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An interactive augmented reality tool for constructing free-form modular surfaces

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ABSTRACT

Although modern software has paved the way for architects to design complex forms, such as free-forms, construction remains challenging, costly, and time-consuming which requires skilled workers. Advanced digital fabrication technologies can offer new ways to fill the gap between design and construction. Augmented Reality (AR) technology is one such technology that has many potentials in various fields, however, its capabilities are not sufficiently explored yet, especially in the field of digital fabrication. This study presents a new affordable interactive multi-marker augmented reality tool for constructing free-form modular surfaces implemented by integrating common accessible devices. The proposed tool consists of two digital cameras, a head-mounted display, a processor, and two markers that enable the user to virtually see the accurate location of any proposed object in the real world. A controlling subsystem was also designed to enhance the accuracy of construction. Method efficiency was studied in five full-scale prototypes. The results showed that the majority of errors (91%) were less than 6 mm, and 2° for lateral placements and orientation errors.

1. Introduction

In the last two decades, the development of digital technology has remarkably affected the nature of architectural design processes. Today, architects and students design many complex forms by using software programs such as Rhino (and its plugin Grasshopper), Autodesk 3DMax, and etc. that require new fabrication techniques for construction. Therefore, Computer Aided Design and Computer Aided Manufacturing (CAD/CAM) technologies are introduced to fundamentally redefine the relation between design and production [35]. Elimination of many technical constraints induced by traditional construction methods has created new opportunities for architects to solve problems in both design and construction of complex forms [27]. Digital fabrication techniques which are defined as the process of constructing objects determined by a digital tool path through the use of computer-controlled machines [16], have provided the ability to design and construct free-form surfaces that are very expensive or difficult to construct using traditional fabrication methods [51].

There are various digital fabrication techniques classified into four main groups in architecture based on their distinctive features [27], including 2D fabrication [26,36], subtractive fabrication [51], additive fabrication [27], and formative fabrication [54]. Along with these groups, the introduction of industrial robots in design and construction has provided new capabilities for architects to remove many constraints in creating free-forms [22,30]. A number of architects have recently tried to develop novel methods of using digital techniques and tools in design and construction of free-form modular surfaces. Pritschow et al. presented an on-site method for automated masonry construction by means of a mobile robot [46]. Gramazio and Kohler proposed a new method for constructing parametric brick walls by utilizing a programmed industrial robotic arm [17], and Augugliaro et al. developed a new field of fabrication called Aerial Robotic Construction (ARC) [2], where flying robots were used to assemble free-forms. Keating et al. introduced a portable digital construction platform for constructing complex structures on-site [23]. Sass et al. investigated digital fabrication methods for designing and assembling plywood complex form at MIT digital design fabrication group [52].

Most of the above mentioned methods and their likes have some limitations in terms of complexity, cost, level of prior knowledge or skill, etc. [68]. Therefore, constructing complex forms remains unachievable for many architects involved in small or medium scale projects due to such limitations. Although some researchers have proposed low-tech tools for construction of complex modular walls [68], their methods are based on using physical blueprints or molds that are not suitable for constructing a real free-form surface. In fact, in these forms, each module has a specific position and orientation in space, so

