Towards 3-D Shape Restructuring for Rapid Prototyping of Joining Interface System

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Abstract -

Ready-made building components and joining systems are generally unfit for existing building structures with irregular shapes. Therefore, unplanned and immediate manual work is dominantly practiced as measuring and manufacturing of the customized joining system is not supported. In this respect, by obtaining 3-D shapes of the existing building components and using them for the customization of the joining parts, construction productivity can be improved while minimizing the construction errors. The aim of this research is to develop a joining interface production system that can be adaptively reconfigured for general renovation of building facades. The proposed system can precisely capture the built geometry of the existing infrastructure and in order to manufacture tailored joint components. This approach can not only enhance the assembly process and quality in renovation process, but also minimize the expenditure by preventing additional manual labor. As a pilot test before introducing 3-D Laser scanning for precise measurement, depth images using Kinect infrared (IR) sensors are utilized in order to register the 3-D shape of irregular building components. This geometry is modified and updated by considering the geometry of the joints, which becomes the interface 3-D model between a prefabricated joint part and an irregular pre-existing building component. For the customized fabrication of the interface 3-D model, a mock-up prototyping is tested using a 3-D printer. A 3-D rapid prototyping system using 3-D depth reconstruction is proposed and developed, for the manufacturing of 3-D joint interface components. Interoperability with BIM tools needs to be considered to integrate the design and production steps. At last, this research contributes towards robotic-oriented lean construction methodologies [1], by eliminating drawbacks by providing a CAD/CAM framework that incorporates modularity, design for assembly (DFA) and design for variety (DFV) principles.

Keywords -

IT Applications; 3-D Shape Registration; Joining System; Rapid Prototyping

1 Introduction

As the needs of owners and occupants change, buildings must be frequently renovated, resulting in a significant amount of recurring costs [2]. Among others, design, fabrication and assembly of new building components in building construction processes are the main procedures that greatly influence on the productivity, and therefore also on the feasibility. Thus, developing an efficient method for the rapid manufacturing of new building components for pre-existing buildings is of great importance in order to cope with increasing number of renovation projects worldwide [3]. Ready-made building components and joining systems are generally not compatible with existing building structures that present irregular shapes. Therefore, unplanned and immediate manual work is dominantly practiced as measuring and manufacturing of the customized joining system is not supported. In this respect, by obtaining the 3-D shape of the existing building components and using them for manufacturing customized joining parts, construction productivity can be improved while minimizing the construction errors.

The research purpose is to develop an adaptive joining interface production system that can be reconfigured for general building refurbishment, particularly for building façades. When fully developed, this system can greatly enhance the building assembly process and the building construction quality in building renovation processes.

This paper is structured in the following manner: in section 2, literature review is presented regarding issues of building refurbishment, additive manufacturing, 3-D rapid prototyping, Building Information Modeling (BIM) and reverse engineering. In section 3 the 3-D shape restructuring system architecture is depicted. Section 4 presents the ongoing development of application tool for the proposed system and finally, in section 5 conclusions and further development steps are provided.

2 Literature Review

2.1 Trend of Building Refurbishment

It is anticipated that most of the buildings in EU will be refurbished until 2050. For example, buildings from 1960s are being renovated several times in Germany and the newly built are expected to go through a same step.

According to EU report [24], refurbishment will be the largest portion of building construction sector in many developed countries. In addition, according to the Korean housing market trends, many building renovation processes will be active within several years by the new motivated building law that allows the horizontal and vertical expansion, in order to increase the housing value and to reduce the building owners' financial burden. As the Korean National Assembly will introduce the law which allows vertical expansion remodeling, construction industry shows great interests in the relevant market. According to industry sources, the vertical extension remodeled apartments that were built the last 15 years in the country, amounts to about 430 million households [25].

