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INTERACTIVE CONSTRUCTION OF AUGMENTED REALITY-BASED SPATIAL AND GEOMETRIC INFORMATION FOR THE VISUALIZATION OF DESIGN AND ANALYSIS RESULTS

Minseok Kim[1], Jae Yeol Lee[1,*], Dong Woo Seo[2] and Jae Sung Kim[2]

[1]Department of Industrial Engineering
Chonnam National University
77 Yongbong-ro, Buk-gu, Gwangju 61186, Korea
kimminseok109@gmail.com; *Corresponding author: jaeyeol@jnu.ac.kr

[2]Supercomputing Modeling & Simulation Center
Korea Institute of Science and Technology Information (KISTI)
245 Daehak-ro, Yuseong-gu, Daejeon 34141, Korea
{ seodongwoo; jaesungkim }@kisti.re.kr

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Abstract. *Augmented reality has been widely used in many applications such as entertainment, engineering design & analysis, and visualization. However, most of the previous research works focused on fiducial marker-based augmentation, which limits the spatial augmentation of design and analysis models into the physical environment. This paper proposes a new approach to interactively extracting augmented reality-based spatial and geometric information for the visualization of design and analysis results using a smart device with an RGB-D camera. The proposed method scans the physical environment with the camera, learns the 3D spatial area by visual key feature identification, and then extracts 3D point clouds for constructing geometric 3D space and geometric models corresponding to physical objects. In addition, it provides a user-centric interaction method for augmenting 3D virtual objects into the physical environment and visualizing related analysis information.*

Keywords: Augmented reality, 3D scanning, Geometric space construction, Design and analysis review

1. **Introduction.** Recently, augmented reality (AR) has been popular to be applied to various kinds of industries such as game, design and analysis, smart factory, and medical training. The reason is that AR enhances the virtual information by augmenting it to the actual reality compared with virtual reality (VR) [1]. Thus, it is expected that the market size becomes larger because AR can increase the efficiency and productivity in many industrial sectors. Especially, in the early stage of product development, various types of product design should be evaluated, and thus their analysis and testing are essential. In particular, modeling and simulation such as structural analysis (SA) and computational fluid dynamics (CFD) should be performed to evaluate the product design during the product development stage. In order to do this, physical environment and virtual design models are required for the analysis such as CFD. Thereafter, the product can be reviewed through interpreted results, and it can be modified repeatedly. In particular, in this process, stakeholders should be able to understand the design and analysis models more easily and accurately for collaboration purpose.

VR can also be used effectively for this purpose, but it is impossible to match virtual design and analysis models with the actual physical environment. Therefore, the use of AR has attracted much attention. In particular, AR can be used more effectively for design evaluation and analysis if virtual objects can be naturally augmented in a real space [2-4]. However, there is a lack of research on how to spatially reinforce virtual objects in the real space and to naturally support immersion and presence. Furthermore, current AR applications mainly focused on augmenting virtual AR objects using fiducial markers, which limits the spatial augmentation of AR data into the real design and analysis environment [2,4]. In other words, the augmentation into actual reality is 3D plane-based not 3D space based. This can reduce the realism and cognitive understanding.

This paper proposes a new approach to extracting augmented reality-based spatial and geometric information for the analysis of design models and their reviews such as CFD and SA using a smart device with an RGB-D camera. It supports 3D area learning and geometric spatial construction of the physical space and physical objects. The proposed method scans the physical space with the camera, learns the 3D spatial area by visual key feature identification, and then extracts 3D point clouds for constructing a geometric 3D space. Furthermore, the user can select points, draw lines, sketch arbitrary polygonal shape, and/or construct 3D geometric shape or space. Therefore, it is possible to more intuitively and naturally augment various kinds of design and analysis information into the physical environment without conventional fiducial markers. This paper is organized as follows. Section 2 reviews related work, and Section 3 overviews the proposed approach. Section 4 presents how to extract spatial and geometric information for design and analysis review in the physical space, and shows some implementation results. In Section 5, conclusions and future research directions are presented.

2. **Related Work.** Several research works have been actively conducted to measure and utilize spatial shape information in a real environment. In particular, they tried to construct a 3D map of the real environment or to scan real objects as virtual 3D objects using RGB data as well as depth data through an RGB-D camera.

