets of devices that are designed to manage, command, direct, or regulate the behavior of a construction robot or other construction equipment, include error modeling, control algorithms, tele-operation systems, and others. The subjects of research on advanced automated systems, which are used to improve the sequencing of construction processes without human/manual involvement, include automated transporting/conveying systems, automated painting systems, and automated pipe installation systems. Research on earth-working equipment deals with incorporation of advanced control technologies into existing machinery which is used for specific on-site earth-working tasks: landfill equipment, compactors, bulldozers, excavators, graders, loaders, shovels, and others. The subjects of research on sensor systems for construction robotics, which has focused on detection and location of objects in order to improve the efficiency of operation of construction robots, include laser radar (LADAR), laser rangefinders, and radio-frequency identification (RFID) devices, among others. The subjects of research on heavy-lifting equipment, including construction manipulators and cranes, which has focused on the development of automatic equipment for use in pick-and-place operations, comprises technologies such as anti-sway control systems, collision warning systems, crane jib lowering systems, and trajectory planning systems. The research on path-planning systems, which has focused on collision-free path planning for construction robot navigation in known or unknown environments, deals with subjects such as localization, position tracking, and trajectory planning.

There are quite a few research topics in the Construction Robotics category with fewer than ten papers apiece. Those topics (which are included in the "Other" entry in Table 3) include underwater construction machines, finishing robots, humanoid robots, robots that are used to support construction work done by humans, robots that are incorporated into other machinery (climbing robots, rescue robots, walking robots, and others), investigation of factors that influence the production of automation technology, and assessment of the economic effects of automation, among others.

4.3 Intelligent Job-Site Management

The purpose of carrying out research in this category is to meet the increasing demand for more effective methods of construction job-site management. Thanks to the research in this category, a number of technologies have been developed to manage the performance of work on construction sites, especially in regard to operations that are fraught with uncertainty (Li *et al*., 2000). Implementation of such technologies leads to greater effectiveness in construction job-site management, improvements in administrative capabilities, increased competition, and greater profits for a construction company (Shiau and Wang, 2003).

Table 4. Category 3: Intelligent Job-Site Management

Topics	No. of papers	Percentage in category	Percentage of all ISARC papers
Construction management systems	166	37%	10%
Sensors and sensing	78	17%	5%
Simulation tools	51	12%	3%
Knowledge management	49	11%	3%
Prefabrication	46	10%	3%
Others	61	13%	4%
Total	451	100%	27%

The topics of research within the Intelligent Job-Site Management category, along with the number and percentage of ISARC papers on each topic, are listed in Table 4. Nearly 85% of the ISARC papers in this category focus on one of four topics: construction management systems, sensors and sensing, simulation tools, knowledge management, or prefabrication.

The subjects of research on construction management systems, which has focused on development of technology to streamline the performance of construction management tasks, include construction planning, cost control, enterprise resource planning (ERP), process management, resource management, schedule control, site/facility layout planning, supply chain management, and quality management. The research on sensors and sensing for modeling of construction environments deal with functions such as site measurement and inspection, site monitoring/modeling, and productivity measurement. The body of research on the application of sensors for data acquisition and processing is growing rapidly, and numerous types of sensors and communication devices, such as LADAR, global positioning systems (GPS), and RFID devices, are already in use on construction sites (Cheok *et al*., 2000; Balaguer, 2004). The research on simulation tools have been developed to analyze the performance of construction project and site operations that are fraught with uncertainty in the past decades (Li *et al*., 2000). This topic includes subjects such as graphic simulation, process simulation, and 3D/4D CAD. The research on knowledge management encompasses a wide range of technologies that are used to search, create, represent, and disseminate knowledge for reuse, awareness, and learning in the construction phase. This topic includes subjects such as database/data warehousing, data mining, information modeling, and issues of interoperability. The subjects of research on prefabrication, which is the typical means of reducing uncertainties related to the construction phase and of meeting the requirements for process industrialization

(Shih *et al*., 2005), include automatic modular construction; industrial, flexible, and demountable (IFD) building systems; industrialized construction; layered fabrication; and pre-assembly.

The remaining research in the Intelligent Job-Site Management category (classified as "Other" in Table 4) deals with issues such as simulation tools, advanced technology for intelligent job-site work, virtual reality systems, case handling in the construction phase, simulation technology, risk management, and recycling of construction waste.