When considering that the annual supply of housings is around 30 to 40 million households, remodeling with vertical extension is up to 11 times the size of the arithmetic formation of new markets. According to the Housing Act Amendments which was submitted to the Korean National Assembly last June in 2013, vertical extension of apartments that are older than 15 years are allowed up to three floors. However, in the case of apartments lower than 15 floors, expansion up two floors is possible for stability. Allowed number of units through the expansion of households is within a 15% range. Allowed expansion of each household is: area 85 m^2 (only area) is less than the maximum 40%, area over 85 m^2 is 30%. As of the end of September, according to the Korean real-estate portal service, apartments older than 15 years that are allowed to be renovated with vertical expansion, reaches a total of 4,285,130 households. Among them, 46.5% (1,992,626 households) are concentrated in Seoul, Gyeonggi, Incheon, etc. in the National Capital Region. Most buildings that were built the last 30 years, have maintained a relatively good structural soundness, so by replacing old facility with new infrastructures such as Mechanical, Electrical, and Plumbing services (MEP), combined with new structural expansion, the economy of building construction can be revitalized even during the harshness of the economic crisis. As the productivity of the construction area has been decreased, the foremost goal in construction is to maximize the productivity for the Return on Investment (ROI). About 10% of the global population work at the construction area but, the productivity has been decreased continuously. As the birth rate in EU and developed countries such as Japan, Korea is decreasing, it is expected that a shortage of workers will be encountered, and safety issues in construction will comprise one of the major concerns that must be tackled, but without admitting construction innovation, this might end up with being very difficult task. From this view point, it is asserted that new technology can minimize the experienced pitfalls.

Figure 1. Pitfall of current building refurbishment (Photo: S.-K. Lee): Unplanned construction frequently leads to higher budget

2.2 Technical Outlook

To reach the goal in case of building refurbishment, interdisciplinary efforts need to be considered. There are several key technologies that can influence on current building refurbishment projects. First is the surveying system which can capture the existing physical as-built configuration. By using the hardware and the supporting software for dealing with huge data (e.g. Big Data), it is possible to acquire huge data within short time. Conventional imprecise measuring that relies on manual methods will be replaced by new computational methods. Moreover, according to current researches on precise measuring system development that targets at forestry growth tracking, maximum error between actual model and captured data is less than 6 mm within 1 meter distance using consumer level stereovision systems [4] (e.g. Microsoft Kinect or Asus Xtion Live Pro). That can enable early design fixation during the whole design stage and as a result, more flexible decision making, such as new production method adaptation. Second is the advancement of Additive Manufacturing (AM) technology which is commonly known as 3D rapid prototyping. Still, 1:1 scale building production is limited as can be seen from the examples of 3D-Shape and Contour Crafting by the USC [5]. By inventing new construction materials and optimization algorithms for production, production for building component can be quite flexible enough to resolve building constraints, and satisfy dwellers' unique and diverse needs. Third is the development of BIM applications in AEC/FM. Decade year's long effort by IAI alliances to make information sharing tools among stakeholders promotes interoperable BIM software development, which will transform construction industry to that of production industries. Open API that is supported by BIM software vendors also can help third party developers program advanced software modules for the specialized information process service (e.g. MagiCAD™ supports MEP design in Revit).

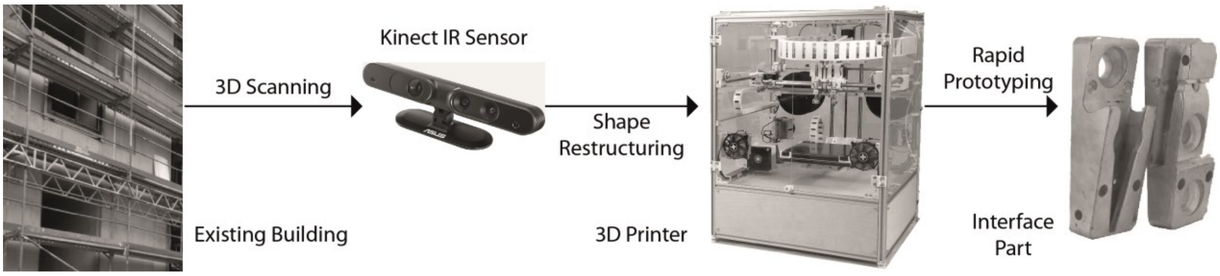

Figure 2. Building refurbishment research process framework

Originally actively developed in Japan for construction automation, specialized assembly robots have been developed worldwide to enhance the constructability by alternating dangerous manual construction works onsite. Effects from this application in construction are not only the improvement of productivity, but also fatal construction accidents can be significantly reduced. For new construction project (e.g. Dubai' Burj Khalifa), for example, factory-like construction equipment is mounted on top of the building to function as onsite construction bed. This kind of construction factory is advantageous in that the working condition is seldom influenced by natural environment, and automated hoisting and moving devices can speed up the whole construction process. However, still the robotics-assisted assembly strategy for the building refurbishment for better assemble-ability did not receive much attention and hoisting vehicles have been planned and operated by human workers nearby.