Endres et al. [5] studied a research to construct a 3D map for the real environment by using an RGB-D camera (Kinect). Visual key points are extracted from RGB images, and then visual key points are mapped into the 3D space using depth information. Dryanovski et al. [6] suggested how to construct a combined 3D model that integrated key features acquired with an RGB-D camera while the user freely moved in a specific space. Whelan et al. [7] proposed a method to integrate the Kintinuous pipeline into the existing dense RGB-D based visual odometry algorithm [8] to construct a 3D space according to the movement of the RGB-D camera.

In addition to the construction of 3D real spaces, there were several research works for constructing 3D models by scanning physical objects. Rock et al. [9] presented a method for recovering a complete 3D model from a depth image of a physical object. They took an exemplar-based approach that retrieved similar objects in a database of 3D models using view-based matching and transferred the symmetries and surfaces from retrieved models. Geiger and Wang [10] suggested an approach to inferring 3D objects and the layout of indoor scenes from a single RGB-D image captured with a Kinect camera. They proposed a high-order graphical model and jointly reasoned about the layout, objects and superpixels in the image. Firman et al. [11] presented a method to build a complete 3D model of a scene, given only a single depth image. They proposed an algorithm that could complete the unobserved geometry of tabletop-sized objects based on a supervised model that trained already available volumetric elements. Kwon et al. [12] generated a high resolution 3D object using a commercial DSLR camera and the low depth information of Kinect. Tanskanen et al. [13] proposed a complete on-device 3D construction pipeline for mobile monocular hand-held devices, which generated dense 3D models with absolute scale on-site while simultaneously supplying the user with real-time interactive feedback.

Although existing research works mainly utilized RGB-D cameras, the positions of the devices were mainly fixed or limited in order to obtain the spatial and geometric shape information of the real environment. Even if the spatial and geometric information was acquired, the results were only 3D meshes based on 3D point clouds. However, those

3D models cannot be directly used in design analysis and review since it is necessary to reconstruct the real environment and physical objects as simple as possible. In addition, the constructed 3D models might be incomplete due to the occlusion and complexity of the physical models. Furthermore, there is few research work that can support spatial and geometric information extraction for visualizing and reviewing design and analysis results in the physical environment. In this paper, we propose an interactive method to simplify the 3D model generation using a smart device with an RGB-D camera. This research takes two steps: 1) boundary construction and 2) 3D shape simplification. The surrounding boundary space is easily constructed by interactive scanning and touching operations. The 3D map or 3D model of the physical object is represented by the enclosing geometric shape or interactively sketched shape.

3. **Proposed Approach.** The proposed approach aims to propose an innovative methodology for 3D area learning and spatial boundary & geometric object construction from 3D point clouds for the spatial augmentation of design & analysis results in the physical space as shown in Figure 1. The AR-based visualization of design & analysis models in the real environment can provide a higher level of immersion for users and help them to understand design & analysis models more quickly. In order to visualize the design & analysis models in the real environment, it is necessary to acquire not only spatial information of the actual surrounding environment but also information about physical objects. For example, to augment a virtual product such as a humidifier on a table in a real environment, 3D spatial information (position, orientation, etc.) of the table must be scanned and simplified as an analysis model. In addition, the spatial boundary of the real environment is also needed to provide information on the fluid analysis of the humidifier.

