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Automated re-prefabrication system for buildings using robotics

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ABSTRACT

Prefabrication has the advantages of simplicity, speed and economy but has been inflexible to changes in design which is a primary reason behind its limited market share in the construction industry. To tackle this drawback, this study presents a Robotic Prefabrication System (RPS) which employs a new concept called “re-fabrication”: the automatic disassembly of a prefabricated structure and its reconstruction according to a new design. The RPS consists of a software module and a hardware module. First, the software employs the 3D model of a prefabricated structure as input, and returns motor control command output to the hardware. There are two underlying algorithms developed in the software module. First, a novel algorithm automatically compares the old and new models and identifies the components which the two models do not have in common in order to enable disassembly of the original structure and its refabrication into the new design. In addition, an additional novel algorithm computes the optimal refabrication sequence to transform one model into another according to the differences identified. Meanwhile, the hardware module takes the motor control commands as input and executes the appropriate assembly/disassembly operations, and returns the desired refabricated structure in real-time. Validation tests on two lab-scaled prefabricated structures demonstrate that the system successfully generated the desired refabrication sequences and performed all assembly operations with acceptable placement precision.

1. Introduction

In theory, most common construction components can be decomposed to a combination of parts and connectors, such as bricks and cement, wooden slabs and mating joints, or girders and bolts. It follows that most construction activities can be broken down into a series of assembly operations to form larger and larger assemblies from individual parts. Over the last few decades, individual elements, also called prefabricated components, have become popular in the construction industry. Prefabrication is a construction practice which manufactures the majority of building's sub-assemblies ranging from wall panels to complete rooms in a controlled factory environment, before transporting the sub-assemblies to the construction site for assembly [1]. Modular buildings and modular homes, which are recently getting more popular in the construction industry, are a representative example of adopting the concept of prefabrication [2]. Compared to site-cast (or in-situ) construction, precast concrete elements offer faster production, lower cost, and more efficient assembly of elements [3]. For example, it has been reported that replacing in-situ concrete casting panels with prefabricated elements has resulted in a 70% reduction in construction time and a 43% reduction in labour cost [4]. Moreover, the use of precast concrete elements leads to a cleaner and safer construction environment [4,5].

Despite these benefits, off-site construction methods are estimated to comprise only around 10% of the construction market of UK [6]. There are numerous technical, financial and regulatory barriers that contribute to such a slow adoption of prefabrication [7]. While the relative prominence of most of these barriers is still open to debate, there seems to be a general consensus within the industry as stated that *“The main disadvantages of prefabrication are inflexibility to changes in design.”* [5]. This study focuses on tackling the main disadvantage of prefabrication: the inflexibility of prefabrication to changes in design.

Current construction industry practice aims to increase flexibility by mass customization to overcome the shortcoming [8]. This involves the mass production of certain core designs which can later be customized using a catalogue of modules: a plain timber panel, for example, can be switched for a panel with thermal insulation layers and window frame components pre-fitted. This approach requires automation as a prerequisite since any change to the repetition of parts slows down production until the entire process is fully automated, including assembly and not just the making of the parts [2]. The need for an automated and mass-customisable construction process thus motivates developments

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in the field of 'robotic prefabrication'. It was argued that the level of automation in making prefabricated building components using robots in the precast concrete industry is high and this has mainly stemmed from the flexible production system which could execute various tasks such as setting moulds and placing reinforcement bars [9].

Even though mass customization using robotic fabrication has improved flexibility during the design process, design changes such as those arising from inspection failures or changes in customer requirements can no longer be incorporated once the design has been physically built. Flexibility can thus be further improved if it becomes possible to *automatically disassemble a prefabricated structure and reconstruct it according to a new design* - a concept which shall be referred to from here onwards as "refabrication".

Not only will a solution to this problem associated with automation and refabrication help accentuate the benefits of prefabrication over bespoke construction and increase its market share, but also it will boost productivity levels. It was reported that approximately 40% of construction projects experience > 10% change [10]. It was also estimated that productivity will drop below the estimated level for projects with > 20% change, and conversely productivity will increase when change is effectively dealt with and kept below 5% [10]. Based on the statistical productivity estimation in the previous study, development of a solution with the capability of automated refabrication can increase the productivity as changes in design can be addressed in a timely and effective manner. Moreover, this solution will provide positive environmental impact: When subjected to customers´ order changes or inspection failures such as a joint failing under load or a component exceeding tolerance limit, a modification of the original structure is much less wasteful than a complete demolition. In this sense, an automated disassembly and refabrication solution in the prefabrication industry can significantly contribute to the development of sustainable construction which attempts to reuse the components and other resources needed for construction [11].