In addition, as the building façade system has developed to integrate energy control system by combining diverse systems, which change the static building façade system into the active system that interacts with environmental entities, onsite joining and interfacing works will be a challenging issue that otherwise hinders the productivity improvement. As a preliminary research for combining those technics that are mentioned above for building refurbishment, a preliminary research on rapid manufacturing method for joining interface will be introduced in this article as conceptually represented in Figure 2.

2.3 Reverse Engineering

Scanning technology using Lasers beam leads to the development of reverse engineering in the construction engineering industry [6]. Reverse engineering generally utters the process of discovering the technical principal of devices and systems, as opposed to the concept of designing. Originally used for the analysis of military and commercial hardware, reverse engineering aims at reasoning design decision making process without prior knowledge of the production process of the original product [7] or only with partial knowledge of the product. While the designing of target objects precedes the production of the objects in general engineering, reverse engineering extracts shape feature information from existing objects. In particular, reverse engineering in the construction industry means the process of extracting shape information from constructed building objects, and utilizes it for additional design changes and production-related activities, etc. [8]. There are active researches to gather information of pre-constructed buildings, bridges, and tunnels for various purposes during their life cycle. Point-cloud data from a 3-D Laser scanner (3-D point cloud) is converted to various CAD representational models, such as B-rep, Constructive Solid Geometry, tessellated surface model, and so on; and the models are utilized for various engineering tasks such as benchmarking, quality control, and advanced drawing information management [9]. But reverse engineering is relatively in its inchoate stage in the construction industry, and is generally restricted to the acquisition of drawings of as-built building structures when there is no drawing information such as in case of historic buildings. Nowadays, for quality control in construction processes, decision making based on numeric analysis by comparing CAD data and 3-D scanned data is necessary. In these applications of reverse engineering, it is challenging to enhance the level of precision of the obtained 3-D shape information as shown in Figure 3.

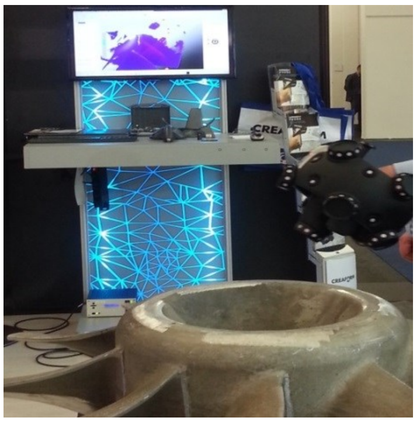

Figure 3. Real-time 3D shape restricting demo (Photo: S.-K. Lee)

2.4 Applications of BIM

The preparation of 3-D parametric building models, which is based on the survey data that serves the design, prefabrication and installation processes, has been the focus of a few studies [10]. As mentioned before, the analysis of the survey data and its conversion into a BIM model is still a major challenge. An additional challenge is how to include non-geometric information in the model as object attributes. Such information can be of importance for the construction processes (information on structural elements onto which the new elements can be mounted, thermal bridges that require additional insulation, damaged elements that need repairs, etc.). In [11, 12], methods for the documenting data on damaged elements in the IFC format are suggested. Basis for all refurbishment activities is always an exact knowledge of the quality and condition of the building fabric. The aim should be to capture all necessary information during the survey in a uniform Building Information Model (BIM) as basis for all further services and activities.