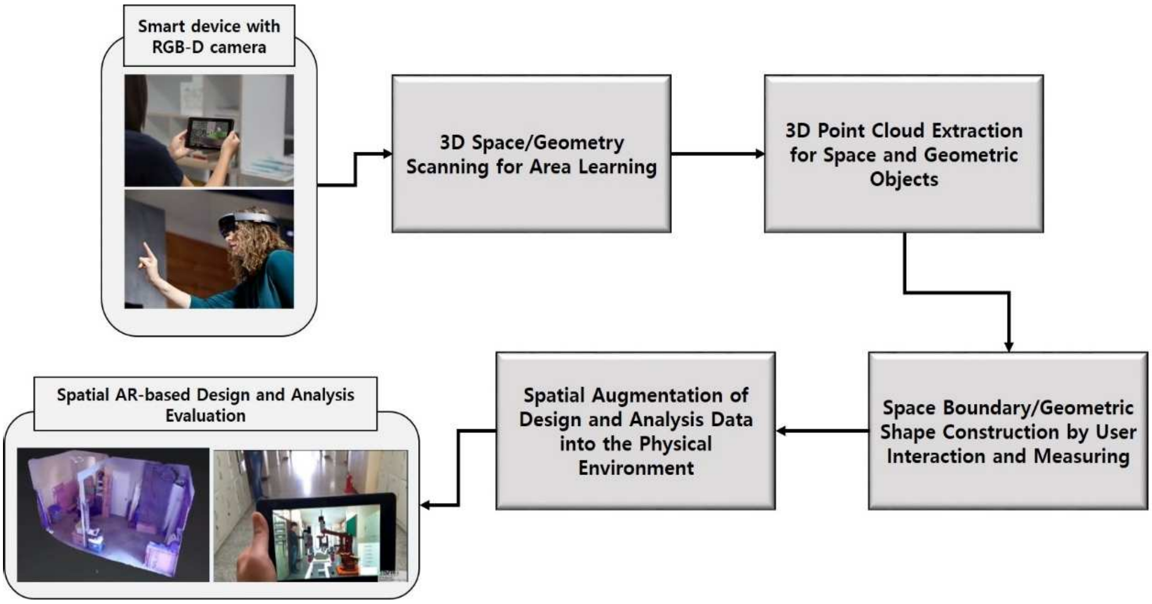


Figure 1. System overview of the proposed approach

In this paper, we use a mobile device with an RGB-D camera to acquire spatial and geometric shape information. In addition, the user can move freely in a wide physical environment and can acquire necessary information for design analysis and review in various locations. Spatial boundaries and geometric objects can be constructed using the touch interface of the mobile device during the scanning of the physical environment. Spatial boundaries such as box shape in the office are limits for enclosing the actual environment such as walls, floors, and ceilings to constrain the design & analysis model and to visualize analysis results within the enclosed boundary for CFD. A simplified geometric object is a polygonal shape of a real object for the spatial augmentation of the design & analysis result.

To support the spatial augmentation, the user first scans the physical space with a smart device with an RGB-D camera [5]. During the scanning, the method extracts visual key features for area learning, which are used to locate design and analysis objects into specified areas. Then, it constructs the spatial boundary of the physical environment such as walls by user's pointing and selecting 3D point clouds of the scanned area. In addition, the user can interactively measure and draw polygonal shape to construct 3D geometric objects. Alternatively, the system can automatically reconstruct simple geometric shape such as cylinder, sphere, and plane by estimating 3D point clouds [9]. Finally, the user can spatially augment design & analysis models into the physical environment and evaluate them more naturally and effectively.

4. **Interactive Construction of AR-Based Spatial and Geometric Information.** One of the main characteristics of the proposed approach is to seamlessly integrate the AR space with the physical space without fiducial markers. Instead, the proposed approach scans the 3D space and performs area learning by extracting visual key features. To evaluate design & analysis results in the physical space, we also measure spatial boundaries and geometrically estimate physical objects that affect the evaluation as shown in Figure 2. This can provide a more viable way of scanning 3D point clouds and extract geometric shape information since it is impossible to automatically extract complex geometric shapes from 3D point clouds.