4.4 Operation and Maintenance

Operation and maintenance is one of the issues that are most attractive to the major stakeholders in the construction industry, because they have become increasingly aware of the importance of ensuring the durability of infrastructure. Therefore, a considerable amount of research has been devoted to improving and optimizing the operation and maintenance of existing infrastructure. In recent decades, both hardware and software systems have been developed for this purpose. The hardware systems, which consist of robots and sensors, are geared toward a variety of applications, such as inspection, monitoring, and maintenance of infrastructure, while the purpose of the software systems has been to use the information generated in the operation and maintenance phase and to provide the decision support for management of that phase.

The topics of research within the Operation and Maintenance category, along with the number and percentage of ISARC papers on each topic, are listed in Table 5. More than 80% of the ISARC papers in this category focus on one of three topics: inspection and monitoring systems, maintenance systems, or facility management systems.

The research on inspection and monitoring systems, which employ various types of sensors, including closed circuit television (CCTV), LADAR, mirror-tele cameras, geographic information systems (GIS), and micro-electromechanical systems (MEMS), deals with a wide range of subjects, such as heating, ventilation, and air conditioning inspection; pipe inspection; and plumbing inspection. The subjects of research on automated maintenance systems include cleaning robots, crack sealers, and pipe repair robots. The subjects of research on facility management systems, which help make decisions on the types of tasks that need to be performed in order to maintain the serviceability of infrastructure and to extend its useful life include various database systems and management systems which are used in the operation and maintenance phase.

The other research in the Operation and Maintenance category (classified as "Other" in Table 5) deals with issues such as disaster prevention, post occupancy evaluation (POE), and development of autonomous systems for buildings of all kinds (including residences).

4.5 Others

The 128 ISARC papers that we placed into the Others category are those that do not belong in any of the previous four categories (or that overlap two or more of those categories). Furthermore, the papers in this category were difficult to group by topic, since relatively few sets of them deal with issues that are sufficiently similar in nature. However, there are two identifiable topics that (combined) account for about 10% of the papers in this category: Life Cycle Management (LCM) and Life Cycle Assessment (LCA). Research in these areas takes into consideration the entire period of a construction project, from initial concept/evaluation to demolition. Other research topics in this category include integrated systems for the entire construction process (as compared to systems that are limited to one specific phase), Web-based systems for communication among the various parties to a construction project, creative construction contracts to enhance the effectiveness of construction activity, unexpected results that stem from new developments in the construction industry, and advanced materials, among others.

4.6 Further Analysis

In the process of categorizing the ISARC papers and outlining the research topics and specific subjects that fall into each of the five major categories, we have gained a better sense of the dominant directions of research in each category. The research in the Planning and Design category has tended to focus on issues such as construction project evaluation and prediction in the planning stage, decision-making information about the design stage, automated design processes, simulated visualization of design components, and cooperative work in the planning and design stage which is geared toward reaping improvements in the accuracy of planning/design work and supporting it more effectively. Overall, the main thrust of research in the Planning and Design category lies in advanced design processes for systems that provide assistance in the design/planning phase, rather than in generation and development of design products per se.

Table 5. Category 4: Operation and Maintenance

Topic	No. of papers	Percentage in category	Percentage of all ISARC papers
Inspection and monitoring systems	73	46%	4%
Maintenance systems	38	24%	2%
Facility management systems	18	11%	1%
Other	31	19%	2%
Total	160	100%	10%

In the Construction Robotics category, the major concern has been the development of construction robots and other automated construction equipment as well as various systems for the robotization of construction processes. Consequently, the focus of research is on promotion of automation in the construction stage via utilization of such equipment.

The goal of much of the research in the Intelligent Job-Site Management category has been to achieve such objectives as real-time monitoring of the construction process, support of the cooperative work in the construction phase, optimization of the construction process through accumulation of past construction information, visualization of construction progress, and expansion of prefabricated construction.

In the Operation and Maintenance category, some of the major goals have been continuous and undisturbed operation and maintenance of completed infrastructure via use of robots and sensors, prompt availability of decision-making information related to operation and maintenance, provision of a unified body of information to enhance the efficiency of construction procedures, and real-time monitoring of the condition of infrastructure in the post-construction phase.