3 3D Shape Restructuring System

3.1 System Architecture

As a basic study for the proposed joining system for building refurbishment, the authors suggested stepwise research models:

1. Scan-planning the work process for building refurbishment
2. Scanning the target building objects using depth images
3. Post processing the acquired data
4. Merging the files using ICP (Iterative Closest Points)
5. Exporting CAD file (.stl file)
6. CAD Modeling and modifying in BIM authoring tool
7. Automatic joint modeling using Add-on Design module
8. Converting the modeled file to STL file for Additive Manufacturing
9. 3D printing
10. Assembly test for verification

3.2 3D Shape Restructuring Algorithm

Infrared sensors such as MS Kinect^{TM} and Asus Xtion Live^{TM} [4] brought low-cost and commercial application quality for depth sensing. These 3-D depth sensors extract a depth image by emitting a structured pattern of light and by measuring the pattern deformation that is transformed by objects in the optical scene. Experimental results show that the random error of depth measurement increases with increasing distance to the sensor, and ranges from a few millimeters up to about 4 cm at the maximum range of the sensor [4]. OpenNI library is used to get the depth map images from the Asus Xtion Live device.

Patterned IR rays are emitted from the IR emitter and the reflected images are sequentially gathered by IR receiver. Maximum spatial resolution of each captured frame is 640x480 pixels, and each pixel value of the IR image represents the distance between the device lens and the reflected object. To convert the depth map image to the actual feature dimension, simple triangulation equation is used to project to the real world. The translated point clouds are converted to STL files from the developed software module and each file is merged using Meshlab software. In [13], a system for accurate real-time mapping of indoor scenes in variable lighting conditions is proposed. The idea is to use a single moving depth camera. They fused all of the depth data that are streamed from the sensor into a single global implicit surface model of the observed scene in real-time. The current sensor pose is obtained by tracking the live depth frame relative to the global model using a coarse-to-fine iterative closest point algorithm (See: http://msdn.microsoft.com/en-us/library/dn188670.aspx). This method is full automation method which use tracking outliers, but in case for building shape registration, only using camera movement can generate a certain level of preciseness for construction.

3.3 Interface design

One of the most important aspects to lead to the automated construction system is developing automatic assembly system using multi-purpose connectors. Currently common fixation technology (bolting, welding), which is time consuming, even when automated, is similar to the automotive industry in terms of adhesive bonding technology. The development of a connector system that connects complex components in a robust way to each other is a key point in complex products such as cars, aircrafts and buildings in particular. In order to support efficient assembly, connector systems need to, for example, be compliant or plug-and-play like.

In construction, the most promising potential for reducing cost is based on reaching a maximum degree of prefabrication by integrating different crafts. And this could considerably reduce the time necessary for interior finishing and completion. Connecting elements have to be examined with regard to positioning, adjustment, and fixation. Transition to automated manufacturing processes should be implemented in current processes of predominant manual installation and assembly, meaning in the fields of mechanical services and interior finishing [14]. In [15], several assembly connectors for the assembly of the modules were developed, considering the structural connection, and electrical and service pipes connections. These connectors ensure automatic performance of complete assembly between modules.

Connector systems can also be designed to support efficient disassembly, re-manufacturing or recycling. In current construction practice, neither real modularity nor applications of connectors that allow for simplified and fast connection are common practice. To structure the on-site environment and reduce complexity on-site (e.g. through the number of assembly operations, or kinematic complexity) an OEM-like industry structure, shifting the creation of components, modules and units to internal and external company suppliers and integrating the principles of Robot Oriented Design (ROD) has to accompany the introduction of Automated/Robotic On-site Factories [16]. Adjusting and fixation processes during on-site assembly have to be reduced to a few minutes or to near zero for each module installation process by connectors in order to approach the high operational speeds of the automated positioning equipment. The developed connectors enable functionality of assembling prefabricated modules themselves, connecting structurally and electrically, and connecting diverse services such as plumbing, ventilation, etc.

The state of research includes prefabricated panels are mainly used as façade cladding or lost formwork [17]. Several concrete molding technologies exist; The two most widely used ones are a densely packed array of pins that are leveled by a flexible top layer [18] and the combination of wider spaced actuators with an interpolating sheet material layer that is bent into shape [19]. Recently, completely waste-free fabrication method of formwork for free-form, cast-on-site, non-repetitive concrete structures using wax formwork elements is introduced in [20], but the research is far from a fully automated robotic molding process.