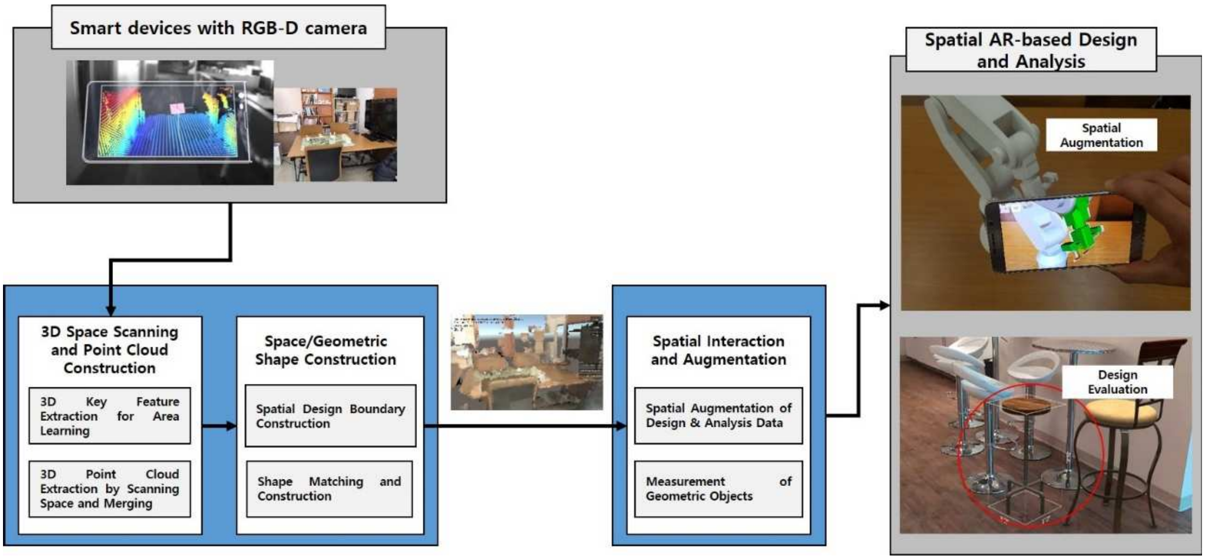


FIGURE 2. Extraction of spatial and geometric shape

To effectively support 3D scanning and area learning, in this research, a Tango$^{\mathrm{TM}}$ device has been utilized since it is a smart device with an RGB-D camera [14]. The spatial augmentation into the physical space can be done by three components such as motion tracking, area learning, and depth perception of the device as shown in Figure 3. The motion tracking allows the device to understand its motion such as translation and rotation of the device as it moves through the physical area. With the motion tracking alone, the device retains no memory of what it sees. The area learning gives the device the ability to see and memorize the key visual features of an actual space – edges, corners, and other unique features so that it can recognize that area again later [14]. In other words, it stores a mathematical description of the visual features it has identified in the physical space. This allows the device to quickly match what it currently sees against

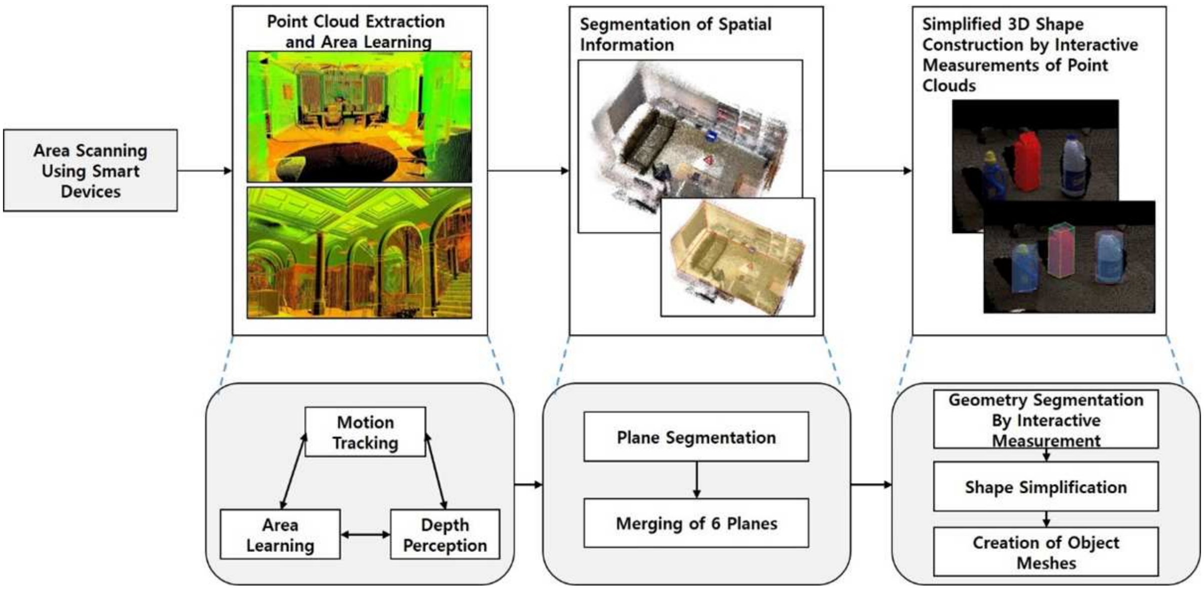
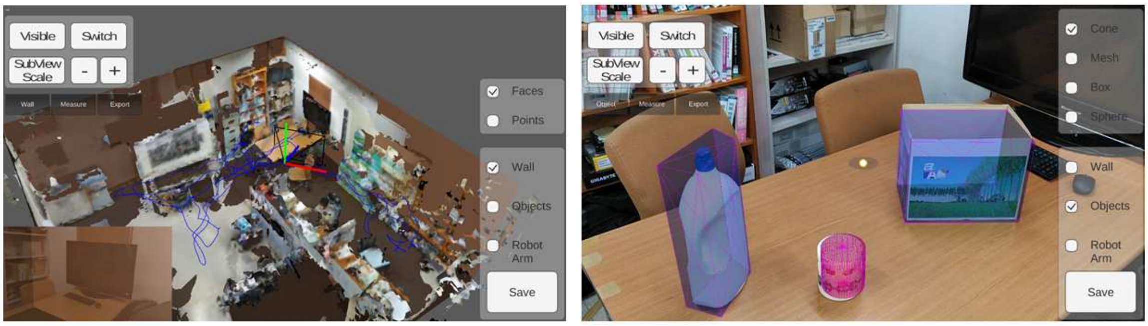