This study presents a new concept and demonstrates the idea to increase the flexibility of prefabrication through the early development of a refabrication system using robotics. A Robotic Prefabrication System (RPS) that employs a new concept "refabrication" is presented here. The RPS consists of a software module and a hardware module which are detailed in Section 3.

The rest of this paper is organized as follows. Section 2 reviews current state-of-practice and state-of-research into robot-aided construction. The proposed system and its modules are then presented in Section 3. Validation tests are conducted and the results are reported and analysed in Section 4. Finally, conclusions are drawn and recommendations for future work are discussed in Section 5.

2. Related work

It is often argued that the construction industry has the features of a loosely coupled system which favours productivity in projects while innovation suffers [12]. A number of researchers have also argued that the construction industry has failed to adopt techniques that have improved performance in other industries such as just-in-time [13] and 'industrialization' of manufacturing processes [14]. In this regard, the construction industry particularly in the prefabrication sector needs to revolutionize by embracing such advanced automation techniques and systems. This section presents related studies and attempts that have been made so far regarding robotic based automation in the construction industry to identify the needs and gaps in knowledge in the current prefabrication domain.

2.1. Robot-aided automated construction in the building industry

Over the past few decades, automation systems using robot technologies has been less favourably developed and applied in the construction and building industry compared to the industrial and the manufacturing industry because of the dynamic and uncertain environments of the industry [8,15]. In an attempt to automate repetitive construction processes and increase the productivity in construction, several robotic systems such as slab finishing robot system and concrete formwork cleaning robot system, were developed in the 1980s [16,17]. Skibnieswski also conducted the feasibility study on selected construction industry processes in order to examine the possibility of using robots in the future construction industry [16]. During the 1990s, Japanese companies and universities led the R & D activities in the field of robot-aided automated construction and the focus was the development of new robotic systems and the automation of existing machinery [9]. These robots developed for house buildings tried to automate certain construction processes such as layering bricks, constructing building walls and facades [18–21]. However, the 'bubble economy' crisis in Japan had reduced investment in the research area, and only few construction robots had succeeded in the market. As the result of the risk of high initial cost and the unsatisfactory return on investment, construction industry had continued to be conservative in "tomorrow's construction robots" [8].

Regarding the recent development of construction robots for buildings, there are some commercial systems available in the market such as SAM [22], Contour Crafting [23] and Oversize 3D printing systems [24]. SAM is a semi-automated mason robotic bricklayer and has a function of laying about 800 to 1200 bricks a day while a human mason can lay about 300 to 500 bricks a day. This robot, however, still requires a human construction worker to tidy up the mortar and place bricks in difficult area such as corners. Another innovative development named Contour Crafting is a layered fabrication system designed for automating the construction of whole structures. This system, however, has not reached the stage of constructing a complete housing or building with a satisfactory accuracy. D-shape is a large 3D printer that uses a layer-by-layer printing process to create stone-like objects. It is reported that the printer still needs to be further developed in order to make larger and more complex buildings [24].

In addition to the commercial systems mentioned above, several academic studies have been conducted. Choi et al. [25] developed a construction robot using pneumatic actuator and servo motor to support construction workers in mounting window glasses or fixing panels. A cable-robot system called 'SPIDERobot' was also developed to perform assembly operations in on-site architectural construction [26]. Chu et al. [27] presented the development of a robotic beam assembly system consisting of a robotic bolting device that performs the main function for the beam assembly work and a robotic transport mechanism that transports the robotic bolting device to target bolting positions around a building under construction. However, it seems that the recent studies have focused on development of robot systems with the purpose of automating the construction or maintenance tasks, which has limitations in overcoming the inflexibility problem mainly occurred in the design and manufacturing phase of a project.

2.2. Robotic prefabrication in the building industry

Robotic systems have been mainly employed in the prefabrication construction industry for the production of modular and prefabricated housing components such as ceilings, walls and roofs. Bock [17] detailed a robotic precast concrete panel factory that utilizes a multifunctional formwork unit which allows flexible production of concrete floors, walls and roof panels. In this factory, a precast manufacturing system, which integrates CAD with Computer-Aided Manufacturing (CAM), controlled concrete distributor to spread the right amount of concrete by taking into account the geometric position of window or door openings according to CAD layout.

Three primary projects which illustrate the advances and the state of the art of the robotic prefabrication in the building industry are: (1) ROCCO [18], (2) FutureHome [19,20], and (3) ManuBuild [21].

ROCCO [18] features two different robotic systems: one for erection