From the micro-level viewpoint, a casting method using RP (e.g. Fused Deposition Modeling) was tested, and proven efficient in case of intricate and complicated pattern designs which cannot be made by a pattern maker in wood or metal [21]. So the development directions are as follows: a) to develop connector systems that robustly connect not only information or simple elements (such as cables, storage systems, etc. in computers), but also physically complex shaped, and sometimes heavy or bulky components to each other, b) to develop standardized interface and connector systems in construction in order to modularize the infill of buildings (different types of connectors should also be used - standardization of connectors will make disassembly quicker and require fewer types of tools), and c) to develop open component system kits which have the ability to be further developed and transformed into new product models or product lines.

3.4 Rapid Prototyping using 3D printer

Laborious formwork can be removed by direct application of additive manufacturing (AM), which can save about 50% of the total concrete work cost [22]. Additional mold parts for metal connectors and elements are needed in order to assemble prefabricated building components to the existing building façade. Additive Manufacturing (AM) can maximize the reuse of the materials by recycling the raw material up to 95%. In principle, in powder-based rapid prototyping techniques, powder compaction is used to create thin layers of fine powder that are locally bonded. An object is made by stacking these layers of locally bonded material, but stiffness for structural building components from powder-based rapid prototyping techniques needs to be tested in a hybrid way such as rapid molding for casting. The objective of the proposed work is to introduce a revolution in on-site construction industry, from mass-production manufacturing to tailor-made manufacturing in which products are manufactured adaptively. For that, Rapid Prototyping (RP) method was used for making molding forms for casting a product or building components. The development directions are as follows: a) a new type of a digitally controllable flexible mold for building element casting, b) minimization of manual work and therefore, errors for high production and assembly quality, c) an economically viable variable formwork process owing to rapid molding time scheduling, low manual work, and low formwork material cost, d) a sustainable onsite building component production process cycle via maximized raw material reuse, e) Optimized onsite Just-in-Time (JIT) production process for enhanced workability by considering work breakdown structure (WBS).

4 Tool Development

Figure 4 depicts the process diagram of building refurbishment project. The old building is scanned using both 3D Laser scanner, for high quality building shape registration, and low-end Kinect depth map sensor for acquiring shapes for interface and joining parts. This CAD information is post-processed via the BIM tool and is quickly measured and verified via 3D rapid prototyping before final module fabrication. Remaining processes such as robotic assembly, logistics via tracking technology, will be combined.

Figure 5 shows an example of multi-service integrated joining system, which function can be alternated flexibly and by introducing structurally sound material such as steel, which can perform as a structural interlocking system between building elements. Figure 6 is an image of connector parts shape registration using Asus Xtion Pro Live.