In terms of the number of ISARC papers published during the period under study, the five most highly researched topics and associated major categories are (in descending order) construction management systems (Intelligent Job-Site Management), control systems (Construction Robotics), automated systems (Construction Robotics), earth-working equipment (Construction Robotics), and sensor and sensing (Intelligent Job-Site Management). The papers on these five topics account for more than 30% of the total; moreover, which are also the ones most closely aligned with the construction phase. In-depth analysis of the content of ISARC papers revealed that they tend to focus on the engineering and technological aspects of the discipline which are related to the construction phase, rather than to the other phases of construction projects.

5. Conclusions

The topics and subjects of research reported in the ISARC papers during the period 1990-2008 (except 1998) were analyzed to identify significant research trends associated with advanced construction technology. Overall, the analysis shows that research on advanced construction technology is most closely aligned with the construction phase, and that the research activities changed and evolved during the period under study, in line with the perceived needs of the construction industry. The analyses presented in this paper show that the majority of research on advanced construction technology has been conducted by academia. In order to meet the diverse needs of the construction industry, however, perhaps a better model would be one of collaboration and multidisciplinary participation. An unfocused and uncoordinated effort among the various R&D sectors (i.e., academia, research institutes, the private sector, and government) leads to chronic under-funding. Therefore, although research on robotics and automation technology in the construction industry is largely carried out by academic institutions, there is a need for increased sharing of research among sectors, with significant input from all stakeholders, in order to stimulate innovation and realize more rapid progress.

As for further research in this area, studies like this could be extended to patent analysis, to provide valuable insights into the extent to which new concepts and techniques are implemented and refined. This should prove to be a valuable aid in understanding the relationship between research and actual applications of advanced technology in the construction industry, and it should serve as a stimulus in speeding up the development of new techniques and theories.

Acknowledgements

This work was supported by National Research Foundation of Korea Grant funded by the Korean Government (KRF-2007-313-D00871).

References

Abudayyeh, O., Dibert-DeYoung, A., Rasdorf, W., and Melhem, H. (2006). “Research publication trends and topics in computing in civil engineering.” *J. Comput. Civ. Eng.*, ASCE, Vol. 20, No. 1, pp. 2-12.

Australian Procurement and Construction Council Inc. (APCC) (2000). *Directions for IT in the construction industry*, APCC, Deakin ACT, Australia.

Balaguer, C. (2004). “Nowadays trends in robotics and automation in construction industry: Transition from hard to soft robotics.” *Proc. 21st Int. Symp. Automation and Robotics in Construction*, IAARC, Jeju, Korea.

Bogdan, C. (2000). *Industry studies 2000: Construction*, The Industrial College of the Armed Forces, National Defense University, Washington, D.C.

Cheok, G. S., Lipman, R. R., Witzgall, C., Bernal, J., and Stone, W. C. (2000). “Field demonstration of laser scanning for excavation measurement.” *Proc. 17th Int. Symp. on Automation and Robotics in Construction*, IAARC, Taipei, Taiwan, pp. 683-688.

Civil Engineering Research Foundation (CERF) (1997). *Commercializing infrastructure technologies: A handbook for innovators*, CERF Report 97-5028, ASCE/CERF, Reston, VA.

Construction Industry Institute (CII) (2003). *Breakthrough process and charter*, Breakthrough Strategy Committee (BTSC) Document 2003-2, The University of Texas at Austin, Austin, TX.

Fully Integrated and Automated Technologies (FIATECH) (2004). *Capital projects technology roadmap*, The University of Texas at Austin, Austin, TX.

Gambao, E. and Balaguer, C. (2002). “Robotics and automation in construction [Guest Editors].” *Robotics & Automation Magazine*, IEEE, Vol. 9, No. 1, pp. 4-6.

Gardner, P. J. (2003). “Automation of the design process.” *Proc. 20th Int. Symp. on Automation and Robotics in Construction*, IAARC, Eindhoven, Netherlands.

Goodrum, P. M. and Haas, C. T. (2002). “Partial factor productivity and equipment technology change at activity level in U.S. construction industry.” *J. Construct. Eng. Manag.*, ASCE, Vol. 128, No. 6, pp.

463-472.

Haas, C., Skibviewski, M., and Budny, E. (1995). "Robotics in civil engineering." *J. Microcomput. Civ. Eng.*, Elsevier, Vol. 10, No. 5, pp. 371-381.

Han, S. H., Kim, H. J., Cho, K. H., Kim, M. K., and Kim, H. (2006). "Research planning methodology for technology fusion in construction." *Proc. 23rd Int. Symp. on Automation and Robotics in Construction*, IAARC, Tokyo, Japan.

