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A methodology to quantitatively evaluate the safety of a glazing robot

Seungyeol Lee [a,2], Seungnam Yu [b,1], Junho Choi [a,2], Changsoo Han [b,*,1]

[a] Center for Cognitive Robotics Research, Korea Institute of Science and Technology, 39-1 Hawolgok-dong, Seongbuk-gu, Seoul 136-791, South Korea
[b] Advanced Robotics Laboratory, Dept. of Mech. Eng., Hanyang University, 1271 Sa-1 dong, Sangnok-gu, Ansan, Kyeonggi-do 426-791, South Korea

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ABSTRACT

A new construction method using robots is spreading widely among construction sites in order to overcome labour shortages and frequent construction accidents. Along with economical efficiency, safety is a very important factor for evaluating the use of construction robots in construction sites. However, the quantitative evaluation of safety is difficult compared with that of economical efficiency. In this study, we suggested a safety evaluation methodology by defining the 'worker' and 'work conditions' as two risk factors, defining the 'worker' factor as posture load and the 'work conditions' factor as the work environment and the risk exposure time. The posture load evaluation reflects the risk of musculoskeletal disorders which can be caused by work posture and the risk of accidents which can be caused by reduced concentration. We evaluated the risk factors that may cause various accidents such as falling, colliding, capsizing, and squeezing in work environments, and evaluated the operational risk by considering worker exposure time to risky work environments. With the results of the evaluations for each factor, we calculated the general operational risk and deduced the improvement ratio in operational safety by introducing a construction robot. To verify these results, we compared the safety of the existing human manual labour and the proposed robotic labour construction methods for manipulating large glass panels.

1. Introduction

Construction has always been a highly labour-intensive industry. Labour usually accounts for at least 25% of the total cost of each project (Tucker, 1988). In spite of this, the construction industries in the United States, Japan, and Korea amongst others are challenged by serious labour shortages. In Korea, construction companies are concerned about a potential labour shortage due to demographic changes and an aging construction work force (the Korean construction industry is expected to fall 423,000 people short in manpower in 2010).

Also, construction remains one of the most hazardous ways to earn a living. The rate of construction accidents in Korea is one of the highest within all industrial accidents. An improvement in construction safety could not only reduce accidents but also decrease the cost of construction and is therefore one of the key goals of the construction industry (Hsiao, 1994).

This information indicates that in today's construction industries of the US, Japan, and Korea, labour shortages have to be overcome and construction accidents must be reduced. In order to surmount these challenges, two approaches have been considered: first, to improve construction processes andx, second, to apply automation and robotics, which have had much success in the manufacturing industry (Roozbeh, 1985; Warszawski, 1985, 1986).

Construction robots and automation technology have the potential to raise productivity, performing tasks efficiently and improving working conditions when applying them to situations in which humans are exposed to safety hazards. Construction is a diverse industry characterized by a dynamic unstructured environment involving safety hazards, temporary activities, and changing weather conditions, which taken together potentially inhibit, greater implementation of automation. There are few industrial robots to be found in construction sites. However, recent years have seen an increase in the development of construction robots and automated systems that can carry out complex sequences of operations with high performance. Examples of these construction robots include wall (façade)-climbing robots for inspection and maintenance, concrete power floating machines, concrete floor surface finishing robots, construction steel frame welding robots, wall panel bricklaying robots, robotic excavators,

* Corresponding author. Tel.: +82 31 400 5247; fax: +82 31 406 6398.
E-mail addresses: suprasy@paran.com (S. Lee), hymecer@gmail.com (S. Yu), junhochoi@kist.re.kr (J. Choi), cshan@hanyang.ac.kr (C. Han).
[1] Tel.: +82 31 400 5247; fax: +82 31 406 6398.
[2] Tel.: +82 2 958 6817; fax: +82 2 958 5629.

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and automated cranes for the assembly of modular construction elements (Isao et al., 1996; Gambao et al., 2000 Ostoja-Starzewski and Skibniewski, 1989; Santos et al., 2003; Masatoshi et al., 1996; Bernold, 1987; Cusack, 1994; Poppy, 1994).

The development of a construction robot and its application to a construction area cannot be achieved by system production alone. Studies on system operation technology are also necessary to ensure that the developed system will be fully effective in operation. Even though the use of automation systems and construction robots in real construction sites will decrease labour intensity and thus reduce work-related musculoskeletal disorders (WMSDs), any inappropriate designs for working processes and environments can cause new types of accidents. Due to the harmful consequences of violent, irregular motions and unnatural postures of the body, poor working postures have been considered as one of the major causes of musculoskeletal disorders in industrial sites by many ergonomists and practitioners of health and safety (Albers et al., 2005; Haslegrave, 1994; Van Wely, 1970; Westgaard and Aaras, 1984). Working postures are as important for the performance of tasks as they are for promoting health and minimizing stress and discomfort during work (Haslegrave, 1994).