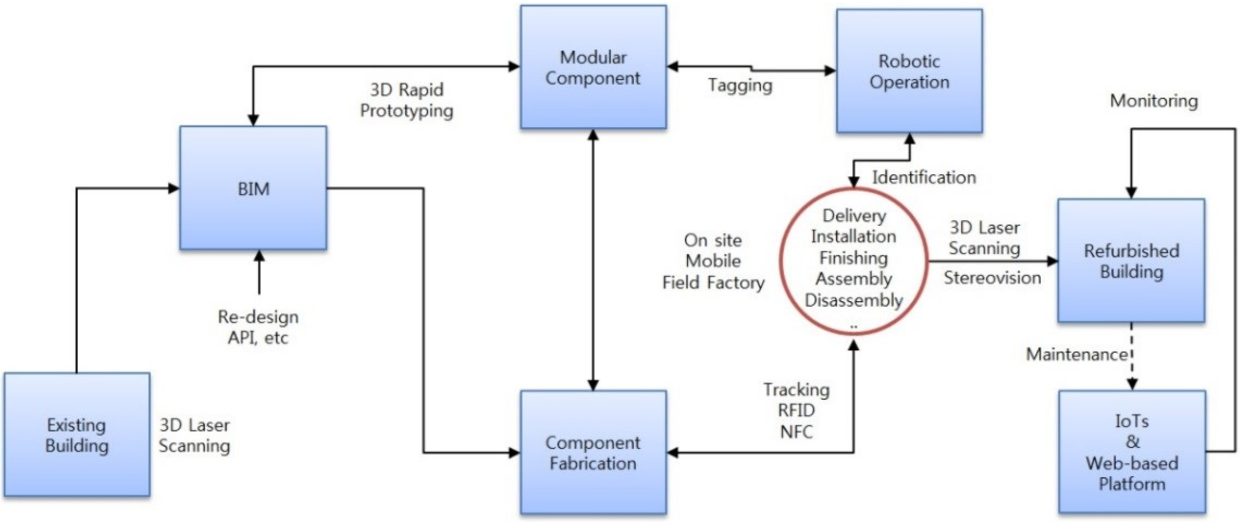

Figure 4. Building refurbishment process framework

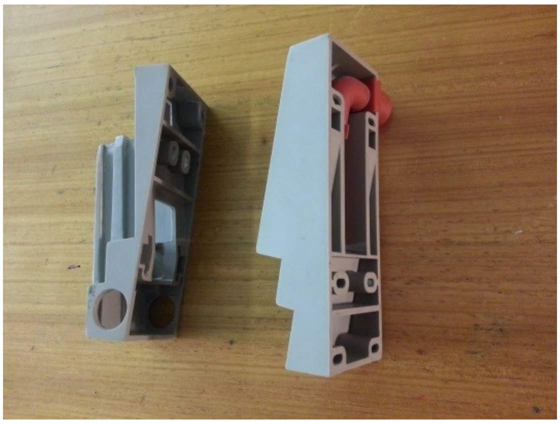

Figure 5. A sample model of multi-service oriented connector and joining system

Figure 6. 3D connector shape registration using depthmap of Xtion Pro Live

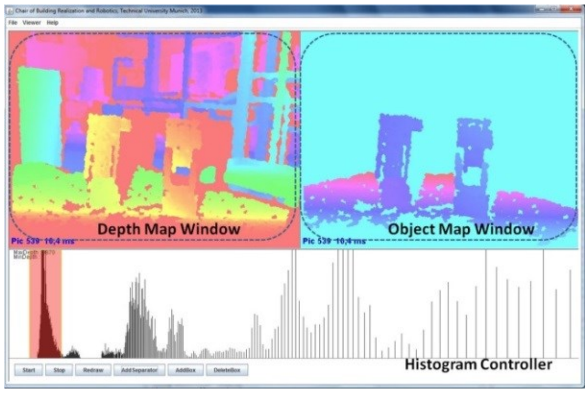

Figure 7. Captured image of software module interface

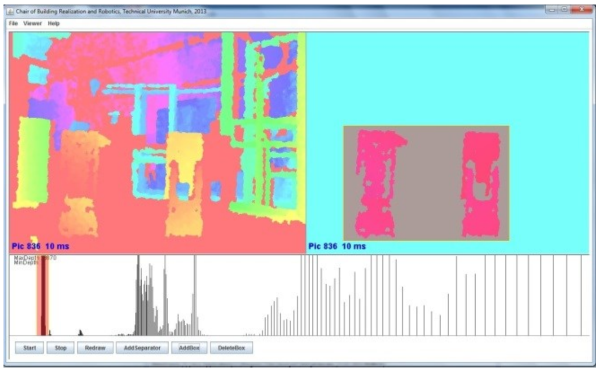

Figure 8. Connector 3D shape registration process

This process will be upgraded by attaching precise motion actuator that can rotate and translate regularly in order to register point clouds for better performance. Figure 7 is an independently developed software interface that can control image streaming software by histogram distribution calculation. The closest point clouds can be sorted based on density and proximity levelness. The point clouds data can be exported as an excel style sheet data (e.g. excel) or Stereo lithography file (.stl) for other post processing such as data merging for better quality control using third party software.

Users can manually modify the focus area if necessary by adding a bounding box in "Object Map Window" as shown in Figure 8.

5 Conclusions and further development

This article's purpose is to describe the preliminary research direction for the building refurbishment project using advanced technology such as reverse engineering, BIM, customized component production and robotics assembly. Judging from each technology level, added value can significantly influence on the productivity of building construction, safety improvement. Next research will be how to integrate those ideas for better performance and optimization. At the end, this study can contribute to the tool development for building refurbishment by combing design for manufacturing and design for assembly. When fully matured, this approach can allow cost-effective principle to work while permitting individual adaptation without increasing cost.

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