Hardie, M., Miller, G., Manley, K., and McFallan, S. (2005). "Experience with the management of technological innovations within the Australian construction industry." *Proc. PICMET '05 Conf.*, Portland, OR.

Kangari, R. and Miyatake, Y. (1997). "Developing and managing innovative construction technologies in Japan." *J. Construct. Eng. Manag.*, ASCE, Vol. 123, No. 1, pp. 72–84.

Laborde, M. and Sanvido, V. (1994). "Introducing new process technologies into construction companies." *J. Construct. Eng. Manag.*, ASCE, Vol. 120, No. 3, pp. 488-508.

Lakmazageri, S. and Rasdorf, W. (1998). "Foundations for research in computing in civil engineering." *J. Comput. Civ. Eng.*, ASCE, Vol. 12, No. 1, pp. 9-18.

Li, M., Lai, Y. T., Chang, S., Huang, Y., and Wang, W. (2000). "Simulation of structural steel erection operation-A case study." *Proc., 17th Int. Symp. on Automation and Robotics in Construction*, IAARC, Taipei, Taiwan.

Nam, C. H. and Tatum, C. B. (1992). "Strategies for technology push: Lessons from construction innovations." *J. Construct. Eng. Manag.*, ASCE, Vol. 118, No. 3, pp. 507-524.

National Research Council (NRC) (1988). *Building for tomorrow: Global enterprise and the U.S. construction industry*, National Academy Press, Washington, DC.

O'Connor, J. T. and Yang, L. (2003). *Associations of technology usage with capital facility project success*, Center for Construction Industry Studies, The University of Texas at Austin, Austin, TX.

Park, M., Nepal, M. P., and Dulaimi, M. F. (2004). "Dynamic modeling for construction innovation." *J. Construct. Eng. Manag.*, ASCE, Vol. 20, No. 4, pp. 170-177.

Pries, F. and Janszen, F. (1995). "Innovation in the construction industry: The dominant role of the environment." *Constr. Manag. Econ.*, Taylor and Francis Group, Vol. 13, No. 1, pp. 43-51.

Ragusa, J. M. and Bochenek, G. (1996). "Product design using virtual environments: A conceptual evolutionary approach." *Proc. Int. Conf. on Engineering Management (IEMC '96)*, IEEE, Vancouver, Canada, pp. 494-499.

Raymond, Y. C. and Choy, L. (2005). "Is IT training in construction industry useful?" *J. Construction Research*, Vol. 6, No. 1, pp. 1-13.

Seaden, G. (1996). "Economics of innovation in the construction industry." *J. Infrastruct. Syst.*, Vol. 2, No. 3, pp. 103-107.

Shiau, Y. and Wang, W. (2003). "Daily report module for construction management information system." *Proc. 20th Int. Symp. on Automation and Robotics in Construction*, IAARC, Eindhoven, Netherlands.

Shih, K., Huang, C., Liu, S., Wu, T., and Wang, M. (2005). "Study on the storage and transportation optimization of prefabrication factory." *Proc. 22nd Int. Symp. on Automation and Robotics in Construction*, IAARC, Ferrara, Italy.

Slaughter, E. S. (1993). "Builders as sources of construction innovation." *J. Construct. Eng. Manag.*, ASCE, Vol. 119, No. 3, pp. 532-549.

Slaughter, E. S. (1998). "Models of construction innovation." *J. Construct. Eng. Manag.*, ASCE, Vol. 110, No. 3, pp. 311-323.

Tatum, C. B. (1986). "Potential mechanisms for construction innovation." *J. Construct. Eng. Manag.*, ASCE, Vol. 112, No. 2, pp. 178-187.

Tatum, C. B. (1989). "Organizing to increase innovation in construction firms." *J. Construct. Eng. Manag.*, ASCE, Vol. 115, No. 4, pp. 602-617.

Wong, J. K., Li, H., and Wang, S. W. (2005). "Intelligent building research: A review." *J. Automation in Construction*, Elsevier, Vol. 14, No. 1, pp. 143-159.

Yamazaki, Y. (2004). "Future innovative construction technologies: Directions and strategies to innovate construction industry." *Proc. 21st Int. Symp. on Automation and Robotics in Construction*, IAARC, Jeju, Korea.

Yang, L. R. (2003). *Influence of technology on project success measures*, PhD Thesis, The University of Texas at Austin, Austin, TX.