Figure 3. Geometric segmentation and simplification



(a) (b)

Figure 4. A conceptual scheme for boundary and geometric shape construction by interactive measurement

what it has memorized before. The depth perception finds and understands the distance to physical objects in the real world with an RGB-D camera.

To evaluate design & analysis models such as CFD and SA, we need to define the spatial boundary and to extract geometric shape from physical objects. Based on the area learning and scanned 3D point clouds, the user can interactively segment the boundaries of the physical space such as walls, floor and ceiling as shown in Figure 3 (middle in the figure). In addition, the user can select a set of 3D point clouds and requests to calculate a simplified geometric shape to cover the point set (right in the figure). Furthermore, the system can suggest a simplified bounding geometric shape that covers 3D triangular meshes for later analysis. Figure 4 shows how to construct an enclosing space from the spatial boundaries calculated from walls, ceiling and floor (Figure 4(a)), and simplified bounding geometric shape of 3D point clouds (Figure 4(b)).

In order to create the enclosing space from spatial boundaries, plane information and 3D coordinates of a point where each plane is in contact with corresponding to a wall, a floor, and a ceiling are required. To make this process simple and intuitive, the user touches the plane corresponding to the wall, floor, and ceiling through the mobile device. This allows the system to obtain each of the spatial boundaries. Finally, we can construct the topology of the enclosing space by calculating intersection points of adjacent three planes corresponding to spatial boundaries or calculating intersection points of lines lying on the spatial boundary of the floor and sweeping the polygon consisting of the intersection points into the ceiling. A geometric shape corresponding to 3D point clouds of the physical object depends on the mapping geometry. In case of a hexahedron, height information is needed together with four vertices, and in the case of a cylinder, the center coordinates, radius, and height information of the cylinder are required.

When this process ends, all the necessary spatial information of the actual space can be extracted in a natural and easy way. Finally, the design & analysis models should be spatially superimposed into the physical environment through interactive and natural user interaction. When the design model or structural analysis model is augmented, the user can freely move around the specified area with the device and review the results. When interaction behavior is attached to design or analysis models, the user can touch the screen to interact with the design & analysis models. On the other hand, when additional analysis such as CFD is needed, the spatial boundary and simplified geometric shapes corresponding to physical objects should be further provided for input parameters and constraints. Furthermore, design and analysis models should be exactly placed in specific locations for the CFD analysis with the help of visual key features. Finally, analysis results will be spatially augmented into the physical space, which can provide a new and innovative way of design and analysis review in the physical environment.