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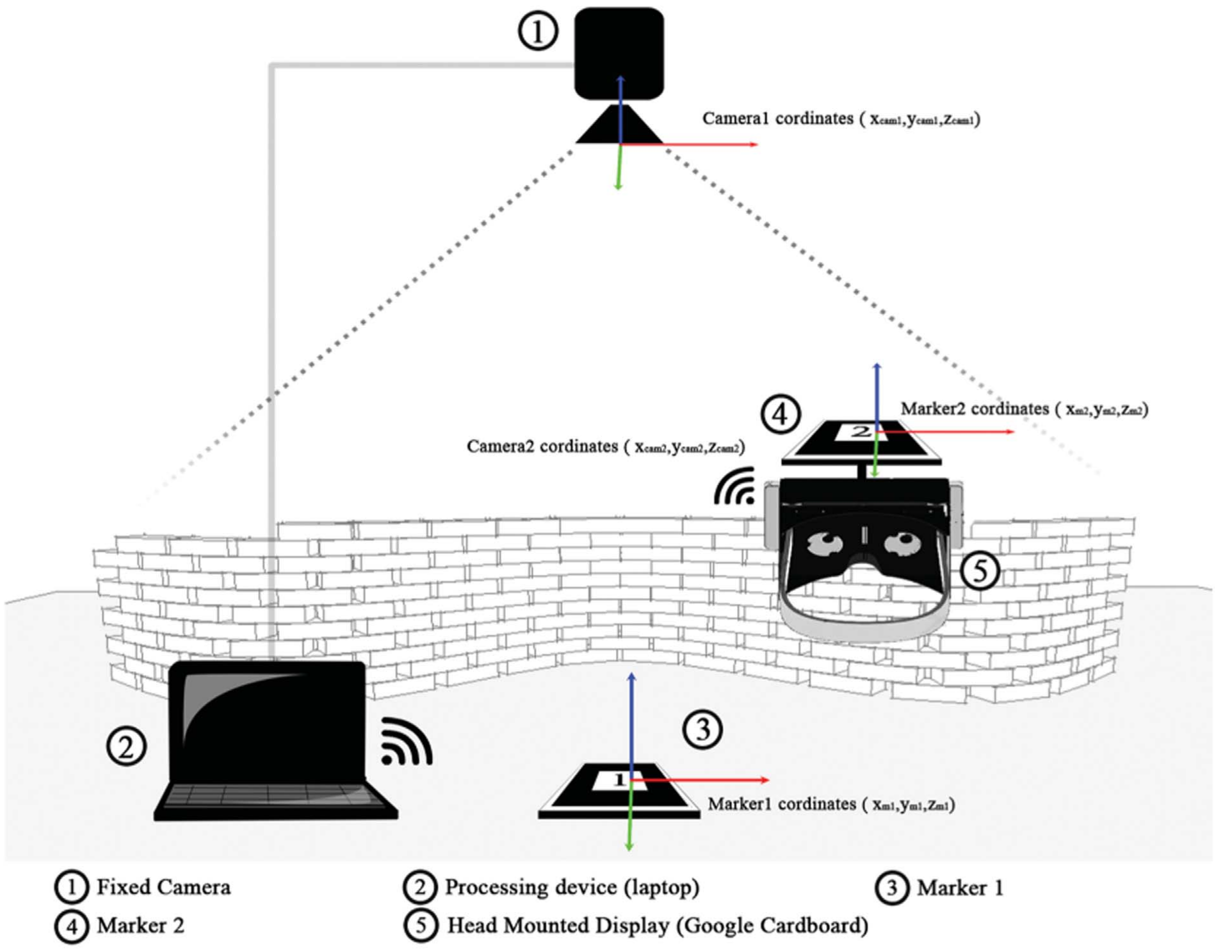

Fig. 1. Components of the proposed digital fabrication method based on multi-marker AR. The virtual guidelines are augmented into the visualization device through WiFi.

there is almost no chance to build complex free-form modular surfaces with reasonable costs by using physical blueprints or molds. This study attempts to present a new low-cost method for constructing free-form modular surfaces based on multi-marker augmented reality technique enables us to construct complex forms by the means of a limited number of commonly accessible devices and software. Obviously, reducing manufacturing costs can encourage architects to use digital fabrication techniques more widely in constructing common buildings. In the following section, a brief description of the augmented reality systems based on their applications is presented.

1.1. Augmented reality

Augmented Reality (AR) is the line between the virtual and real world that enhances the real world by overlaying additional virtual information [3,15]. It usually appears in conjunction with the term Virtual Reality (VR) that can simulate the whole world in a computer [67]. In fact, AR is a place on a continuum of interfaces, spanning from real environment at one side to virtual environment at the other side, as defined by Milgram and Kishino [34]. The tendency for using AR tools in practical applications including design [6], construction [5,19,53,70], manufacturing [40–42,48], entertainment [11,45,58], and education [10,12,20,24], delivers a better quality of life.

Architecture is one of the application domains for AR, especially in design and planning. A noticeable body of research exists on the boundless applications of AR technologies in architecture. Chi et al. presented a review on AR applications in architecture, engineering, and construction [9], and a detailed literature review of AR in architecture was done by Wang [61]. In addition, numerous studies were conducted in this field that can generally be classified into four groups or phases [1]: design [8,39,66], construction [32,33,63], post-completion [64,69], and education [50]. In the design phase, AR applications are used for visualization. This allows architects to interact with virtual spatial data and features of a proposed design in its final context [57]. In the construction phase, AR applications can overlay Building Information Modeling (BIM) data information directly on the construction site to aid constructors through the assembly procedure [39,62]. In the post-completion phase, AR can be used as an application for intricate maintenance procedures, and repair tasks on buildings [64]. And finally, in education, AR applications can be used for educational purposes by designing mobile learning media (m-learning) in the field of architecture and building construction [13]. Despite all these attempts in the field of AR, only a few studies were conducted on the application of AR capabilities in digital fabrication area, especially in constructing free-form modular surfaces.

2. Research goals and method

The aim of this study is to offer a new practical and affordable ways to construct free-form modular surfaces. To build a free-form surface with modular elements such as a brick, we need a construction plan that determines the specific position and rotation of the modules in space. This plan can be prepared manually (e.g. traditional draftsmanship) or can be developed digitally by the means of an industrial robot. However, both of these methods have some limitations. In the case of traditional methods, there is almost no chance to build complex forms with justifiable cost, because each element has a specific position and orientation in space. Industrial robots have the ability to position each