Material handling, which constitutes almost half of all construction work, causes problems for workers because the materials and equipment used for construction are heavy and bulky. Handling heavy materials has been mostly eliminated for outside work by cranes and other lifting equipment. Such equipment, however, is not available for all precise work. To satisfy the large glass panel (curtain-wall) manipulating needs of precise work, a Curtain-wall Installation Robot (CIR) has been successfully developed and applied (Lee et al., 2006).

In order to prove the advantages of the new installation method using a CIR, it is compared to the existing installation method (manpower) at a real construction site. By measuring and averaging the time consumed in installing a large glass panel, we can compare the productivity of each installation method. In terms of the safety of the installation methods, however, the quantitative evaluation methods are not yet satisfactory. To obtain qualitative results, we distributed a questionnaire to each large glass panel installer. These questionnaires instructed them to give their opinion of their current large glass panel installation method relating to the degree of labour intensity, environmental risk, and convenience (difficulty of the installation work). It is necessary to expand these criteria for the evaluation of construction robots to include not only productivity but also safety.

Generally, the methods for preventing construction accidents can be classified into two main categories. The first category includes eliminating the causes of accidents and preparing safety plans to prevent similar accidents from occurring by analyzing past statistics and collecting accident data from the same or similar construction fields (e.g. Hinze and Russell, 1995; Hunting et al., 1994; Kisner and Fosbroke, 1994; Snashall, 1990). The second category includes applying safety plans to the design stage by estimating new potential accidents and analyzing the potential causes. We have previously conducted studies estimating the risk grades for each construction building type and developing a safety evaluation method using the first prevention method (Slaughter and Eraso, 1997). This method requires evaluations based on long-term past accident statistics; however, there are restrictions for evaluating the safety of using a prototype construction robot on a real construction site.

In this study, as an example of the second safety evaluation category, we evaluated the current safety conditions by estimating the risk factors based on the risk probability, number of workers, frequency of operations, and estimated maximum loss. This diversified analysis more objectively approaches an improvement in safety by removing or reducing the potential accident-causing factors of construction robots.

First, we selected the risk factors with which we could quantitatively evaluate the safety of CIR construction. Based on the selected factors, we established a potential safety evaluation index. To verify this, we evaluated the safety of each of the manual and robotic large glass panel installation construction methods.

2. Overview of the quantitative safety evaluation

Determining the safety of construction sites requires an evaluation method for a risk index, which can be defined as the 'probability of injury and/or loss of human life and/or materials,' and is generally evaluated based on the degree and occurrence probability of the risk. A quantitative safety evaluation of a construction robot requires a process that can analyze and evaluate the potential risk index at the development stage. After completion of the development, we can obtain the final results of the safety evaluation through the statistical data on accidents derived from the long-term application of the CIR to construction sites.

The comparison of the quantitative risk index of manual constructions to that of robotic constructions most importantly requires the selection of the appropriate evaluation factors. Consequently, we classified the evaluation objects into two categories: the 'worker-related parts' and the non-worker-related 'working environments.' Other items outside of the evaluation objects were estimated under the same conditions to provide objectivity.

Among the evaluation objects, the risk evaluation factor of the 'workers' represents the musculoskeletal load caused by inappropriate working postures. The non-worker-related 'working environments' evaluation factor includes various environmental conditions that may cause work accidents and the amounts of time workers are exposed to these factors. Finally, safety is evaluated by substituting the deduced risk factors into the proposed evaluation equation.

In brief, we suggest a methodology to quantitatively evaluate the safety of a specific working process in a construction site, considering the risk evaluation factors resulting from the labour intensity of the workers and the working environments and the times of exposure to these risk factors for both manual and robotic work.

3. Risk evaluation factors

3.1. Posture load

'Posture load evaluation' is a method of analyzing the posture loads of workers to evaluate their labour intensities. Inappropriate working postures are major elements that increase the frequency of accidents by causing various musculoskeletal issues and decreasing workers' concentration (Bernard, 1997; Kee, 2002; Kilbom, 1994; Putz-Anderson, 1988; Van Wely, 1970; Westgaard and Aaras, 1984). In other words, the minimization of posture discomfort can reduce the risk of musculoskeletal problems and accidents and can further improve construction productivity and quality. According to 2005 data from the Korean Ministry of Labour patients with physical work-related musculoskeletal disorders account for 38.7% (2901 persons) of the total work-related patients (7495 persons).

The observational method was used to evaluate the harmful effects of inappropriate postures and how they may cause musculoskeletal issues with the goal of avoiding the use of expensive equipment and minimizing work obstacles. Typical posture analysis tools include the Ovako Working Analysis System (OWAS; Karhu et al., 1977), Rapid Upper Limb Assessment (RULA; McAtamney and Corlett, 1993), and Rapid Entire Body Assessment