We use Tango^{TM} device to extract the augmented reality based spatial and geometric shape information for the real environment and to construct the 3D map and 3D models of the real environment and physical shapes. Because Tango^{TM} has an RGB-D camera, it can extract 3D point cloud information in real time while freely moving in a space like an office. The augmented reality environment has been implemented using Unity3D [15]. First, a space boundary is reconstructed to augment the geometric shapes & analysis models. Then, the user touches all parts of the wall, ceiling, and floor through the Tango^{TM} display. The shape of the spatial boundary can be not only a box shape but also a different 3D volumetric shape. After the spatial boundary is constructed, a geometric shape inside the spatial boundary is also created. The geometric shape can be modeled with various basic shapes such as a box, sphere, a cylinder and a sketch-based 3D shape. In addition, if a 3D model exists, it can be augmented to a desired position in the real space without generating a geometric shape (Figure 5).

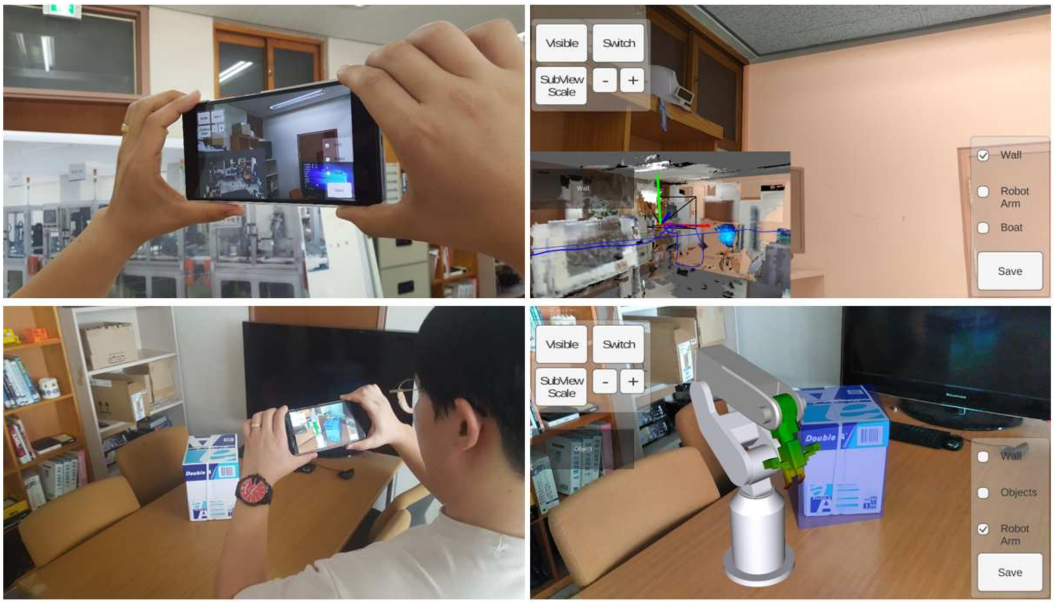


FIGURE 5. Implementation results: scanning the physical environment, constructing spatial boundary, and augmenting an M&S result into the physical space

5. **Conclusions.** This paper proposed a new approach to extracting augmented reality-based spatial and geometric information for design and analysis review using a smart device with an RGB-D camera. The proposed method scans the physical environment with the camera, learns the 3D spatial area by key feature identification, and then extracts 3D point clouds for constructing geometric environment. In addition, the user interacts with the learned area to superimpose design & analysis models into AR-based physical environment. Furthermore, the user can select points, draw lines, sketch arbitrary polygonal shape, and/or construct 3D geometric shape or space. Therefore, the proposed approach can help users to more naturally superimpose various kinds of design & analysis models into the physical environment without conventional 2D markers.

However, when modeling a simplified geometric shape, the user has to manually construct it by directly specifying vertices or height. However, in future studies, we will improve the proposed method to automatically classify and generate it by the object segmentation algorithm based on the 3D point cloud instead of manual generation. We will also perform a usability analysis to evaluate the proposed approach.

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